sustainability

MDPI

Article

The Prospect and Future of Green Hydrogen in the Continent of Africa

Firoz Alam [1,*], Yingai Jin [2], Xingjun Hu [2], Nawshad Haque [3], Masud Rana [1], Saifuddin Ahsan [1], Ivan Tolj [4] and Quamrul Alam [5]

1 School of Engineering (Aerospace, Mechanical and Manufacturing), RMIT University, Melbourne, VIC 3000, Australia; s3587163@student.rmit.edu.au (M.R.); s3847808@student.rmit.edu.au (S.A.)
2 College of Automotive Engineering, Jilin University, Changchun 130022, China; jinya@jlu.edu.cn (Y.J.); hxj@jlu.edu.cn (X.H.)
3 Commonwealth Scientific and Industrial Research Organisation (CSIRO), Melbourne, VIC 3168, Australia; nawshad.haque@csiro.au
4 Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, HR-21000 Split, Croatia; itolj@fesb.hr
5 School of Business and Law, Central Queensland University, Melbourne, VIC 3000, Australia; q.alam@cqu.edu.au
* Correspondence: firoz.alam@rmit.edu.au

Abstract

Hydrogen (H_2) produced by renewable energy offers a unique opportunity for a green energy transition, especially when dealing with hard-to-abate industries such as fertiliser, steel, and heavy transportation. Having vast renewable energy potential, the continent of Africa is expected to be a green H_2 production leader, aiding the world's clean energy transition. The aim of this study is to examine the possibilities, obstacles, and future of green H_2 production in Africa. The study has reviewed Africa's announced green H_2 projects and initiatives and examined the continent's renewable energy (solar and wind) and its potential impact on electrification and green H_2 production. The study reveals that green H_2 produced in Africa using solar energy is expected to cost between \$6/kg and \$10/kg. In arid regions with abundant solar energy but limited water resources, LCOH levels would rise sharply. There is a considerable regional variation in the predicted levelised cost of green H_2 produced by wind power across Africa. At a capacity factor of 40% or more, the lowest LCOH costs about \$6/kg, while at a factor of 10% or lower, it costs about \$26/kg. The total announced investment in green H_2 projects across 16 African countries amounts to approximately 293 billion US dollars; this includes 11 projects in very early stages, 4 projects in emerging stages, and 1 project in the exploratory (aspiration) stage. Considering current and expected green H_2 technology readiness, cost, global market opportunity, resource availability, and relevant infrastructure, this study proposes a six-stage comprehensive strategy roadmap for green H_2 production in Africa. The study also finds that the African continent can achieve more socioeconomic development by focusing on universal electrification and industrialisation instead of primarily focusing on green H_2 production by renewable energy for export. Establishing green H_2 as a mainstream commodity is a multi-stage process that would unfold over decades, not years. Africa's immediate focus would be better served by moving a small number of viable pilot projects to FID, while unrealistic production targets should be reset and paused based on market realism.

Keywords: African continent; clean (green) hydrogen; solar energy; wind energy; electrification; electrolyser; levelised cost of hydrogen (LCOH); electrolyser technology readiness

Check for updates

Academic Editor: Krzysztof Sornek

Received: 21 August 2026
Revised: 18 October 2026
Accepted: 20 October 2026
Published: 25 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Hydrogen is increasingly becoming a global focus as a reliable energy carrier to decarbonise the energy-intensive industrial and transport sectors. It is the most utilised element in industrial processes, serving as a key feedstock and energy source. Currently, "grey hydrogen" leads the H_2 sector; it is produced from natural gas via steam methane reforming (SMR). The production of "blue hydrogen" follows the same process as grey hydrogen but incorporates carbon capture and storage (CCS) technology. In contrast, "green hydrogen" holds significant potential for reducing greenhouse gas emissions, as it can be produced through water electrolysis using renewable energy sources such as solar and wind [1]. Global production of H_2 surpassed 110 million tonnes in 2025 [2]. The current global market for H_2 is approximately 174 billion US dollars and continues to grow annually. H_2 is primarily used as a feedstock for ammonia production, refining, and basic chemicals. At present, the production of H_2 relies on fossil fuels for over 99% of its output. To achieve decarbonisation and net-zero goals, a transition to "green H_2" is essential to meet existing demand. Decarbonising these "hard-to-abate" industries is expected to lead to nearly a six-fold increase in global H_2 demand by 2050. Consequently, there is an ongoing international effort to produce green H_2 at a reduced cost, aiming to match the prices of grey or blue H_2 by leveraging renewable energy sources (primarily solar and wind) and cost-effective technologies.

The projected utilisation of H_2 based on production energy sources by 2050 is illustrated in Figure 1a while Figure 1b presents H_2 production categories using colour codes that correspond to various energy sources and technologies [3]. As shown in Figure 1a, blue H_2 is anticipated to dominate the market by 2050, resulting in a significant reduction in the production of CO_2-intensive grey H_2. Additionally, while Figure 1a indicates that green H_2 production is expected to increase and make a notable contribution to the H_2 energy mix by 2050 and beyond—due to advancements in technology and decreasing costs—it is projected to remain relatively minor overall. In contrast, blue H_2 is expected to account for three-quarters (¾) of the global H_2 market by reducing grey H_2 production, contingent upon the successful scaling and maturation of carbon capture and storage (CCS) technologies.

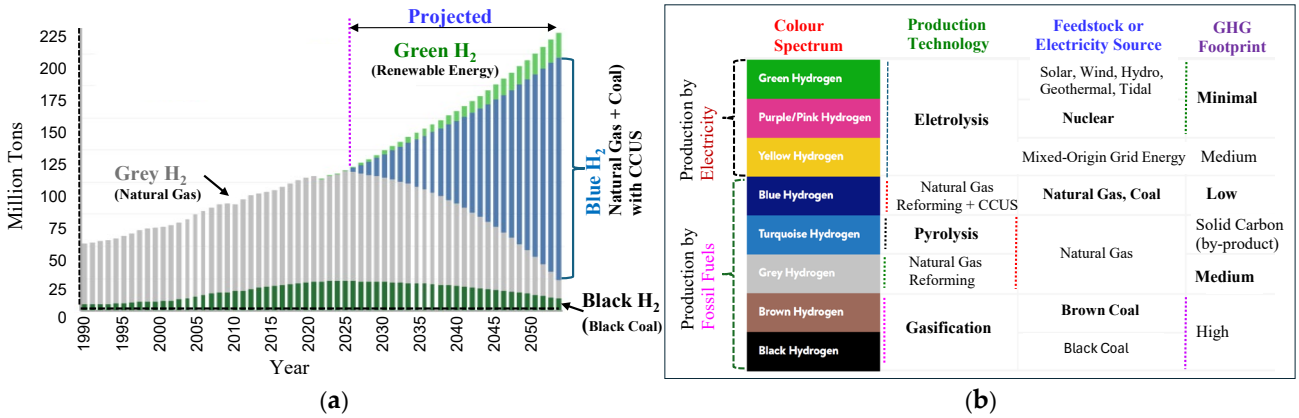


Figure 1. Global H_2 demand, current and future production by energy sources. (**a**) Global H_2 demand (1990–2050) [4]; (**b**) H_2 colour code based on energy source and production method.

The continent of Africa is a focal point because of its immense potential for green H_2 production. Even though the continent is rich in resources, there are enormous energy-related challenges. Well over 640 million people in Africa do not have access to electricity. The continent has the world's lowest electricity access rate, a little over 40% [5,6]. With an average continental consumption of 617 kWh, Sub-Saharan Africa (excluding South Africa) has a per capita power consumption of just 180 kWh, much lower than the 13,000 kWh per capita in the USA, 6500 kWh in Europe, 10,000 kWh in Australia, and 3500 kWh in

Asia [7–9]. In addition, renewables are still in their infancy, making up just 20% of Africa's power mix, with 15% coming from hydropower and only 5% from other forms of renewable energy (mainly solar and wind) [10]. The UN's Sustainable Development Goal (SDG) 7 is to ensure that all people have access to affordable and clean energy; similarly, the UN's SDG 2 is to eliminate hunger, ensuring food security. Both goals are envisioned to drive sustainable socioeconomic development, 'access to power' and industrialisation. In this context, first and foremost, developing nations, particularly those in Africa, are in desperate need of attaining universal electrification and energy self-sufficiency. It is critical to evaluate the possible effects on energy availability for the majority of the population in Africa, as 32 of the world's 44 least developed nations are located there. Given its vast untapped economic, demographic and social potential, Africa deserves more attention. With the current population growth rate, Africa is projected to become the world's second-most populous continent, led by Nigeria, the Democratic Republic of the Congo (DRC), Ethiopia, and Egypt, with an estimated 2.5 billion people by 2050 [7,10]. Thus, new consumer markets will emerge in future, the world's ecosystem and migratory patterns between continents are set to be altered, and sustainability transitions will be influenced, leading to significant economic growth and development opportunities for African nations [11], particularly in sectors such as renewable energy, agriculture, and technology. Before focusing on energy transitions and usage between regions and continents, Africa must prioritise using, monitoring, and managing its energy and mineral resources for the welfare of its people [12–14].

The energy security risks facing Africa have not been thoroughly studied, analysed, or reported in the open literature. Researchers and policy analysts have paid less attention to the resource curse risks associated with potential green H_2 exports from Africa compared to other energy sources. While a growing trend in the literature compares the rollout of green H_2 in Africa to extractivism, much of this research remains broad and lacks the in-depth analyses necessary to adequately address the complex socioeconomic needs and environmental impacts on local communities and the wider population [7,15].

Table 1 highlights a significant knowledge gap in the contemporary literature from open sources concerning the utilisation of Africa's energy resources for electrification and sustainable green H_2 production. The table also highlights the knowledge gap regarding the need for a strategic roadmap that prioritises energy resources for electricity generation alongside a focus on green H_2 production, which can lead to accelerated industrialisation, job creation, a transition to green energy, and decarbonisation in Africa.

Table 1. Contemporary literature and knowledge gaps in green H_2 initiatives in Africa.

Author (s)	Key Findings	Knowledge Gaps
Sadik-Zada et al. [7]	• Analysed Western nations' green H_2 initiatives and projects in Africa, primarily Egypt, Morocco, Namibia, and South Africa. • The European Union is shifting its energy dependence from Russia/the Middle East to African nations, with political and economic consequences.	• No H_2 roadmap for Africa is proposed. • Importance of universal access to electricity for Africa's nations is not underscored. • Geopolitical and long-term economic consequences and impact of value chains were not elaborated.
Msweli et al. [16]	• Study focused on green H_2 technologies and their role in sustainable energy access in remote and off-grid areas within Sub-Saharan Africa. • The study explored H_2 production suitability in Africa. • The study highlighted the necessity of public subsidies for green H_2 production due to the scarcity of finances and water in Sub-Saharan Africa.	• No H_2 roadmap for Africa is proposed. • Importance of universal access to electricity for Africa's nations is not underscored. • Geopolitical and long-term economic consequences and impact of value chains were not elaborated. • No evaluation of announced green H_2 projects in Africa or elsewhere.

Table 1. *Cont.*

Author (s)	Key Findings	Knowledge Gaps
Egli et al. [17]	• Mapping the cost competitiveness of African green H_2 imports to Europe. • Undertook a techno-economic study of H_2 exports to Europe. • Predicted green H_2 cost under a range of scenarios.	• No recommendations and conclusions were made from the study. • No H_2 roadmap for Africa is proposed. • The importance of universal access to electricity for Africa's nations is overlooked.
Uhrorakeye et al. [18]	• The study highlighted Africa's potential for green H_2, and current green H_2 project initiatives. • Over 80% of current green H_2 initiatives funded by European countries as loans. • Green H_2 projects in Africa are negligible on a global scale. • Significant gaps were found in policy formulation and infrastructure, as well as a shortage of skills.	• The need for universal access to electricity for Africa's nations is not underscored. • Geopolitical and long-term economic consequences and impact of value chains were not elaborated. • No H_2 roadmap for Africa is proposed.
Tiktas and Hepbasli [19]	• The study focused on seven elements: a) water sourcing, b) land issues, c) procedural justice, d) benefit-sharing, e) local value-capture instruments, f) environmental safeguards, and g) monitoring and enforcement capacity on potential green H_2 production in selected countries of Africa.	• No H_2 roadmap for Africa is proposed. • Discussion on universal access to electricity for Africa's nations is not underscored. • Geopolitical and long-term economic consequences and impact of value chains were not elaborated.
Chigbu et al. [5]	• The study analysed green H_2 production and its impact on Africa's land, environment, ecology and socio-economy. • Underscored green H_2 production's adverse effects on land, water resources, ecology, society, and environment. • Doubtful about potential for green H_2 from Africa to foster a global green H_2 transition.	• No H_2 roadmap for Africa is proposed. • Geopolitical and long-term economic consequences and impact of value chains were not elaborated. • Discusses land-based infrastructure and export facilities.
Lahnaoui et al. [20]	• The study focused on the feasibility of green H_2 economies in western and southern African regions and their readiness for green H_2 production and exports. • Underscored the complexity of developing green H_2 economies and highlighted the need for nuanced, region-specific approaches considering technical, socioeconomic, geopolitical, and environmental factors.	• No H_2 roadmap for Africa is proposed. • The study does not emphasise the importance of universal access to electricity for the African continent. • The geopolitical and long-term economic consequences, as well as the impact of value chains, were not elaborated upon in relation to green H_2 production in Africa. • No assessment of announced green H_2 projects in Africa.
Dagnachew et al. [1]	• The study focused on foreign green H_2 initiatives in Africa and their political and socioeconomic consequences. • The study recommended African countries engage in equitable business partnerships with foreign countries and demand technology transfer.	• No H_2 roadmap for Africa is proposed. • The study did not examine the significance of providing universal access to electricity for Africa's population and its impact on socioeconomic development. • No critical review of announced green H_2 projects in Africa or other parts of the world.
Medinilla & Dekeyser [21]	• Looked at the prospect of green H_2 for future industrialisation in Africa. • Highlighted the necessity of high-risk associated green H_2 ventures that need comprehensive policies and plans.	• No H_2 roadmap for Africa is proposed. • Importance of universal access to electricity for Africa's population and industrialisation is not underscored. • Geopolitical and long-term economic consequences and impact of value chains were not elaborated upon.

Table 1. *Cont.*

Author (s)	Key Findings	Knowledge Gaps
Agyekum [22]	• Explored Africa's readiness for green H_2 production along with opportunities and challenges, especially land issues, skills shortages, and lack of a regulatory and policy framework. • Underscored Africa's potential for green H_2 production and characteristics of export to the European market.	• No H_2 roadmap for Africa is proposed. • Impact of electrification on Africa's population and industrialisation is not underscored. • Cost of green H_2 by renewable energy source (wind, solar) not explored.

As shown in Table 1, there are significant knowledge gaps in the literature regarding Africa's strategic roadmap for sustainable and profitable green hydrogen (H_2) production and export. There is a lack of critical reviews on announced green H_2 projects, both within Africa and globally. Furthermore, information on the levelised cost of green H_2 production in Africa, based on available renewable energy resources, remains scarce. Additionally, there is insufficient data on the need for electrification, particularly given that nearly half of the continent's population lacks access to electricity. Moreover, no comprehensive studies exist that assess the viability of green H_2 production for export, including the modes of shipment and purchase commitments from potential buyers. Therefore, the objectives of this study are to:

(a) Evaluate green H_2 production technology, readiness level, cost, and levelised cost of green H_2 in Africa.
(b) Analyse the possibilities and obstacles of green H_2 production in Africa in light of the continent's renewable energy potential, resources and global green H_2 project progress.
(c) Examine the impact of universal electrification with renewable energy on Africa's socioeconomic development and industrialisation.
(d) Recommend a comprehensive six-stage green H_2 production strategy and roadmap for the continent of Africa.

The findings of the study aim to assist stakeholders—including governments, policymakers, implementers, investors, researchers, and academics—who are involved in renewable energy, the green H_2 sector, electrification, and the global clean energy transition by aiding them in creating better policies and allocating resources effectively for the use of renewable energy in all areas where it is applicable, as well as for the production of green and low-carbon H_2 and its derivatives, such as ammonia (NH_3). A six-stage roadmap for comprehensive green H_2 production developed in this study aims to offer significant and innovative aspects that focus on integrating renewable energy sources with local socioeconomic needs, universal electrification, and industrialisation, along with an emphasis on collaboration among stakeholders to ensure successful implementation. The green H_2 production strategy roadmap proposed in this study is based on current global green H_2 project status as well as future technology development expectations.

The novelty of the study lies in the integrated assessment of Africa's renewable-energy and green H_2 potential and the development of a six-stage strategic roadmap that prioritises universal electrification, industrialisation, and local socioeconomic benefits alongside green H_2 development.

The article is structured as follows: Section 1 provides a general overview of the African continent, focusing on energy potential and knowledge gaps in the use of renewable energy as a priority. Section 2 elaborates the research approach and methodology. Section 3 reviews the current green H_2 production technologies, including their readiness levels, system capacities, efficiencies, critical minerals required, economic viability, and energy

balance. Section 4 explores Africa's renewable energy resources (solar and wind); green H_2 production potential; levelised cost; announced H_2 projects; and locations. Section 5 discusses the need for electricity in Africa and its impact on socioeconomic development, industrialisation, and GDP growth. Section 6 analyses the challenges of green H_2 production in Africa, encompassing the availability of land and water resources, export demand, the prospect of decarbonisation and socioeconomic development, green H_2 use in transport, and the role of Africa's critical minerals. Section 7 reviews the global status of green H_2 projects and outlines a strategic roadmap for green H_2 production in Africa, detailing stage-wise development by 2060. Section 8 provides a comprehensive discussion of Africa's priorities regarding electrification, green H_2 production, and the advantages of the proposed roadmap for H_2 production strategies and the mode of shipment for exports. Finally, Section 9 furnishes the major conclusions of the study and recommendations.

2. Research Approach and Methodology

This study adopts a structured evidence-review and quantitative comparative-analysis approach to examine the prospects, challenges, and future development of green H_2 in Africa. The methodological framework combines the collection, critical evaluation, validation, and synthesis of quantitative and qualitative evidence from the peer-reviewed literature, institutional reports, industry publications, and other relevant technical sources. The analysis focuses particularly on renewable electricity generation from solar and wind resources, green and low-carbon H_2 production technologies, technology readiness and performance, production costs, announced green H_2 projects, and the implications of renewable-energy allocation for electrification and industrial development in Africa.

Evidence was collected from a broad range of multidisciplinary and subject-specific databases and research libraries. The multidisciplinary sources included Scopus, Web of Science, and Google Scholar. The engineering and technology literature was obtained from ScienceDirect, Springer, Wiley, IEEE Xplore, INSPEC, and the ASCE Library, while energy- and environment-specific sources included Energy and Power Source, GreenFILE, and Environment Complete. Governmental and intergovernmental sources included reports and datasets from the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), U.S. Department of Energy (DOE), and National Renewable Energy Laboratory (NREL). Relevant industry evidence was obtained from sources including the Global Wind Energy Council (GWEC), BloombergNEF, McKinsey Energy Insights, BP Energy Outlook, and OPEC publications. Additional evidence was obtained from ProQuest Dissertations and Theses Global, peer-reviewed conference proceedings, government reports, and publications of international organisations, including the World Bank, International Monetary Fund (IMF), Asian Development Bank (ADB), African Development Bank, United Nations Development Programme (UNDP), Food and Agriculture Organization (FAO), and World Health Organization (WHO).

Data collected from these sources was used to establish the technological, economic, resource, and socioeconomic context of renewable energy and H_2 development. Particular attention is given to evidence concerning solar and wind resources, H_2 production technologies, technology readiness, production efficiency and cost, announced green H_2 projects, infrastructure requirements, and constraints affecting large-scale deployment. Rather than considering the retrieved evidence independently, the study comparatively synthesises information from different sources to identify consistencies, variations, technological and economic constraints, and implications for green H_2 development in Africa. Citation tracking was additionally employed to improve the coverage of the relevant literature. Backward citation tracking involved examining the reference lists of key articles and foundational review studies to identify earlier relevant publications. Forward citation tracking was un-

dertaken primarily through Scopus and Web of Science to identify subsequent studies citing these publications. Where clarification of published information was considered necessary, the original authors or relevant experts were contacted when possible.

A modified PICO framework was used to organise and evaluate the collected evidence. In the context of this study, the population/system of interest (P) comprises renewable electricity and H_2 production systems relevant to Africa, including solar parks, onshore and offshore wind farms, green and low-carbon H_2 production systems, and national or regional electricity grids. The intervention/exposure/phenomenon of interest (I) encompasses the deployment and utilisation of renewable electricity and H_2 production technologies. The context (C) is the African energy system, with particular consideration of resource availability, electricity access, industrialisation, infrastructure, technology readiness, and socioeconomic conditions. The outcomes (O) include renewable-energy and H_2 production potential, technological performance and readiness, economic feasibility, production costs, project-development prospects, and implications for electrification and socioeconomic development.

Data validation and cross-checking were conducted, as renewable energy and H_2 datasets from various sources may differ due to variations in methodologies, definitions, reporting periods, and publication dates. In instances of conflicting values, comparisons were made across the available sources, taking into account their methodological and institutional credibility. Established international energy datasets and reports, particularly those published by the IRENA, IEA, and GWEC, were given greater weight where appropriate. If discrepancies could not be resolved directly from the published material, efforts were made to consult the original source or author when feasible. This validation process aimed to minimise inconsistencies that may arise from merging multiple datasets and reporting systems.

Finally, the validated evidence was synthesised in accordance with the objectives of the study. The analysis was used to assess Africa's renewable-energy and green H_2 potential and constraints; evaluate relevant technologies, technology readiness, and production costs; examine the relationship between renewable-energy development, universal electrification, and industrialisation; assess announced green H_2 projects in Africa in the context of wider global project developments; and formulate the proposed six-stage strategic roadmap for green H_2 development in Africa. This analytical sequence distinguishes the authors' synthesis and interpretation from the individual data and findings obtained from the underlying literature and institutional sources.

3. Green H_2 Production Technologies, Readiness Levels and Cost

Water electrolysis is the most dominant green H_2 production method. It uses renewable electricity, such as solar, wind, or hydro, to separate water into H_2 and oxygen. Alkaline, Proton Exchange Membrane (PEM), and solid oxide water electrolysis methods are the most common. Along with these, new technologies including photoelectrochemical processes, biological methods, and biomass gasification are appearing. These technologies are considered green when they produce almost no carbon dioxide emissions. Due to their numerous benefits and technological readiness levels, including increased efficiency, scalability, and their capacity to be integrated with renewable energy sources, alkaline, PEM, and solid oxide water electrolysis are the prime focus for green H_2 production. At each stage of technology development, from early fundamental research to full commercial implementation, technologies are evaluated using one of nine technology readiness levels (TRLs). TRL 1 represents the most immature stage, while TRL 9 indicates the most advanced. The levels are defined as follows: TRL 2 involves identifying practical applications and describing concepts; TRL 3 encompasses lab-scale testing and validation of critical functions; TRL

4 refers to small-scale prototypes tested in a controlled lab environment; TRL 5 includes prototypes tested in simulated or near-real environments; TRL 6 describes fully functional prototypes tested in realistic settings; TRL 7 involves near-production systems demonstrated under actual operating conditions; TRL 8 signifies the final system fully tested and certified for real use; and TRL 9 denotes the most advanced stage.

Technology readiness levels (TRLs) for electrolyser technologies show considerable variation, reflecting their developmental status from the research stage to commercialisation. To understand the technology readiness levels for each technology, it is essential to evaluate their status, challenges faced, and prospects for their use in global decarbonisation processes [2,23,24]. Among all electrolyser technology, Alkaline Water Electrolyser (AWE) is considered the most mature, with a technology readiness level (TRL) of 9, already in the commercial stage [25,26], as shown in Figure 2. This high maturity level is due to its long developmental history, robust design, and well-established manufacturing processes. The design of the AWE system is for operation under constant process conditions; however, efforts are being made to adapt it for operation with intermittent renewable energy sources such as solar and wind power [27]. For operational flexibility, conventional AWE systems require a minimum load of 40% to prevent gas crossover, though advanced systems with separated electrolyte loops can achieve minimum loads as low as 10–15% as shown in Figure 2c.

The stack lifetime of AWE is generally 80,000–100,000 h [28], the longest among electrolyser technologies. The cost of AWE stacks is predicted to fall substantially from US$261–419/kW in 2020 to US$56–85/kW by 2030, driven primarily by increased current density and the replacement of expensive materials with cheaper alternatives due to increased current density and the replacement of expensive materials. A similar reduction in CAPEX for PEM electrolysers is anticipated (see Figure 2a). By 2030, the CAPEX for both AWE and PEM electrolysers is expected to align closely. The CAPEX for AEM is projected to be comparable to that of both AWE and PEM electrolysers by 2045. In the case of SOEC, while the CAPEX is predicted to decrease, it would remain higher beyond 2050, as illustrated in Figure 2a. This future cost reduction potential, together with its maturity, positions the AWE as a key technology for affordable green H_2 production [29,30].

The Proton Exchange Membrane (PEM) electrolyser has a TRL of 7–8 as shown in Figure 2d, signifying its widespread use; however, it still encounters challenges related to cost and the long-term durability of iridium-based catalysts [23,25]. The PEM electrolyser is considered the most promising and effective technology for green H_2 production on an industrial scale due to its ability to produce high-purity H_2 with rapid response times to intermittent renewable energy sources. PEM is considered better technology for directly connecting to variable solar and wind power, as it has potential to deal with loads as low as 0–10% and has great operational flexibility. The stack lifetime ranges from 50,000 to 80,000 h, which is shorter than AWE due to membrane degradation and catalyst dissolution. The cost of a PEM stack was in the range of US$415–1157/kW in 2020; however, it is predicted to fall to US$268–253/kW by 2030, driven by increased current density, reduced catalyst loading, and manufacturing scale-up. Currently, research is being carried out to improve efficiency using optimisation of bipolar plates and flow channel patterns [31–33].

Solid Oxide Electrolyser Cells (SOECs) are currently at the laboratory scale and considered at a TRL of 5–6, as shown in Figure 2d, signifying pilot-scale demonstrations, but are presently hindered by high-temperature material stability and system integration issues. SOECs are a promising method for reducing CO_2 emissions and generating H_2 fuel, especially when coupled with renewable sources of energy. The thermolytic and kinetic benefits of SOECs ensure their promising potential for direct integration into electric grids and subsequent chemical synthesis pathways. SOECs operate at high temperatures, using waste

heat from industries for increased efficiency. However, operational issues currently hinder the scaling up of SOECs, necessitating mitigation for increased H_2 production. Presently, SOECs have limited operational flexibility with a minimum load requirement of 20–30% due to thermal gradient constraints, and cold start times exceeding 600 min make them unsuitable for direct renewable integration. Stack lifetime is currently 10,000–30,000 h, significantly shorter than low-temperature alternatives [34–36].

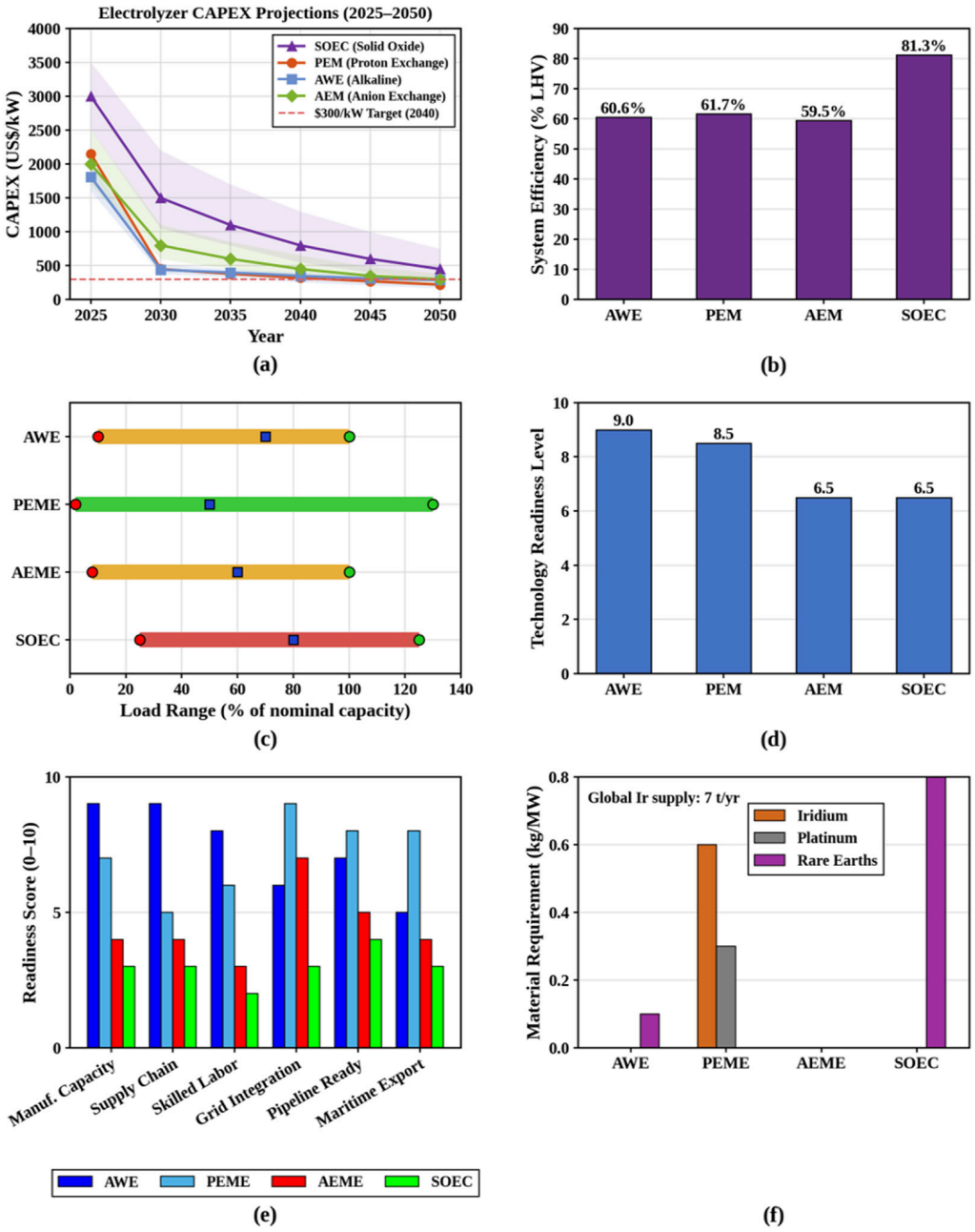


Figure 2. Techno-economic and material intensity metrics for water electrolysis technologies. (**a**) CAPEX projection (2025–2050, normalised), (**b**) system efficiency (% LHV), (**c**) operating load range (% of nominal capacity), (**d**) technology readiness level (TRL), (**e**) technology readiness score, (**f**) global material supply risk. Note: The projection of development extending to 2050 serves as the study's long-term planning horizon. Developments occurring beyond 2050 are subject to considerably greater uncertainty concerning factors such as population growth, technological advancements, costs, policies, and infrastructure.

The Anion Exchange Membrane (AEM) electrolyser is an emerging method, presently at a TRL of 6.5 as shown in Figure 2d. AEM aims to combine the low-cost material advantages of AWE (using non-precious metal catalysts) with the design simplicity and dynamic response capabilities of PEM. AEM is a promising method for cost-effective, non-precious group metal operation, but validation of AEM longevity and performance is required. AEM electrolysers can operate with a satisfactory partial load capability with a minimum load range of 5–12%, positioning them between AWE and PEM in terms of operational flexibility [2,25].

Figure 2e presents the readiness scores for each of the four electrolysers, evaluated according to factors such as manufacturing capacity, advancements in the supply chain, the availability of skilled human resources, grid integration capabilities, pipeline readiness, and maritime export potential. However, current stack lifetime is limited to 5000–10,000 h, with rapid performance decay at elevated current densities due to membrane degradation. AEMs seek to combine the benefits of AWE (cost-effective materials) and PEM (high density, dynamic operation), making AEMs a promising method for cost-effective, efficient, and green H_2 production [37,38].

A multi-dimensional sensitivity analysis of the costs of making green H_2 is shown in Figure 3. It also shows the most important factors that would affect cost competitiveness by 2050. The analysis is divided into three parts: (a) cumulative cost reduction potential from key drivers, (b) sensitivity to capital expenditure (CAPEX) and electricity costs, (c) sensitivity to system efficiency and annual full load hours, and (d) sensitivity to weighted average cost of capital (WACC) and stack lifetime [26,39,40].

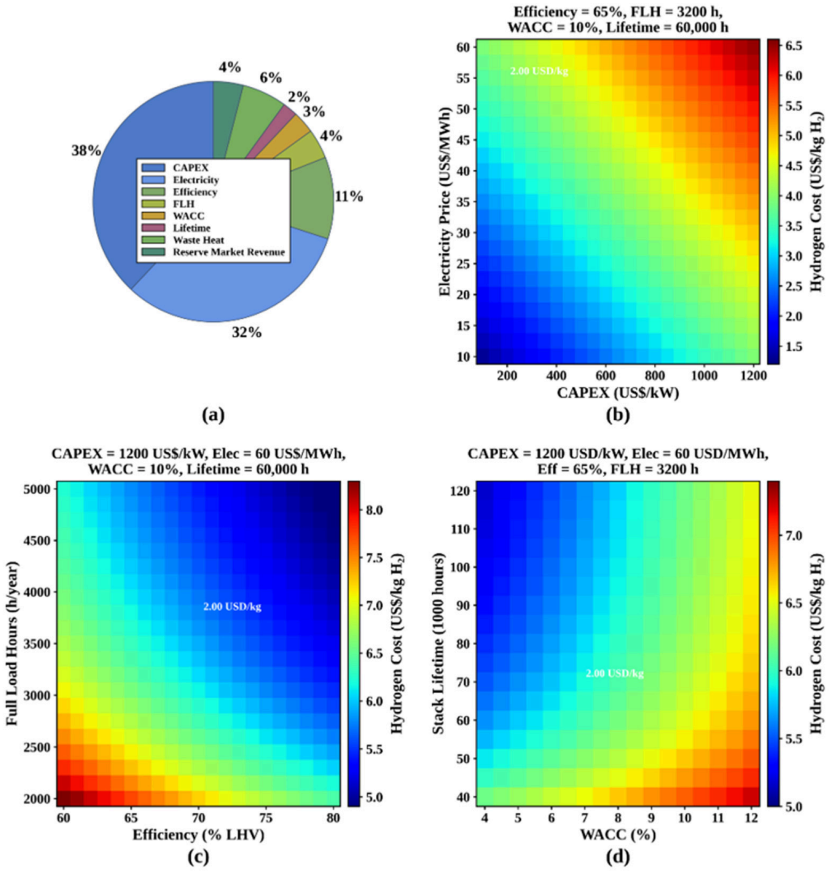


Figure 3. (**a**) H_2 cost reduction potential by 2050 considering potential cost parameters, (**b**) sensitivity of H_2 cost to efficiency and full load hours, (**c**) sensitivity of H_2 cost to CAPEX and electricity cost, and (**d**) sensitivity to weighted average cost of capital (WACC) and stack lifetime. Note: FLH denotes full load hour in Figure 3a.

3.1. System Boundary and Functional Unit

This study adopts a cradle-to-gate system boundary. The analysis includes renewable electricity generation, water treatment, and electrolysis. Downstream processes—including H_2 compression, storage, transport, and end use—are excluded unless explicitly stated.

The functional unit is 1 kg of green H_2 produced at the electrolyser gate. All costs are expressed in US$ per kg H_2 (US$/kg H_2), and all water consumption is expressed in litres per kg H_2 (L/kg H_2).

Where LCOH values from other studies are cited for comparison, any expansion of the boundary (e.g., to include compression) is stated explicitly in the relevant table footnote. This boundary is consistent with common LCOH conventions in the literature and ensures comparability across studies.

3.2. LCOH Estimation Approach

The generalised H_2 cost estimation framework shown in Equations (1)–(4) is used to determine the levelised cost of green H_2 production. The model integrates key cost drivers, including electrolyser capital cost (CAPEX), operational expenditures (OPEX), inflation, discount rate, and salvage value, while adjusting for regional variations in electricity, water, and O&M costs. The levelised cost of H_2 (LCOH) is estimated using a discounted cash flow formulation as given in Equation (1).

$$\mathrm{LCOH} = \frac{\mathrm{CAPEX}_{el} + R_{cost} + \sum_{y=1}^{n}\left[\mathrm{OPEX}_{fix,annual}\cdot(1+i)^{y}\cdot\frac{1}{(1+r)^{y}} + \mathrm{OPEX}_{var,annual}\cdot\frac{1}{(1+r)^{y}}\right] - \frac{SV}{(1+r)^{n}}}{\sum_{y=1}^{n} m_{H_2,annual}(y)\cdot\frac{1}{(1+r)^{y}}} \quad (1)$$

where:

LCOH: Levelised cost of H_2 (US$/kg).

CAPEX_{el}: Total electrolyser system cost (US$), where

$$\mathrm{CAPEX}_{el} = \mathrm{CAPEX}_{el,US\$/kW}\cdot P_{el}$$

and $\mathrm{CAPEX}_{\mathrm{el,US\$/kW}}$ is the specific capital cost per kilowatt derived from technology-specific cost equations.

R_{cost}: Replacement cost (US$), representing stack replacement over the project lifetime.

$\mathrm{OPEX}_{fix,\,annual}$: Total fixed annual OPEX (US$/year), assumed as 4% of $\mathrm{CAPEX}_{\mathrm{el}}$.

$\mathrm{OPEX}_{-var,annual}$: Total variable annual OPEX (US$/year), defined in Equation (2).

$$\mathrm{OPEX}_{var,annual} = E_{cost,annual} + W_{cost,annual} \quad (2)$$

where $E_{cost,annual}$ is the annual electricity cost and $W_{cost,annual}$ is the annual water cost. Twelve (12) litres of water was assumed to be required per kilogram of H_2. Desalinated water was considered at a cost of 3 US$/m^3.

i: Country-specific inflation rate as per the World Bank data 2023–2024.

r: Discount rate (7%, typical).

SV: Salvage value (US$), assumed as 3–4% of $\mathrm{CAPEX}_{\mathrm{el}}$.

n: Project lifetime (25 years).

y: Year index (1, 2, ..., n).

$\mathrm{m}_{H2,annual(y)}$: Annual H_2 production in year y (kg/year), defined in Equation (3).

$$m_{H_2,annual}(y) = \frac{P_{el}\cdot CF_{el}\cdot 8760}{SEC} \quad (3)$$

where:

P_{el}: Installed electrolyser capacity (kW);

CF_{el}: Electrolyser capacity factor (0–1);
8760: Annual operating hours (hours/year);
SEC: Specific energy consumption (kWh/kg H_2).

Therefore, the denominator of Equation (1) can be written equivalently as shown in Equation (4).

$$\sum_{y=1}^{n} m_{H_2,annual}(y) \cdot \frac{1}{(1+r)^y} = \sum_{y=1}^{n} \left(\frac{P_{el} \cdot CF_{el} \cdot 8760}{SEC} \right) \cdot \frac{1}{(1+r)^y} \quad (4)$$

The cost reduction parameter for levelised cost of H_2 (LCOH) is shown in Figure 3a, which illustrates the percentage of future cost reduction potential due to technology innovation and ongoing research. Starting from a baseline configuration of 1200 US$/kW CAPEX, 65% efficiency, and 8% WACC, reducing CAPEX to US$400/kW yields a 38% reduction in H_2 production cost. Improving electrolyser efficiency to 75% contributes an additional 4% cost saving, while lowering the weighted average cost of capital (WACC) to 4% reduces costs by a further 6%. Incorporating reserve market revenue at 15% provides an additional 4% reduction. Collectively, these cumulative improvements indicate that green H_2 production costs could decline by more than 50% by 2050 under optimised conditions.

Figure 3b illustrates the two largest costs: the cost of electricity and the cost of capital. The cost of electricity is the primary factor, and reducing it from US$60/MWh to US$20/MWh results in significant savings. Although cuts to CAPEX are important, their impact is relatively minimal. This indicates that access to affordable renewable electricity is crucial for making green H_2 competitive in terms of pricing.

The sensitivity of H_2 production cost to electrolyser efficiency and full load hours reveals distinct trends as shown in Figure 3c. While efficiency improvements yield cost reductions, the marginal benefits diminish beyond the 70–75% efficiency threshold. In contrast, increasing full load hours—representing higher electrolyser utilisation—produces a consistent, near-linear decline in H_2 cost. This finding underscores that maximising operational uptime is often more impactful than pursuing incremental efficiency gains. The analysis also reveals that by 2050, the principal determinants of green H_2 cost competitiveness are expected to be: (i) low-cost renewable electricity, with threshold values below US$20–30/MWh; (ii) high electrolyser utilisation rates, expressed as annual full load hours; and (iii) sustained capital expenditure reductions driven by economies of scale and learning-by-doing. Attaining cost parity with fossil-based H_2 necessitates securing abundant, low-cost renewable energy resources and maximising operational capacity factors. Although efficiency enhancements and favourable financing conditions contribute to overall cost reductions, they remain insufficient as standalone measures [26,41,42]. The expected improvement in green H_2 cost competitiveness towards 2050 is associated with the anticipated declining solar and wind CAPEX/OPEX, lower electrolyser CAPEX through technological learning and economies of scale, improved electrolyser operating flexibility at lower minimum loads, and higher utilisation through the optimisation of the renewable-generation-to-electrolyser capacity ratio. These factors increase annual full-load hours and reduce the contribution of electrolyser CAPEX to the LCOH.

3.3. Economic Viability of Green H_2

The economic viability of green H_2 in Africa lies in comparing it to the conventional H_2 production pathways. Techno-economic analyses from different sources, including the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA), show distinct cost tiers among production methods [2,26,43]. Grey H_2 produced via steam methane reforming (SMR) without carbon capture remains the least expensive option at US$1.50–2.50/kg. This pathway currently dominates global H_2 supply (~95% of total H_2 demand) but produces a substantial carbon footprint of 10–20 kg CO_2e/kg H_2. For African

nations with natural gas resources (Nigeria, Algeria, Mozambique, Egypt), grey H_2 presents a low-cost baseline against which green alternatives must compete. However, carbon pricing mechanisms exceeding US$100/ton CO_2 are projected to render grey H_2 uncompetitive by 2030 in the European market. Figure 4 shows the projected levelised cost trends of green, grey, and blue H_2 from 2025 to 2050 [39,44,45]. On the other hand, blue H_2 combining SMR with carbon capture and storage (CCS) costs around US$2.00–US$3.50/kg [39,46]. The figure also indicates that the levelised cost of green H_2 is expected to be on par with the cost of blue H_2 by 2048 and grey H_2 by 2045.

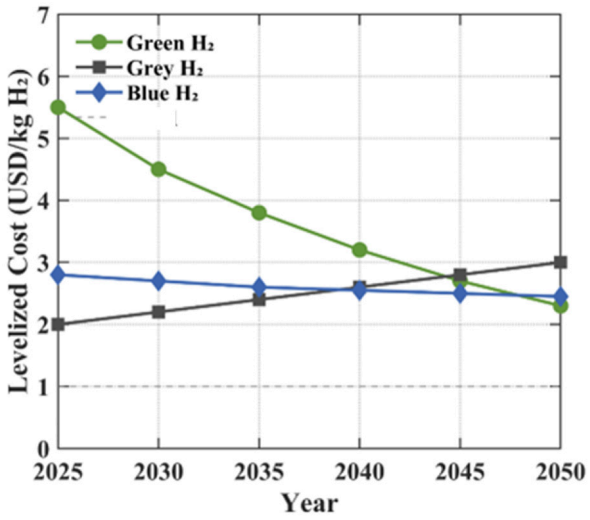


Figure 4. LCOH based on different energy sources.

This pathway offers a transitional option for fossil fuel-endowed African countries, potentially leveraging existing natural gas infrastructure while reducing emissions by 56–93%, depending on capture rates. However, blue H_2 economics will be dominated by CCS costs, natural gas price volatility, and regulatory support mechanisms [39]. Green H_2 produced via renewable-powered electrolysis currently costs US$3.50–US$6.00/kg—approximately 2–4 times higher than grey H_2. This current price gap of US$2.00–US$4.00/kg represents the fundamental economic challenge facing African green H_2 development. The cost of electricity constitutes more than 64% of the levelised cost of H_2 (LCOH) for all electrolyser technologies, making renewable electricity prices the dominant cost driver [39]. A reliable water supply system for H_2 production is particularly challenging due to high transportation expenses over long distances. Therefore, H_2 production facilities must be located near sustainable water sources such as rivers, aquifers, or desalination plants (albeit at high cost) to ensure both technical feasibility and economic viability [47]. Table 2 presents a side-by-side comparison of different H_2 production pathways, including their conversion efficiency, cost range, technology readiness level (TRL), constraints, and regional deployment capacity.

As shown in Table 2, the AEM values are based on published techno-economic assessments reporting LCOH average values of around US$5.50/kg H_2 under baseline conditions, with potential reductions under favourable electricity prices and scale assumptions. For SOECs, published projections indicate approximately US$3.2/kg H_2 depending on electricity/heat costs, plant scale, efficiency, and technology assumptions [48–50].

Table 2. Quantitative comparison of H_2 production pathways [47–50].

Production Pathway	Conversion Efficiency (% LHV)	Cost Range (US$/kg H_2)	TRL	Limitations	Regional Deployment Capacity
Grey H_2 (SMR without CCS)	65–75	1.50–2.50	9	High CO_2 emissions (10–20 kg CO_2e/kg H_2).	Global; 70 Mtpa production; concentrated in regions with natural gas (Middle East, North America, Russia).
Blue H_2 (SMR with CCS)	60–70	2.00–3.50	7–8	CCS capture rates 56–93%; requires CO_2 storage sites; 10–20% efficiency penalty.	North Sea, US Gulf Coast, Middle East; limited by CO_2 storage availability.
Green H_2—AWE	60–70	3.50–6.00	9	Lower current density (0.2–0.8 A/cm^2); gas crossover; slower dynamic response; corrosive electrolyte.	Africa, MENA, Latin America; regions with high solar/wind resources and baseload renewables.
Green H_2—PEM	60–70	4.00–7.50	7–8	Iridium scarcity (0.55–0.64 kg/MW vs 7 t/yr supply); strict ultrapure water requirement.	Europe, Japan, Korea; grid support applications; decentralised industrial use.
Green H_2—AEM	50–65	5.00–6.00 (projected)	5–6	Low durability membrane, and rapid decay at high current density.	Rural/off-grid applications; decentralised systems in low- and middle-income countries (emerging).
Green H_2—SOECs	70–85	3.50–5.50 (projected)	6–7	Thermal cycling constraints; materials degradation; rare earth dependence (Y, La); high operating temperature (700–900 °C); slow startup (>10 h).	Industrial clusters with waste heat; CSP regions; geothermal integration.

3.4. Quantitative Energy Balance of Green H_2 Production

The Sankey diagram in Figure 5 presents a quantitative energy balance for a green H_2 production system based on solar photovoltaic generation using the PEM electrolysis process. Of the total gross solar electricity input (100%), the system delivers 62% H_2 output on a lower heating value basis, with total system losses of 38–45% [2,26,51,52].

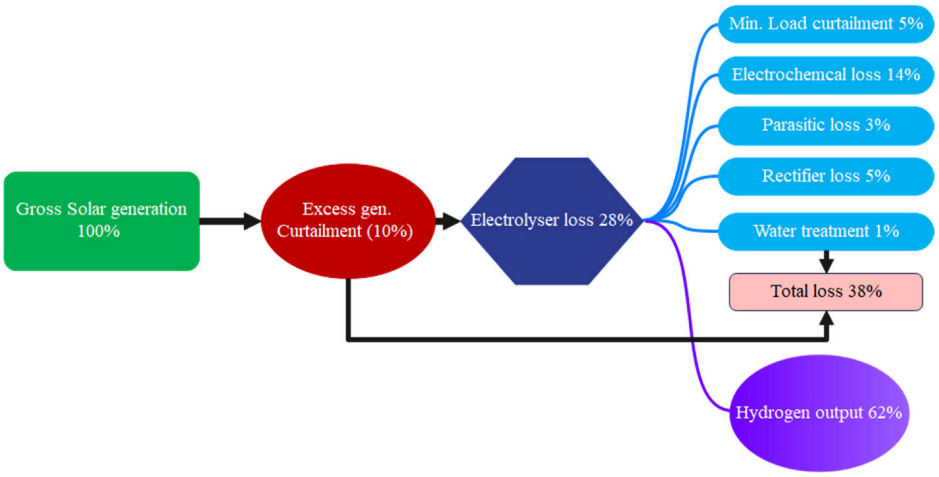


Figure 5. Solar-to-H_2 energy conversion and loss breakdown based on PEM electrolysis process.

These losses comprise curtailment (10–15%) due to load mismatch excess generation or grid constraints, minimum load curtailment (5%) arising from electrolyser partial load operation, electrochemical losses (14%) from stack inefficiency, rectifier losses (5%) from AC/DC conversion, parasitic losses (3%) for auxiliary systems such as cooling and pumps, and water treatment (1%). This energy balance aligns with industry benchmarks for PEM electrolyser systems, where typical system efficiencies range from 60 to 70% depending on operational conditions and technology maturity.

4. Africa's Renewable Energy and Green H_2 Potential

Africa possesses significant renewable energy sources (solar, hydro, wind, and geothermal). Table 3 shows current power generation by energy source, electrolyser deployment potential and probable H_2 production per year along with demineralised water needs. As shown in Table 3, twenty (20) major countries in Africa need an estimated 40 giga watt (GW) renewable power and fourteen (14) giga litres (GL) of demineralised water to produce approximately 1.4 million tons of green H_2.

Table 3. Estimated electricity generation in 2024 by twenty (20) major African countries [53–55] and electrolyser deployment potential, annual H_2 production and water demand.

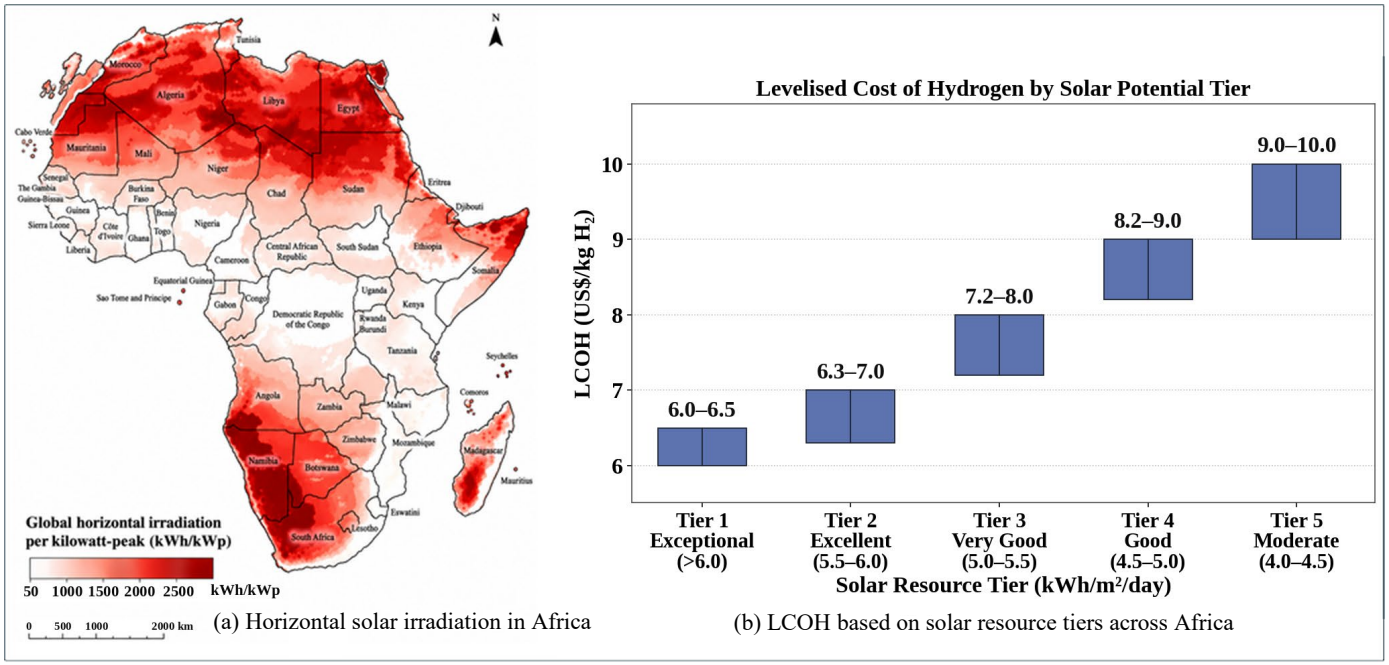
Country	Estimated 2024 Generation Terawatt-Hours (TWh)	Key Sources in 2024	Electrolyser Deployment Potential (GW)	Annual H_2 Production (Ton/Year)	Annual Water Demand (GL)
South Africa	220–240	Coal (~80%), renewables (wind/solar ~10%), nuclear and other (~10%)	10	418,182	4.18
Egypt	210–230	Natural gas (~75%), hydro, wind and solar (~25%),	12.54	400,000	4.0
Algeria	80–90	Natural gas (~97%), solar (<3%)	1.45	46,364	0.46
Nigeria	30–35 (grid) + off-grid	Gas (~80%), hydro (~19%), solar minimal on grid (~1%).	0.18	5909	0.05
Ethiopia	20–25 (GERD boosting)	Hydro (~90%), wind, solar (~10%)	1.28	40,909	0.409
Morocco	45–50	Coal (~60%), renewables (wind, solar, hydro) (~40%)	8.12	259,091	2.59
Libya	35–40	Oil and gas (almost 100%)	0	0	0
Ghana	25–30	Gas (~60%), hydro (~35%), solar, wind (~5%)	0.78	25,000	0.25
Kenya	12–15 (grid)	Geothermal (~40%), hydro (~30%), wind, solar (~10%))	0.76	24,545	0.24
Tanzania	10–12	Gas (~60%), hydro, renewables (~40%)	0.67	20,000	0.20
Angola	18–20	Hydro (~70%), gas, solar (~30%)	1.08	34,545	0.34
Zambia	18–20	Hydro (~85%), solar (~15%)	1.62	51,818	0.51
Zimbabwe	10–12	Coal (~50%), hydro (~50%)	0	0	0
DRC	10–12 (mainly hydro)	Hydro (~95%), wind, solar (~5%)	0.31	10,000	0.10
Côte d'Ivoire	12–14	Gas (~70%), hydro (~30%)	0	0	0
Senegal	6–8	Oil/gas (~80%), renewables (~20%)	0.59	19,019	0.19
Tunisia	22–24	Natural gas (~95%), renewables (~5%)	0.65	20,909	0.20
Sudan	15–18	Hydro (~60%), oil/gas (~40%)	0	0	0
Mozambique	20–22	Hydro (~80%, Cahora Bassa), gas (~20%)	0	0	0

Note: The comprehensive power generation data for 2025 in every African country is not yet available, as the data collection is ongoing and official datasets (e.g., International Energy Agency—IEA, U.S. Energy Information Administration—EIA, or African Development Bank—AfDB) typically lag by 1–2 years.

This study primarily focuses on solar and wind energy among the various renewable energy sources in Africa, as these resources are more widely available across the continent. They are also the main renewable sources linked to large-scale green hydrogen (green H_2) projects and the deployment of electrolysers. While geothermal resources have considerable potential due to their dispatchability and high-capacity factors, their geographical concentration requires specific geological and resource assessments tailored to particular locations.

4.1. Solar Energy in Africa

Africa possesses vast solar energy resources, with most regions receiving more than 2500 h of sunlight each year and having global horizontal irradiation (GHI) much higher than that of Europe, Asia, and much of North America. African countries are roughly grouped into five energy tiers, as depicted in Figure 6. As shown in Figure 6a, Tier 1 belongs mostly to Northern African nations and Namibia. The lowest tier is the moderate group with daily solar irradiation of 4 kWh/m^2 [56]. Figure 6b indicates the levelised cost (LCOH) of green H_2 based on daily solar irradiation. The estimated LCOH of green H_2 ranges from US$6/kg to US$10/kg. The lowest cost (US$6/kg) is in mainly desert regions of Tier 1 countries except Mauritania and Somalia. However, the desert region has acute water scarcity which would ultimately increase the LCOH. With moderate solar irradiation in Tier 5 countries, the LCOH of green H_2 is the highest (US$10/kg).



(a) Horizontal solar irradiation in Africa (b) LCOH based on solar resource tiers across Africa

Figure 6. Solar resources and LCOH based on tiers in Africa [57–59].

Capitalising on the renewable energy (solar, wind and geothermal) potential, a series of green H_2 project initiatives have been undertaken in African countries (Mauritania, Morocco, Namibia, Kenya, Egypt, Algeria, South Africa). The investors are mainly from Europe and the oil-rich Gulf region.

The underlying assumptions and expected LCOH in 2030 of these green H_2 projects are shown in Table 4. These ambitious projects rely on a set of shared underlying assumptions, which are Sustained Global Demand, Massive Investment Mobilisation, Infrastructure Development, and Technology Maturity and Cost Reduction within the next four years. A synopsis of these four underlying assumptions is highlighted below.

Table 4. Advantages of resources, infrastructure, LCOH and underlying assumptions.

Region/ Country	Resources Advantages	Infrastructure Advantages	Estimated LCOH (Wind/Solar) (US$/kg) in 2030	Underlying Assumptions
Mauritania	Solar & wind resources	• Recently established legal framework and dedicated authority. • Near European coast.	5.25/3.16	Government support will successfully de-risk projects and attract billions in foreign direct investment needed to build the required transmission and desalination infrastructure.
Morocco	Solar & wind resources	• Strategic ports (Tanger Med, Jorf Lasfar). • Salt cavern storage. • Proximity to Europe.	5.56/3.59	Morocco's proximity to Europe, combined with the EU's REPowerEU plan to import 10 million tons of green H_2 annually by 2030.
Namibia	Solar & wind resources	• Operationally integrated plant at Walvis Bay and port. • Dedicated H_2 Academy.	4.92/4.40	Skills and ecosystem built around green H_2 projects will enable Namibia to scale up rapidly and capture value through local industrialisation, such as green steel production.
Kenya	Geothermal, wind & solar resources	• Existing geothermal grid. • Coastal location for seawater uses. • Export via Mombasa.	5.66/6.83	Kenya can leverage its strong renewable base to create a dual-purpose facility, co-locating a large data centre with H_2 production to maximise economic efficiency and drive local industrial growth.
Egypt	Solar & wind resources	• Suez Canal Economic Zone (SCZONE) with port and power infrastructure.	4.91/3.19	Egypt's strategic location on a major global trade route, combined with strong government support and successful international partnerships (like with Norway's Scatec) will solidify its role as a regional and global export hub.
Algeria	Solar & wind resources	• Existing natural gas pipelines for conversion, industrial site at Arzew.	5.36/3.56	Algeria can leverage its established role as a strategic energy partner to Europe, using its industrial sites (like the 50 MW plant in Arzew) and existing pipelines to become a leading clean energy supplier.
South Africa	Solar & wind resources	• Proposed integrated corridor linking generation (Northern Cape) to export hub (Saldanha Bay).	5.17/5.17	Single-platform approach can solve grid bottlenecks and attract the estimated US$50 to US$150 billion in investment required over 15 years, generating up to US$8 billion in annual export revenue.

Sustained Global Demand: It is assumed that Europe and other markets would continue to prioritise decarbonisation and will import green H_2 and its derivatives (like ammonia and e-methanol) in massive volumes, despite potential competition from other global producers and geopolitical volatility [60,61].

Massive Investment Mobilisation: All these projects require billions of US dollars (or equivalent) in upfront capital. The assumption is that public funds (from development banks and government programmes) can successfully "de-risk" the initial stages, paving the way for large-scale private investment [62,63].

Infrastructure Development: Each country assumes it can build the necessary supporting infrastructure, which includes long-distance transmission lines, new or expanded port facilities, water desalination plants, and H_2 storage facilities, often in challenging environments [64,65].

Technological Maturity and Cost Reduction: The business models assume that the technology for producing, transporting, and using green H_2 will continue to mature and that

costs will fall along projected learning curves to make the fuel competitive with fossil fuels [60,66].

All these four assumptions are expected to be valid for the next four years (i.e., by 2030) to attain a levelised cost of green H_2 at around US$5/kg, which poses a significant challenge to achieve.

The solar energy potentials, major H_2 project initiatives, their maturity and announced investment in Northern Africa, Southern Africa, Eastern Africa, and Western Africa are shown in Table 5. The countries in Northern Africa, Southern Africa, and Eastern Africa have an average solar irradiation of 5.5 kWh/m^2/day, while the countries in Western Africa have an average of around 5.0 kWh/m^2/day. The table also shows that the daily solar irradiation among the countries in the same region is not uniformly spread. The total announced green H_2 project investment in Africa's 16 countries, totalling approximately 293 billion US dollars equivalent, is shown in Table 5, of which 11 projects are in very early stages, 4 projects are in the emerging stage and 1 project is in the exploration (aspiration) stage. As shown in Table 5, most of these projects have not reached the final investment decision (FID) stage yet.

Table 5. Solar potential, current status in Africa [57–59,67,68] along with project maturity and investment announcement.

Country	Solar Potential	Major Projects and the Status	Maturity	Investment in US$ Billion
Northern Africa				
Morocco	5.5–6.5 kWh/m^2/day	Noor Ouarzazate (580 MW CSP + PV)—world's largest CSP plant. Target: 52% renewable energy by 2030.	Emerging	31.0 (industrial rollout)
Egypt	5.5–7.0 kWh/m^2/day	Benban Solar Park (1.8 GW)—one of world's largest PV plants. Ambitious H_2 plans.	Emerging to mature	88.5 (planned investment)
Algeria	5.5–6.5 kWh/m^2/day	Solar programme for 15 GW by 2035. First large-scale plants operational in Saharan regions.	Early-stage	0.5–1.0 (planned)
Tunisia	5.0–5.5 kWh/m^2/day	Multiple 100 MW+ tenders. Strong focus on solar for desalination and industrial use.	Early-stage	1.0–2.0 (planned)
Southern Africa				
South Africa	4.5–6.5 kWh/m^2/day	REIPPPP programme: ~6.2 GW solar installed. Massive private investment due to energy crisis.	Mature (strategy), emerging (projects)	50.0–150.0 (corridor)
Namibia	6.0–7.0 kWh/m^2/day	Best solar resource globally. Green H_2 projects (Hyphen) driving multi-GW solar plans.	Emerging to mature	10.0–15.0
Botswana	5.5–6.5 kWh/m^2/day	Scaling up with 100 MW+ tenders. Ideal for mining sector decarbonization.	Early-stage	0.5–1.0 (planned)
Zambia	5.5–6.0 kWh/m^2/day	Scaling Solar programme successes. GET FiT programme expanding rooftop and utility-scale.	Early-stage	0.5–1.0 (planned)

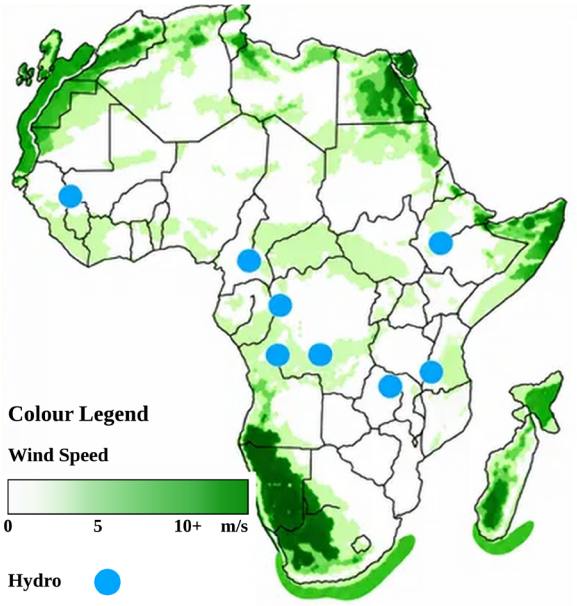
Table 5. *Cont.*

Country	Solar Potential	Major Projects and the Status	Maturity	Investment in US$ Billion
Eastern Africa				
Kenya	5.0–6.0 kWh/m^2/day	Garissa Solar (55 MW) + booming commercial and industrial (C & I) market. Strong pay-as-you-go solar home systems.	Early-stage	1.0–2.0 billion (planned)
Ethiopia	5.0–6.5 kWh/m^2/day	Tendaho Solar (125 MW) under construction. Ambitious 10-year plan for 10 GW solar.	Early-stage	1.0–2.0 (planned)
Tanzania	5.0–5.5 kWh/m^2/day	Scaling Solar programme (150 MW). Strong mini-grid development for rural electrification.	Early-stage	0.5–1.0 (planned)
Rwanda	4.8–5.2 kWh/m^2/day	8.5 MW solar plants + innovative mini grids. High government commitment.	Early-stage	0.2–0.5 (planned)
Western Africa				
Nigeria	4.0–6.0 kWh/m^2/day (North: Excellent)	1 GW + pipeline under development. Strong C & I market. World Bank support for 1 million solar connections.	Early-stage	2.0–3.0 (planned)
Ghana	4.5–5.5 kWh/m^2/day	Bui Solar (250 MW hybrid with hydro). Renewable Energy Master Plan targets 10% solar by 2030.	Early-stage	0.5–1.0 (planned)
Senegal	5.0–5.5 kWh/m^2/day	Several 30–50 MW plants are operational. Ambitious 30% renewable target by 2025.	Early-stage	0.5–1.0 (planned)
Mali	5.5–6.5 kWh/m^2/day	Excellent resource but limited development due to instability. Some mini-grid projects.	Exploratory	0.0

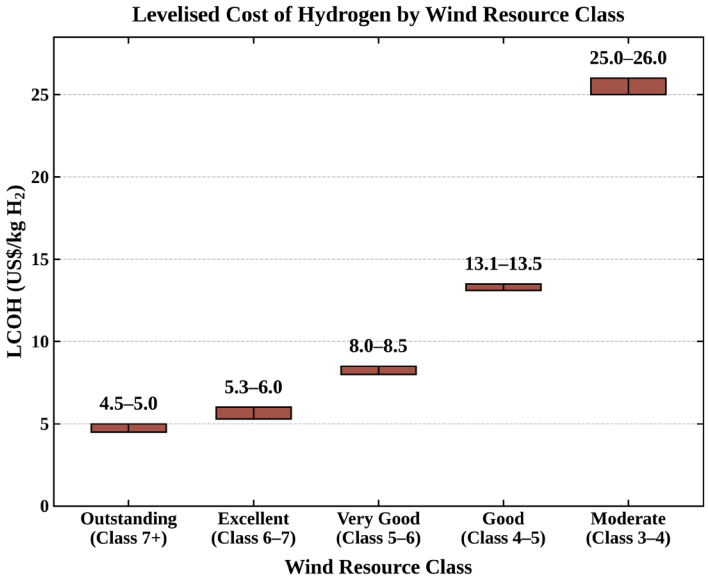
4.2. Wind Energy in Africa

Africa possesses abundant wind energy, particularly along coastlines, mountain ranges, and certain interior locations as shown in Figure 7 and Table 6. Although solar energy is the dominant source of renewable energy presently in Africa, wind provides valuable complementary power generation, particularly at night and during dry seasons. Additionally, wind has greater capacity factors compared to solar energy [69].

Table 6 presents the status of wind power in selected countries across Northern Africa, Eastern Africa, Southern Africa, and Western Africa. As of 2024, the continent's total installed wind power capacity was approximately 1.9 GW. The uptake of wind power in Africa has been considerably slower compared to other regions globally, accounting for only about 1% of the total installed wind capacity worldwide. This slow deployment of wind power can be attributed to a complex combination of financial, infrastructural, technical, and regulatory challenges. These challenges include limited investment, inadequate grid infrastructure, a lack of technical expertise, and insufficient policy frameworks that impede the development of wind projects.



(a) Wind and hydro energy distribution across Africa



(b) LCOH based on wind resource classification

Figure 7. Africa's continent-wise wind and hydro energy resource distribution, and LCOH based wind resource classes adapted from [70].

Table 6. Installed, under-construction and planned wind power projects in Africa [71–73].

Country	Key Resource Areas	Installed Capacity (2024)	Major Projects and the Status
Northern Africa			
Morocco	Atlantic Coast (Tarfaya), Tangier, Essaouira	1500+ MW (Africa's 2nd largest)	Tarfaya Wind Farm (301 MW)—Africa's largest until 2024. Target: 5 GW wind by 2030.
Egypt	Gulf of Suez, Red Sea coast, West Nile	1800+ MW (Africa's largest)	Gulf of Suez Wind Farms (multiple 500 MW+ projects). Green H_2 plans driving massive expansion (10+ GW pipeline).
Tunisia	Cap Bon, Bizerte, Sidi Daoud	245 MW	Several 100 MW projects under development. Strategic interconnection to Italy planned.
Algeria	Adrar (Saharan region), Kabylie coast	15 MW (minimal)	Vast potential but limited development. First major 10 MW project in Adrar operational.
Eastern Africa			
Kenya	Lake Turkana (extraordinary corridor), Ngong Hills, Marsabit	435 MW	Lake Turkana Wind Power (310 MW)—largest in Sub-Saharan Africa. Capacity factor ~62% (world-class).
Ethiopia	Tigray highlands, Adama region, Eastern escarpments	324 MW	Adama I and II (153 MW), Ashegoda (120 MW). Ambitious plans despite conflict setbacks.
Tanzania	Singida region, Makambako gap, Mufindi highlands	0.3 MW (negligible)	Singida Wind Farm (300 MW) under construction (2024 start). First major project.
Djibouti	Ghoubbet area, Gulf of Tadjoura	~0	Exceptional resources (9+ m/s). Pilot projects and feasibility studies for 50 MW+.

Table 6. *Cont.*

Country	Key Resource Areas	Installed Capacity (2024)	Major Projects and the Status
Southern Africa			
South Africa	Eastern/Western Cape coasts, Northern Cape interior	3400+ MW (Africa's leader)	REIPPPP programme driver: multiple 140 MW farms (e.g., Khobab, Loeriesfontein). Massive private investment (corporate PPAs).
Namibia	Lüderitz, Aus, Oranjemund (coastal)	55 MW	Lüderitz Wind Farm operational. Tsau Khaeb project (400 MW) in development for green H_2.
Mauritius/Réunion	Island wind corridors	70 MW (combined)	Important for island energy security. Challenged by land constraints but offshore potential.
Madagascar	Southern tip (Cap Sainte Marie), highlands	~0	Exceptional but completely undeveloped. 30 MW project planned at Cap Sainte Marie.
Western Africa			
Senegal	Taiba N'Diaye (first major project), coast	158 MW	Taiba N'Diaye Wind Farm (158 MW) operational. Additional 100+ MW in pipeline.
Mauritania	Nouakchott coast, Nouadhibou peninsula	35 MW	Nouadhibou Wind Farm (30 MW). Key for mining sector decarbonization (iron ore).
Cabo Verde	Across islands (Santo Antão, São Vicente)	30 MW (25% of generation)	Model for island wind integration with solar + storage. Target: 50% wind in mix.
Nigeria	Plateau State, Jos, coastal Lagos	10 MW (negligible)	10 MW Katsina Wind Farm (underperforming). Several 100 MW projects were announced but stalled.

A detailed breakdown of the levelised cost of green H_2 by wind class and capacity factor in various regions of Africa is shown in Figure 7b. The wind resource classification is defined by wind speeds at a site, typically ranging from poor (Class 1) to outstanding (Class 7 or higher). The classification provides a standardised way to: (a) estimate the energy production potential of a site; (b) compare different sites for development priorities; and (c) determine the technological and economic feasibility. Higher wind classes generally justify more robust and expensive turbines. The key parameter used is the average annual wind speed at a standard height (historically 50 m or 10 m above ground level), often combined with a measure of wind power density (watts per square metre, or W/m^2).

The northern and western Sahara, Eastern Africa, and areas adjacent to the Red Sea and the Arabian Sea (Horn of Africa) possess significantly greater wind resources and capacity factors (above the world average) compared to other areas, as shown in Figure 7b. Thus, the estimated levelised cost of green H_2 generated by wind power notably varies among regions in Africa. The lowest LCOH is estimated to be around US$5.5/kg. For example, in Southern Africa and Central Eastern Africa, where the wind capacity factor on average is 15%, the levelised cost of green H_2 ranges from US$8/kg to US$26/kg.

A comprehensive overview of Africa's wind power—covering theoretically and technically viable as well as currently installed capacity and capacity factor—is presented in Figure 8. This figure indicates that the estimated technically feasible wind power on land exceeds 5000 GW, with an additional 100 GW available offshore [69,70]. As of 2024, the total wind power capacity that is either installed, under construction, or planned is approximately 8.5 GW. The wind capacity factor in Northern, Western, and Northeastern Africa is above 40%, which is significantly higher than the global average of about 28% [69].

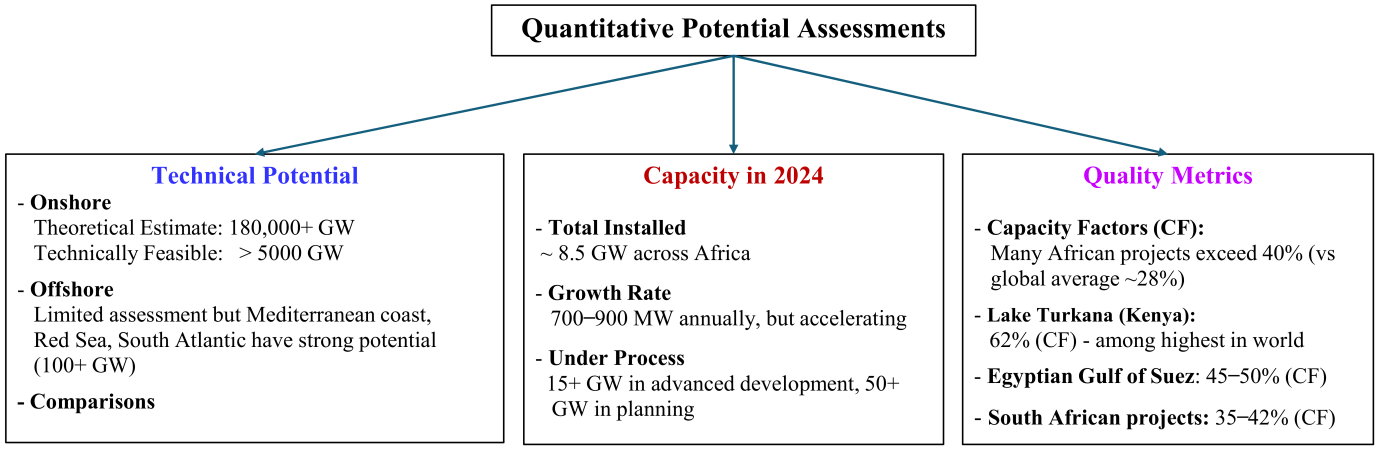


Figure 8. Quantitative assessment of Africa's wind resources.

4.3. High-Yield Green H_2 Production Hotspots in the Continent of Africa

A comparative assessment of high-yield green H_2 production hotspots across Africa, integrating key resource availability (solar irradiation and wind speed), water accessibility, and overall viability based on published sources is presented in Table 7. Coastal locations—namely the Gulf of Suez (Egypt), Western Sahara Coast (Morocco/Mauritania), and Namib Coast (Namibia)—exhibit the highest viability (★★★★★) due to excellent solar and wind resources coupled with seawater desalination potential. Inland sites such as Lake Turkana (Kenya) and Northern Cape (South Africa) show moderate viability (★★★☆☆) due to limited freshwater availability or high desalination costs. The Central Sahara region (Niger, Chad, Mali, Sudan), despite exceptional solar resources, is rated non-viable (★☆☆☆☆) due to severe water scarcity and distance from coastal desalination sources.

Table 7. Comparative assessment of high-yield green H_2 production hotspots across Africa [50,74–76].

Hotspot	Country	Key Resource	Water Source	Viability
Gulf of Suez	Egypt	Solar GHI 6.0; Wind Class 7	Seawater desalination.	★★★★★
Western Sahara Coast	Morocco/Mauritania	Solar GHI 6.0–6.5; Wind Class 7	Seawater Desalination.	★★★★★
Namib Coast	Namibia	Solar GHI 6.5–7.5; Wind Class 6–7	Seawater desalination.	★★★★★
Mediterranean Coast	Algeria	Solar GHI 5.5–6.0; Wind Class 5–6	Seawater desalination.	★★★★☆
Lake Turkana	Kenya	Wind CF 62% (world-class)	Lake Turkana (saline).	★★★☆☆
Northern Cape	South Africa	Solar GHI 6.5	Limited freshwater.	★★★☆☆
Central Sahara	Niger, Chad, Mali, Sudan	Solar GHI > 6.0	No water source.	★☆☆☆☆

Note: Global Horizontal Irradiance (GHI) is the total amount of shortwave radiation received from above by a horizontal surface on the earth, measured in watts per square metre. It represents the total solar energy, combining both direct sun rays and diffused scattered sunlight. GHI is the sum of Direct Normal Irradiance (DNI) (sunlight from the direct beam) and Diffuse Horizontal Irradiance (DHI) (scattered sunlight). It is expressed as $GHI = DHI + DNI\,COS(\theta_Z)$, where θ_Z is the solar zenith angle.

The analysis confirms that coastal regions with access to seawater desalination represent the most suitable locations for green H_2 development in Africa. Inland green H_2 projects require careful water resource planning, while water-scarce desert regions are unsuitable for large-scale deployment despite their excellent renewable resource potential.

Apart from the production of green H_2, African nations face similar challenges to those of other emerging nations in generating electricity and utilising solar energy for various applications. Table 8 summarises these challenges, their impacts, and potential solutions. Key issues include inadequate or absent grid infrastructure, a lack of funding, ambiguous policies, limited local capacity, currency volatility, and instances of payment defaults.

Table 8. Barriers to realisation of full solar energy potential in Africa [22,57–59,67,68].

Challenges	Impact	Emerging Solutions
Grid Infrastructure	Limited transmission in high-potential areas	Hybrid systems, smart mini-grids, strategic transmission investments
Financing Costs	High cost of capital (10–15% vs. 2–4% in Europe)	De-risking instruments (guarantees, blended finance), local currency financing
Policy Uncertainty	Inconsistent regulatory frameworks	Improved PPAs, clear procurement programmes, government commitments
Local Capacity	Skills gap in engineering and maintenance	Training programmes, technology transfer requirements in projects
Currency and Payment Risk	Currency volatility and utility off-taker risk	Hard currency PPAs, escrow accounts, World Bank partial risk guarantees

4.4. Green H_2 Cost Projection Based on Electrolyser Technologies with Solar Power

The projected levelised cost of green H_2 using four electrolyser technologies—Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), and Solid Oxide Electrolysis (SOECs)—is illustrated in Figure 9. This cost estimation is based on the IEA Net Zero Emissions (NZE) Scenario for regions with exceptional solar resources (GHI $>$ 6.0 kWh/m^2/day). The estimated costs are presented for the years 2025, 2030, 2040, and 2050.

The projections incorporate declining renewable electricity costs from US$25–30/MWh (2025) to US$10–12/MWh (2050), electrolyser CAPEX reductions (AWE: US$800–1000/kW in 2025 to US$35–45/kW in 2050; PEM: US$1000–1200/kW to US$45–60/kW), improving capacity factors (20–25% to 28–32%), and declining weighted average cost of capital (12% to 6%). Carbon pricing rising from US$50/ton to US$200/ton further enhances green H_2 competitiveness against fossil-based alternatives.

SOECs achieve the lowest 2025 costs (US$5.5–6.5/kg) due to superior efficiency, while AWE reaches parity with SOECs by 2050 (US$2.0–2.5/kg). PEM costs decline from US$6.5–7.5/kg to US$2.2–2.8/kg, and AEM—the least mature technology—falls from US$7.0–8.0/kg to US$2.5–3.0/kg. All technologies approach cost parity with grey H_2 (US$2.5/kg) between 2040 and 2050, demonstrating the economic viability of green H_2 under the NZE scenario.

The projected levelised cost of H_2 (LCOH) for onshore wind resources across different wind power classes, based on the IEA Net Zero Scenario (NZE) is shown in Figure 9. Green H_2 costs are determined by using alkaline electrolyser (AWE) technology with electricity from dedicated wind farms. The results show that higher wind classes yield significantly lower H_2 costs due to superior capacity factors. Outstanding wind resources (Class 7+, CF 45–58%) achieve LCOH of US$4.8/kg in 2025, expected to reduce to US$1.6/kg by 2050—reaching cost parity with grey H_2 (US$2.50/kg) by 2040.

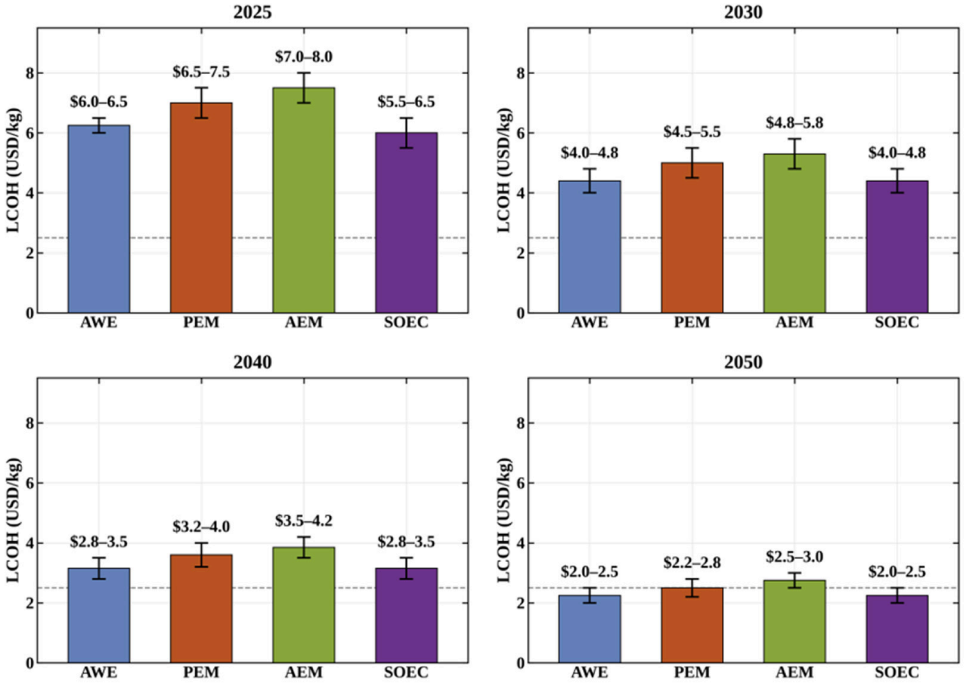


Figure 9. H_2 cost projections by electrolyser type (2025–2050) form solar PV.

As shown in Figure 10, excellent wind resources (Class 6–7, CF 32–45%) follow closely, reaching $2.0–1.5/kg by 2050. Very good wind resources (Class 5–6, CF 20–32%) achieve US$8.5/kg in 2025, reducing to US$2.5/kg by 2050—approaching parity but remaining slightly above grey H_2 costs.

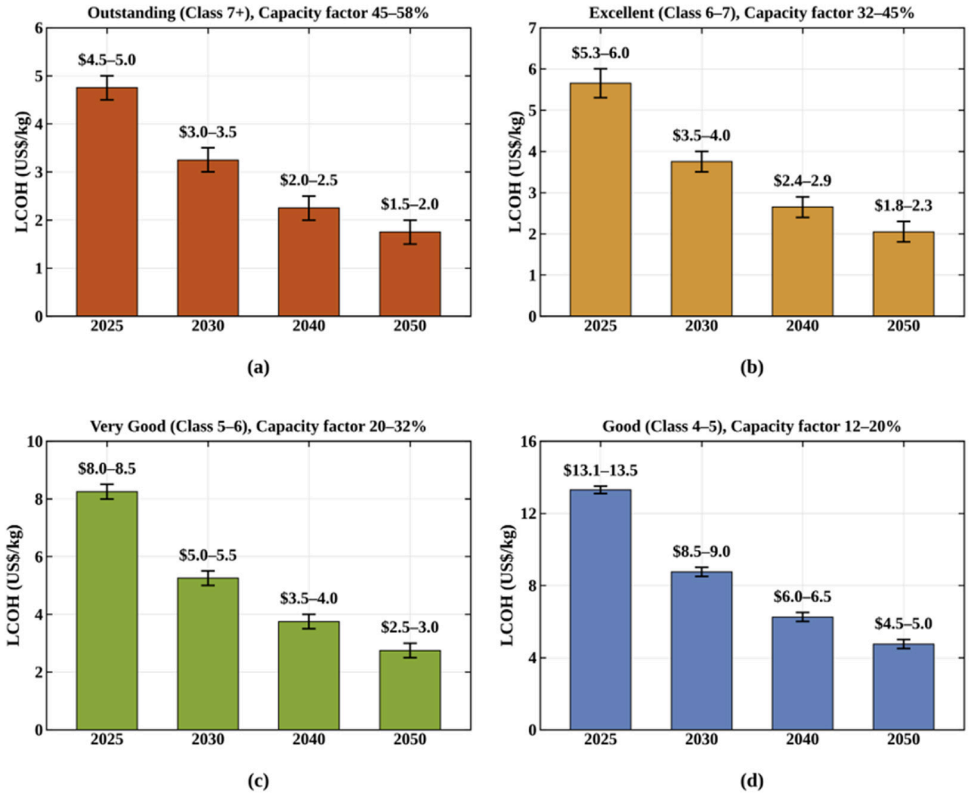


Figure 10. Projected LCOH reduction trend (2025–2050) for: (**a**) wind class 7+ and capacity factor 45–58%, (**b**) wind class 6–7 and capacity factor 32–45%, (**c**) wind class 5–6 and capacity factor 20–32%, and (**d**) wind class 4–5 and capacity factor 12–20%.

Good wind resources (Class 4–5, CF 12–20%) remain above US$9.0/kg by 2050, indicating marginal economic viability without hybrid solar complementation (Figure 10). The analysis confirms that wind classes 4 and above (CF > 20%) offer viable pathways for green H_2 production, while lower wind classes require hybridisation with solar PV to achieve cost competitiveness. These projections assume continued electrolyser cost reductions, declining renewable electricity costs, and supportive carbon pricing policies aligned with the NZE scenario.

5. Electrification in Africa: A Priority Need

The continent of Africa with its 1.57 billion people (19% of the world's total) is the fastest-growing continent, with predictions suggesting that its population can exceed 4 billion by 2100. Africa is made up of 54 sovereign nations. Notable demographic features include a high rate of urbanisation and a relatively young median age of about 19 years [77,78]. Despite having enormous potential in conventional and renewable energy, Africa's current per capita energy consumption is the lowest in the world. Of the forty-four (44) least developing countries in the world, thirty-two (32) are in Africa, as shown in Figure 11.

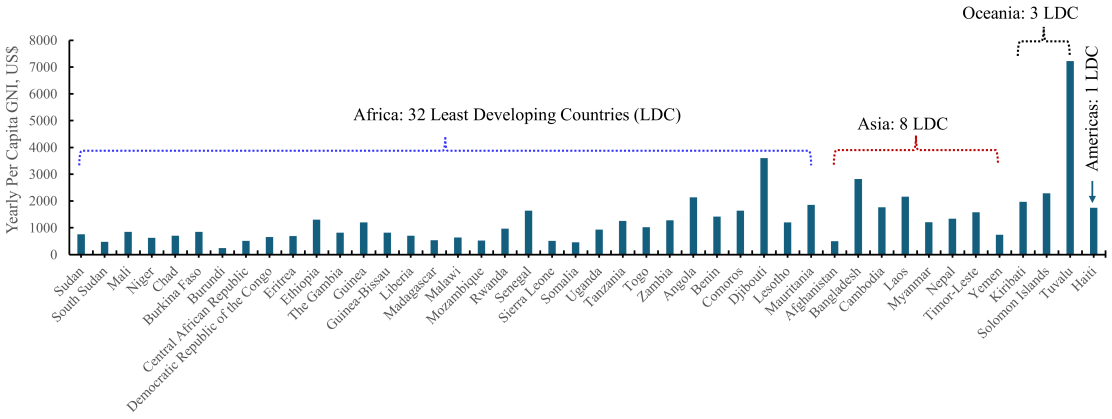


Figure 11. Least developing countries in the world (Africa: 32, Asia: 8, Oceania: 3 and Americas: 1). Note: The UN's Least Developing Country (LDC) criteria are based on a combination of low income, human assets (health, education), and economic and environmental vulnerability, not just per capita gross national income (GNI).

Access and infrastructure challenges are particularly prevalent in Africa, especially Sub-Saharan Africa. At present, over 640 million people (~43% of the total population) in Africa lack reliable access to electric power, which is considered vital for industrialisation and socioeconomic development [79]. With Africa's rapidly growing population and urbanisation, power demand increases over 3% annually, the highest of any continent [46].

Although underutilised for the most part, the continent is well-positioned for a clean energy future, thanks to its essential minerals, and massive solar and wind energy. Figure 12a illustrates the installed power generation capacity of all 54 countries in Africa in 2024. Figure 12b illustrates the availability percentage of electricity in Africa. Only ten (10) countries out of fifty-four (54) have universal access to reliable power. Power outages are widespread in the other forty-four (44) nations, particularly in Sub-Saharan Africa. The figure illustrates that no country in Africa has an installed power generation capacity greater than 5000 MW (5 GW), out of 54 countries. South Africa, Egypt, Algeria, Morocco, and Libya are the only six nations with installed power generation capacities over 5000 MW. At present, the continent of Africa uses nearly three-quarters of fossil fuels (coal, gas and oil) to generate electricity as shown in Figure 13a and the percentage of power generation by energy source indicated in Figure 13b. Per capita electricity consumption is a key indicator

of economic development, industrialisation, and quality of life. There is a massive disparity between Africa and the rest of the world, as shown in Table 9. The world's lowest consumption, ranging from 500 to 800 kWh, underscores the severe energy access crisis in the continent. Even this average does not show the complete picture, as a few higher consumers, such as those from South Africa (~4000 kWh due to its industrialised economy), Algeria, Libya, Egypt, and Mauritius, push the average number up. Extremely low consumption is in Sub-Saharan Africa (excluding South Africa), averaging below 200 kWh per capita. Per capita power consumption in Africa is fifteen (15) times lower than in North Africa, thirteen (13) times lower than in Oceania, eleven (11) times lower than in Europe, four (4) times lower than in Central and South America, and three point six (3.6) times lower than in Asia (Table 9). Africa is home to about 80% of the world's unconnected population to electricity [46,79], and 595 million people would still be without power by 2030 as per the current rate of electrification [80]. Africa's total power generation in 2024 was estimated around 965 TWh, with South Africa and Egypt accounting for more than 40%.

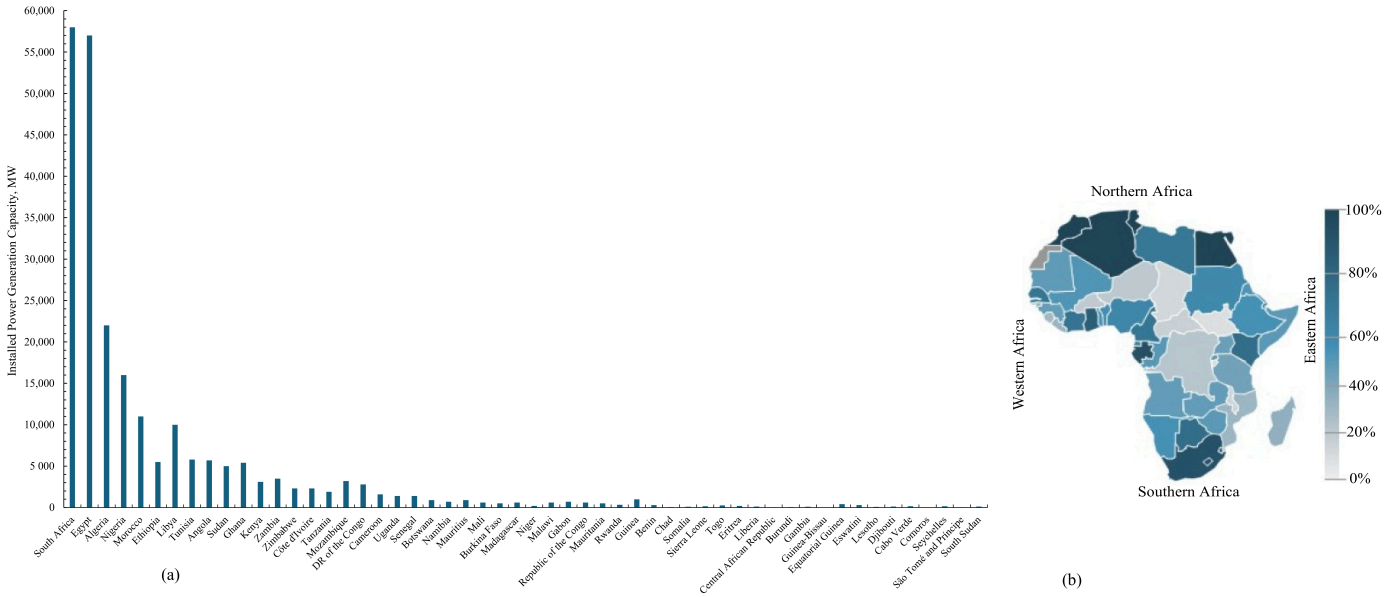


Figure 12. For all 54 African countries: (**a**) installed power generation capacity in 2024 by country, and (**b**) power access (% of population) by country, data source [54–56,81,82].

Africa's conventional fossil fuel reserves are concentrated in only a few regions, especially in North Africa (Libya, Algeria, and Egypt), West and Central Africa (Nigeria and Angola), and Eastern Africa (Mozambique and South Sudan).

Southern Africa dominates coal production, and East Africa is emerging as a gas producer. Determining Africa's precise total oil, gas, and coal reserves is difficult because the figures fluctuate due to new discoveries, re-evaluations of existing fields, and production. Africa produces around 9% of the world's coal (115 billion tonnes), 7.2% of oil (125 billion barrels), and 7.2% of natural gas (17.5 trillion cubic metres) annually [67,68,83]. Libya, Nigeria, Algeria, and Angola have the largest oil reserves; South Africa, Zimbabwe, and Mozambique have coal; and Nigeria, Algeria, Mozambique, and Egypt have the most natural gas deposits. Some countries such as Algeria, Angola, Libya, Mozambique, and Nigeria are exporting their fossil fuels to Europe and Asia due to low local consumption, poor industrialisation, and a lack of energy distribution facilities and networks within the continent.

The differences in power consumption clearly illustrate the energy divide among African nations and between Africa and the rest of the world. Developed countries utilise

substantial amounts of electricity to support their advanced economies and lifestyles, whereas much of the developing world, especially in Africa and parts of Asia, still faces challenges in accessing basic electricity. For instance, in 2025, Africa's total installed electricity generation capacity was merely 285 GW.

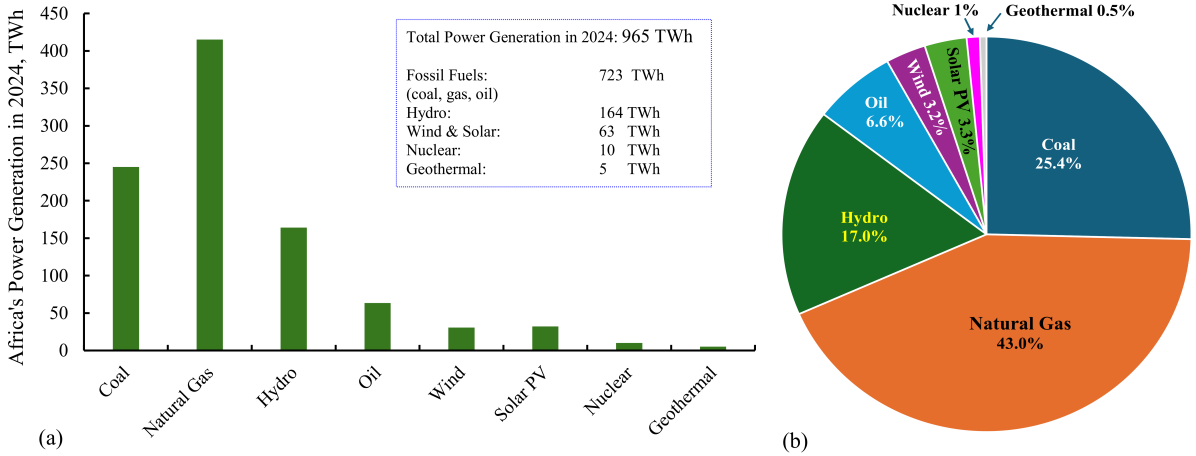


Figure 13. Africa's electricity mix in 2024: (**a**) generation by source (TWh) and (**b**) share of total generation (%), adapted from [84–90].

Table 9. Per capita power consumption summary in 2024 [91–93].

Rank	Continent/Region	Yearly Per Capita kWh	Comments
1	North America	13,000–15,000	Highest consumption, driven by the USA and Canada (lifestyle and industry consumption).
2	Oceania	8000–10,000	Largely dominated by Australia (high usage).
3	Europe	5500–7000	High but moderated by efficiency and policy.
4	South and Central America	2000–3500	Middle range, reliant on hydro, varied by country.
5	Asia	2000–4000	High disparity among countries, dominated mainly by China, followed by Japan, South Korea, and Gulf nations.
6	Africa	500–800	World's lowest, due to lack of development and persistent access challenges.

Electrification serves as a crucial catalyst and transformative force for socioeconomic development throughout Africa. The movement towards generating power (electricity) through renewable energy goes beyond illuminating homes; it is fundamentally about unlocking human potential, stimulating economic growth, and enhancing resilience to climate-related challenges [94,95]. Access to electricity generates a multiplier effect, creating additional advantages that contribute to economic growth, increase GDP (Gross Domestic Product), improve infrastructure, enhance health, open new markets, create jobs, and alleviate poverty.

The electricity sector, encompassing generation, transmission, and distribution, serves as a productivity multiplier by facilitating a transition from low-productivity, manual, and time-intensive activities to high-productivity, mechanised, and automated processes. Research demonstrates a strong correlation between a country's electrification rate and its GDP per capita. A one-percentage-point (1%) increase in electrification can result in a 2% increase in GDP growth, contingent on the region and existing infrastructure [96,97].

Reliable electricity is an essential prerequisite for attracting both domestic and foreign direct investment (FDI). Table 10 summarises the impact of electricity access on GDP, education, health, infrastructure, commercial activities, industrial growth, employment creation, and poverty alleviation. The evidence overwhelmingly supports the notion that enhancing electricity access—especially when transitioning from no access to basic access and from basic access to reliable, productive-use access—plays a crucial role in driving economic growth. Prior studies indicate that average household income, microenterprise revenue, non-agricultural employment, school enrolment, and total productivity (comparing electrified and non-electrified contexts) increase by 20–30%, 25–40%, 5–9%, 5–7%, and 1.5%, respectively [98–101].

Table 10. Effect of electricity access on various sectors, key benefits and mechanisms.

Sector	Key Benefit	Mechanism
(a) GDP Growth	• Increased productivity and output.	- Enable mechanisation, automation, and attract investment.
(b) Education	• Improved learning outcomes.	- Enable study after dark, use computers/internet, and attract better teachers.
(c) Infrastructure	• Functionality of critical systems.	- Power water pumps, telecom networks, traffic systems, and transportation.
(d) Health	• Lower mortality and better care.	- Enable cold chains, surgical equipment, and reduce indoor air pollution.
(e) Commercial Activities	• Higher revenue and new businesses.	- Extend operating hours and enable value-added services.
(f) Industrial Growth	• Scalable, competitive manufacturing.	- Provide the reliable, high-capacity power needed for machinery and mass production.
(g) Employment Creation	• More and higher-quality jobs.	- Create jobs in energy, enable new enterprises, and boost productivity in existing ones.
(h) Poverty Alleviation	• Increased income, reduced expenses.	- Free up time, replace costly fuels, and improve health and education outcomes.

Research conducted in West Africa from 2000 to 2022 indicates that enhanced electricity access has contributed to an increase in GDP per capita and boosted industrial activity [102]. Similarly, studies focused on Sub-Saharan Africa reveal a significant relationship among electricity access, infrastructure, and economic growth [103]. A 2018 review highlights the strong correlation between electricity access and utilisation with development, particularly in terms of macro-level causation [104]. A study conducted in 2025 on Senegal's rural electrification programme offers strong evidence. Employing quasi-experimental methods, researchers discovered that households with electricity access experienced, compared to non-electrified households [105], (a) a 39.5% increase in non-food expenditure; (b) a 39.2% rise in non-agricultural employment, including small businesses; and (c) significant educational improvements: children were 45.3% more likely to be enrolled in school and studied 63.3% longer, with the impact on attendance being even more pronounced for girls. Figure 14 demonstrates that even small percentages of electricity access (1%, 5%, and 10%) can significantly influence national GDP growth across all thirty-two (32) least developed countries in Africa.

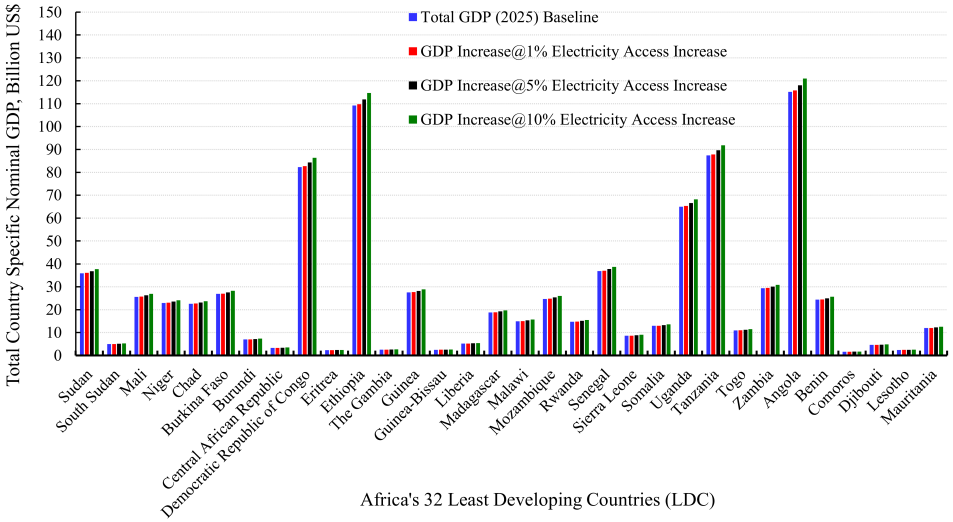


Figure 14. Impact of electricity access to GDP growth in Africa's thirty-two (32) least developing countries.

Thus, prioritising hydrogen (H_2) export without first ensuring universal electricity access for its citizens and industries, risks transforming Africa into a "green sacrifice zone." In this scenario, its renewable resources would assist wealthy nations in decarbonising, while the local population remains without power and in poverty.

6. Constraints, Limitations and Dilemmas in Africa's Green H_2 Production

The development of green H_2 in Africa faces a complex array of interrelated challenges despite having vast renewable energy potential.

6.1. Availability of Land

Green H_2 production by renewable power generation, large-scale electrolysis and renewable energy park require large amounts of land, and it is perceived that African nations possess vast unused land compared to densely populated Asia and Europe. Africa's perceived unused land is a potential cornerstone of the global energy transition [46,57,58]. Africa's coastlines (e.g., Namibia, Morocco, Somalia, South Africa, and Egypt) offer high onshore and offshore wind potential, particularly for consistent, high-capacity factor generation. The East African Rift holds significant geothermal potential. Africa, as the world's second-largest continent by both area (approximately 30.37 million square kilometres) and population (over 1.58 billion people) after Asia, covers roughly 20% of Earth's total land area and about 18–19% of the world's population [106,107]. The continent's population density is roughly 52 people per square kilometre. Due to its low population density, there is a perception that the continent has vast 'unused or uncultivated' land (60–65%) which is a misleading myth and colonial-era narrative, as various reports and data indicate otherwise [108–110]. The definition of 'unused' is often applied to Africa's land which is not under large-scale, industrial cultivation visible from space [109], ignoring practical reality on the ground. All land in Africa is used for grazing (areas are used for livestock, a primary livelihood for millions), shifting cultivation (a traditional farming method that involves rotating fields to maintain soil fertility, meaning land is left fallow to recover, but not abandoned), foraging and gathering (many communities rely on wild foods, medicinal plants, and other resources from these landscapes), sacred and cultural practices (land often holds deep spiritual and cultural significance), and ecological systems (forests, wetlands, and savannahs to provide critical ecosystem services, from carbon storage to water regulation). Thus, there is no such massive extent of empty land in Africa. Only a small

piece of land called 'Bir Tawil' stands as an unusual exception. Bordering Egypt and Sudan, this tiny desert area encompasses 2059 square kilometres [111,112]. Both Sudan and Egypt do not recognise each other's borders due to a historical inconsistency between the 1899 border and the official 1902 boundary adjustment. 'Bir Tawil' is barren, waterless, and uninhabitable, with summer temperatures reaching 45 °C [111,112]. Such high temperatures are not conducive to efficient solar power generation.

Meanwhile, Africa's land faces increasing competing pressures from multiple directions as shown in Table 11. There is a vital connection between so-called 'unused land' and green H_2 production in Africa. The large-scale solar and wind farms require vast areas of land for gigawatt-scale 'green H_2 valleys' or mega-parks. It is crucial that the development of this new industry does not repeat the mistakes of the past by treating African land as 'empty' or 'unused'. The land identified for green H_2 projects is often the same land used by communities for grazing or foraging, or that holds other cultural and ecological significance [113]. Ensuring that H_2 development benefits local populations and respects existing land rights is a central challenge and opportunity for the continent, requiring careful planning and inclusive policies to avoid a new wave of land dispossession [114].

Table 11. Pressure driver on land in Africa with some examples [113].

	Pressure Driver	Examples
(a)	Critical Minerals	Surge in mining for cobalt (DRC), lithium (Zimbabwe), and other minerals essential for the global green transition.
(b)	Carbon Markets	Large-scale land acquisitions for carbon offset projects, tree planting, and biodiversity schemes.
(c)	Agricultural Expansion	Growth of commodity crops like palm oil, sugarcane, and rubber are often for export.
(d)	Renewable Energy	Vast solar and wind projects, like the Lake Turkana Wind Power project in Kenya, which can displace communities.
(e)	Rapid Urbanisation	African cities are expanding faster than any other region, converting surrounding farmland.

Table 12 summarises some key differences between the common perception or narrative and the on-the-ground reality of Africa's landmass.

Table 12. Key differences between common perception and on-the-ground reality of Africa's landmass [108,109].

Aspect	General Perception	Reality
Land Status	Vast tracts of 'unused' or 'vacant' land are available for development.	Land is used for grazing, fallow in rotation, foraging, and cultural practices.
Primary Farmers	Smallholder farmers are unproductive and need to be replaced.	33 million smallholders produce up to 80% of the continent's food on 80% of its farmland.
Development Model	Industrial agriculture will create jobs and boost economies.	Industrial farms are often mechanised, create few jobs, and can lead to debt for smallholders.
Land Governance	Land needs formal titling to be productive.	Customary systems, which are preferred by the majority (e.g., 81% of women in one study), are often ignored, leading to dispossession.

Despite there being almost no unused land in Africa, there are some degraded areas with significant renewable energy potential, particularly in abandoned open-cut mines, deserts, and semi-arid regions. However, utilising so-called "unused" or degraded land necessitates careful planning that considers the social context and promotes beneficial community land use, as this degraded land may serve as a vital resource for local communities. Development should supplement existing land uses rather than displace them, ensuring that local communities receive benefits. Opportunity exists in repurposing abandoned coal mines. A global report identified that twenty-eight (28) countries, including South Africa, have recently abandoned surface coal mines that are suitable for solar repurposing, with a potential 288 GW of solar capacity [115]. These sites, typically degraded and located near existing power grid infrastructure, are ideal for solar repurposing. South Africa hosts the most extensive open-cut coal mines in Africa, primarily in the Mpumalanga, Gauteng, and KwaZulu-Natal provinces, with over 50% of its coal production coming from open-cut methods. In addition to South Africa, Zimbabwe, Botswana, and Mozambique also have open-cut coal mines. Furthermore, there are open-cut mines located in the Democratic Republic of the Congo, Zambia, Guinea, Tanzania, and Namibia. Some of the degraded land from mining can also be utilised for solar and wind energy harvesting for green H_2 production. Overall, there are opportunities for renewable energy projects in the Sahara/Sahel regions for solar and wind energy, as well as in the Nama Karoo for solar energy. Abandoned mine land in southern Africa and small hydropower sites throughout Sub-Saharan Africa represent valuable, more localised options. Transforming land use requires policy frameworks that prioritise renewable development on degraded land, investment strategies that recognise the importance of linking reclamation with green energy, and community engagement that creates local jobs and meets local needs.

6.2. Water Challenges for Green H_2 Production in Africa

A key component of green H_2 production is water. Water sources (rainwater, surface water, groundwater, river waters, sea water), energy technologies, energy sources, and industrial processes all have a role in the amount of water needed and its cost [1,116]. Theoretically 9 kg of water is needed for 1 kg of H_2 production [117,118]; however, a recent study [119] indicates that 40–90 kg of seawater is required for 1 kg of green H_2 production. H_2 production uses a certain amount of water, which may not be entirely recovered, leading to increased water use in practice, especially considering that the theoretical water requirement of 9 kg for 1 kg of H_2 production can escalate to 40–90 kg/ for 1 kg of H_2 when using seawater for green H_2 production [117–119]. There is a formidable challenge in water supply for green H_2 production in Africa due to the mismatch of water and renewable energy locations. Most of Africa's best solar and wind resources are in water-scarce regions (e.g., Sahara, Namibia desert). On the other hand, coastal desert regions (e.g., Mauritania, Namibia, Western Sahara) lack freshwater and require the use of solar or wind energy to desalinate seawater at a higher cost. Using desalinated sea water, Africa's potential green H_2 export industry must compete for scarce water resources and a global competitive market. Simultaneously, closing the freshwater access gap requires US$30–50 billion/year for water infrastructure investment in Africa—a sum larger than current announced H_2 investments. The cost of supplying freshwater varies dramatically. In major cities, piped water can cost US$0.5–$2 per m^3, but in rural or arid areas, trucked water or desalination can cost US$5–$15 per m^3. At present, more than thirteen (13) African countries including Egypt, South Africa, and Libya face extreme water stress. Most African countries face infrastructure deficits (lack of treatment plants, pipelines, storage reservoirs, desalination facilities), a shortage of finances and skilled human resources and institutional management, and a climate change effect (unpredictable droughts, floods, supply disruption). Without

careful planning and allocation of significant finance to water resources, green H_2 projects can worsen Africa's water stress and jeopardise the future economic viability and export competitiveness of green H_2 projects.

6.3. Uncertain Export Demand

The global demand for green H_2 exports is highly volatile and uncertain, primarily due to a significant disconnect between ambitious policy objectives and commercial realities. Green H_2 producers have difficulties finding buyers who are willing to sign long-term purchase contracts. In contrast, high prices and the absence of mandatory demand deter potential buyers. According to the IEA [2], cumulative firm off-take agreements represent less than 5% of the potential production capacity of announced projects by 2030. A fundamental challenge facing green H_2 export projects is the scarcity of "bankable" demand. Much of the demand indicated by buyers is only in the form of memoranda of understanding or non-binding letters of intent, which can be rescinded at any time. At present, only a limited number of countries are potential importers of green H_2 and its derivatives, such as ammonia, methanol, and synthetic fuels, from Africa. These countries include Germany, the Netherlands, Belgium, France, Spain, Italy, Portugal, Norway, and the UK in Europe, as well as Japan, South Korea, and Singapore in Asia. Each of these countries has distinct goals for importing green H_2 and its derivatives. Green H_2 imports are primarily destined for: (i) heavy industry (steelmaking—green steel—and chemical production, particularly ammonia and methanol); (ii) power generation (co-firing ammonia in coal-fired power plants, particularly in Japan and South Korea); (iii) transportation (shipping as ammonia/methanol and possibly aviation as synthetic fuels); and (iv) energy storage and grid balancing (using H_2 to store excess renewable energy. However, no firm commitment or off-take agreement has yet been secured between exporters and importers for the purchase of green H_2 from Africa [2,120–122]. In the absence of long-term "take-or-pay" contracts, green H_2 projects are unable to secure financing, leading most export-oriented initiatives to stall or be cancelled.

6.4. Decarbonisation Prospects from Green H_2

Green H_2 has the potential to decarbonise hard-to-abate sectors within Africa as well as other industrialised countries' heavy industry (steel, cement, and fertiliser). Green ammonia is vital for sustainable growth of staple foods for humans and animals. Africa is not self-sufficient in food production. Nearly 285 million people (~20% of the total population) are undernourished [123]. Africa's annual food import costs range from US$50 billion to US$70 billion; however, some recent estimates put the costs closer to US$100 billion. Without significant and strategic initiatives, it is expected that this cost will increase to US$110 billion by 2025/2026 [124]. The large amount of spending demonstrates a significant dependence on imported food (rice, wheat, etc.), despite the continent having over 60% of the world's arable land. The import dependency is often attributed to factors, including:

(a) Low productivity due to the use of traditional, low-intensity subsistence farming methods resulting in limited output.
(b) Insufficient investment, caused by financial hardship, has resulted in low or no funding for fertiliser production and procurement, agricultural tools and machinery, harvesting technology, and food processing industries. This deficiency contributes to the continent's difficulties in meeting its increasing food demand.
(c) Inadequate infrastructure due to poor road, rail, port and harbour infrastructure that leads to high costs for internal trade and distribution.

In 2021, Africa imported fertiliser worth around US$3.7 billion. However, recent data suggests that Africa's entire fertiliser market (including local production and import) was

worth US$54.77 billion in 2025, with most nations significantly reliant on imports [125]. While Africa produces a substantial amount of fertiliser (about 30 million metric tonnes per year), most of it is sold outside of the continent, leaving individual countries to import most of their needs. Sub-Saharan Africa imports approximately 90% of its fertiliser, primarily from outside the continent. Ethiopia, Côte d'Ivoire, Zambia, Kenya, and the Democratic Republic of the Congo are Africa's top net fertiliser importers. Imports are primarily from Germany, Russia, Saudi Arabia, China, and Qatar [126]. African nations are vulnerable to external market shocks and price volatility as they are dependent on imports. Additionally, high transport and distribution expenses add to the cost for farmers and rising food prices. Green ammonia production and its utilisation for food production in Africa can help the continent to achieve self-sufficiency in food production and enhance its food security.

The green H_2 for Africa's transportation sector possesses potential to achieve both decarbonisation of transport sector goals and local economic growth. Due to technological and economic realities, it is necessary to take a systematic and staged approach. Locally produced green H_2 utilisation in African transportation is expected to enhance local value, achieve energy sovereignty, improve city cleanliness and reduce CO_2 emissions. Its success, however, is dependent on focused deployments in heavy transportation, overcoming financial barriers through innovation, and a strongly coordinated government policy that prioritises domestic advantages with export prospects.

New energy vehicles (battery-electric, plug-in hybrid electric, hybrid electric and fuel cell electric) are on the rise globally [127]. Fuel cell vehicles use onboard stored green H_2 as a clean energy carrier to power them, enabling efficient, zero-emission transportation with refuelling times comparable to conventional vehicles. A schematic of a H_2 fuel cell vehicle is shown in Figure 15a. In 2025, the worldwide number of road vehicles powered by H_2 fuel cells is in the range of 100,000 units. The market for passenger cars (including SUVs) and commercial vehicles (trucks and buses) is heavily segmented, with the number of commercial vehicles rising, while the fuel cell passenger car market has experienced a recent slowdown due to factors such as high green H_2 costs, limited infrastructure including refuelling stations, and competition from battery electric vehicles. The number of passenger cars is around 70,000 units (South Korea—35,000, Japan—25,000, and China—3200), while the global number of commercial vehicles is around 30,000; almost all of them are in China. There are around 1150 H_2 refuelling stations in the world; 560 stations are in China, and the remaining ones are mainly in South Korea and Japan, with a few in the USA and the European Union [128–131].

Green H_2-powered road transportation vehicles have yet to achieve a commercially viable status, primarily due to the high costs associated with the production of green H_2, as well as the transport and refuelling infrastructure required. As of 30 June 2025, China has constructed and operationalised 560 H_2 refuelling stations, with an initial target of over 1000 stations across various provinces. The average number of service vehicles per refuelling station is fewer than forty-five (45). This costly infrastructure, coupled with low utilisation rates, hampers operational viability. A report by Luo et al. [132] indicates that despite China's leadership in green H_2 production and the establishment of necessary infrastructure, the H_2 refuelling stations still struggle with low usage rates, leading to inefficiencies in operations. Moreover, numerous obstacles persist at each stage of this chain, including technological immaturity, high overall costs, and inadequate cross-link coordination. For example, operating a 12-metre urban bus in Beijing costs CN¥230 (US$35), compared to CN¥247 (US$37) for a fossil fuel bus and CN¥320 (US$48) for a pure electric bus. Consequently, using H_2 fuel cell buses is 30% more expensive than operating fossil fuel buses and 39% more costly than using pure electric buses. Currently, most H_2 refuelling stations have a refuelling capacity of either 500 kg/day or 1000 kg/day.

The investment required for equipment at a 500 kg/day station ranges from CN¥5 million (US$0.8 million) to CN¥7 million (US$1.1 million) per set. For stations that can hold 1000 kg/day, each set of equipment usually costs between CN¥9 million and CN¥10 million (about US$1.4 million and US$1.5 million). If integrated H_2 refuelling stations are equipped with imported machinery for both H_2 production and refuelling, the equipment costs may reach CN¥15 million to CN¥20 million (US$2.3 million to US$3.0 million) per set. It is anticipated that costs will be significantly higher in Africa and other regions. Thus, effective coordination throughout the entire industrial chain—including H_2 production, storage and transportation, refuelling, and application—is essential for the healthy development of H_2 energy in the transportation sector.

Hydrogen-powered locomotives and trains are currently transitioning from experimental stages to early commercial deployments with the primary goal of decarbonising non-electric rail systems. The H_2-powered freight locomotive market has global potential, and is projected to reach US$26.7 billion by 2032 [133]. Passenger trains are currently in their commercial and experimental phases in China and Germany. Alstom Coradia iLint, a H_2-powered light passenger train, was first introduced in Lower Saxony, Germany. In Foshan, China's CRRC introduced a H_2-powered tourist tram. Canadian Pacific and CRRC Datong are testing H_2-powered freight train locomotives for long-distance uses. Figure 15b–d shows green H_2-powered passenger trains and locomotives of CRRC (China), Alstom Coradia iLint (France/Germany) and Canada Pacific, respectively. Although they require a lot of storage space for longer-range, heavy-freight routes, most passenger trains employ 35 MPa (megapascals) compressed H_2 [133], which offers excellent efficiency. Furthermore, H_2-powered freight trains in Australia, India, Namibia, and France, as well as refitted HydroFLEX trains in the UK, are all in their early planning phases. As the world's largest manufacturer of high-speed trains, locomotives (train engines), and metro rail carriages, China's state-owned enterprise China Railway Rolling Stock Corporation (CRRC), with over CN¥273.06 billion (US$39 billion) in revenue in 2025 [133–135], is significantly ahead with H_2 fuel cell trains, transitioning from testing to early adoption for urban and industrial use, surpassing Alstom (France) and Siemens (Germany). CRRC's key H_2-powered vehicles are the C Nova H2 (200 km/h, 1200 km range) [136], a 250 km/h train (under development with a higher range) and a tourist train (2025) designed for cold climates. China is positioning green H_2 as a solution for 'dual-carbon' goals, with a long-term plan to replace thousands of diesel trains with cleaner alternatives.

As of April 2026, there is some turbulence in the market for H_2-powered trains globally, but less so in China. For example, French company Alstom halted H_2 train development in France when government assistance ended, and Germany's transport operator Rhein-Main-Verkehrsverbund (RMV) withdrew its 18-train iLint fleet in late 2025 due to fuel cell reliability issues. Lower Saxony in Germany is converting Alstom Coradia iLint H_2 trains to battery-electric trains for future purchases due to cheaper operating costs than H_2.

Hydrogen-powered transport, particularly in rail systems, encounters a range of interconnected technical, economic, and operational challenges that hinder its widespread implementation. The details of these limitations are as follows:

(a) High fuel costs: Green H_2 is currently 2–3 times costlier than diesel or grid electricity. Until production scales up and electrolyser costs fall, fuel costs remain a major barrier.

(b) Lack of refuelling infrastructure: Outside a few demonstration projects, H_2 refuelling stations are usually unavailable. Building a network of production, storage, and dispensing sites requires billions of US dollars or equivalent money in upfront investment before trains can run at scale.

(c) Energy efficiency losses: H_2 is fundamentally less efficient than battery-electric systems. Electric → battery → motor: ~70–80% efficient.

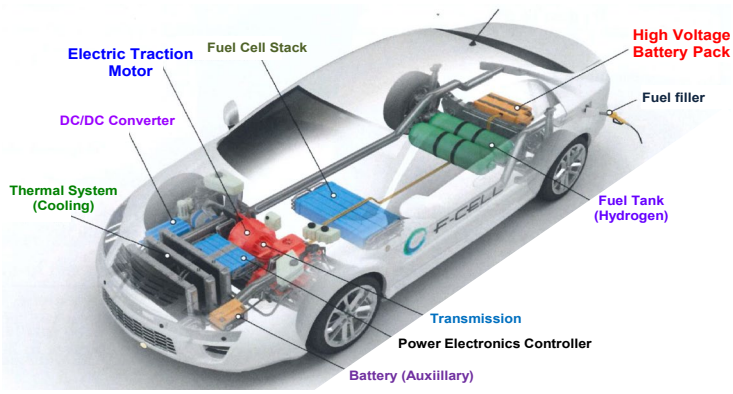
Electric → H_2 → fuel cell → motor: only ~30–40% efficient.

Hydrogen is impractical for train routes with current or potential electrification because of its high cost and poor efficiency relative to electric systems, which make it less viable in terms of energy usage and operating expenses.

(d) Storage and onboard space: Hydrogen has very low volumetric energy density. To have sufficient storage for range, trains need large, heavy, high-pressure tanks (350–700 bar) [133] or cryogenic liquid H_2 systems, which take up passenger/cargo space and add weight.

(e) Safety and public acceptance: High-pressure H_2 is highly flammable and can cause embrittlement in metal tanks and pipes. Regulators and local communities often raise concerns about fires or explosions in tunnels, depots, and refuelling stations near populated areas.

(f) Locomotive power limits (especially for freight): Fuel cells typically deliver lower peak power than a diesel engine. Heavy freight or high-speed passenger trains require enormous fuel cell stacks plus batteries to handle peak loads, which increase complexity and cost.



(a) H_2 Fuel Cell Vehicle (schematic)



(b) CRRC's urban hydrogen train on the test track in Changchun, China



(c) Alstom Coradia iLint hydrogen train in Lower Saxony, Germany



(d) Canadian Pacific hydrogen fuel-cell locomotive in Calgary, Canada

Figure 15. Green H_2-powered passenger car, train and locomotive, adapted from [128,129,137–139].

Despite the existing limitations and challenges, H_2-powered road vehicles—such as cars, buses, and trucks—as well as trains show promising potential. Currently, they lag behind battery-electric or fully electrified systems in terms of cost, efficiency, and infrastructure. However, they hold better prospects for very long, non-electrified routes, especially when equipped with substantial battery and H_2 storage for extended ranges. As technology advances and the necessary value chains, logistics, and infrastructure are established, H_2-powered passenger trains and freight locomotives are anticipated to become more competitive regarding cost, reliability, and environmental benefits. Consequently, Africa can aspire towards green H_2-powered transportation in the future, but it will need to wait for technology to mature, relevant logistics and value chains to be developed, and, crucially, for costs to decrease to an affordable level.

The global green H_2 market was estimated to be worth US$12.31 billion in 2025. It is projected to grow to US$231.32 billion by 2035, representing a compound annual growth rate (CAGR) of 34% from 2026 to 2035 [130]. The anticipated expansion of the green H_2 market from 2025 to 2035 is illustrated in Figure 16.

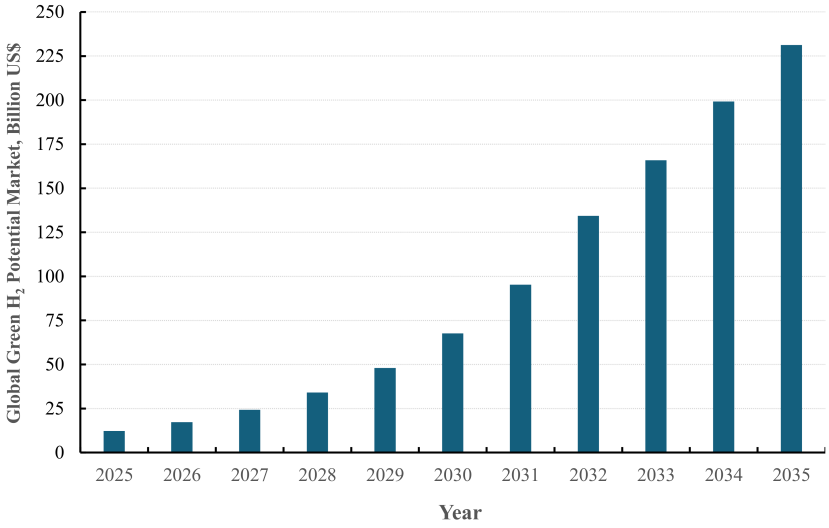


Figure 16. Global green H_2 potential market (2025–2035), data source [140].

6.5. Africa's Critical Minerals and Their Role in Green H_2 Production

The continent of Africa possesses vital critical minerals required for green H_2 production and water electrolysis technologies. Different water electroliser types use different materials, and each comes with its own supply challenges in current and future scalability. AWE (Alkaline Water Electrolyser) is the most established option and mainly uses nickel and zirconium. Nickel is key for electrodes due to its durability and works well as a catalyst, while zirconium oxide strengthens the diaphragm. AWE needs a lot of nickel (around 3500–4000 kg/MW). Even though nickel is common, demand from industries like EV batteries puts pressure on supply. PEM (Proton Exchange Membrane) water electrolysers are efficient and flexible but depend on rare platinum group metals. Platinum is used at the cathode and iridium (a rare earth element) at the anode. Iridium is extremely scarce, with only 7–10 tons produced each year globally. To scale PEM technology, iridium use needs to drop by nearly 97%. Solid Oxide Electrolyser Cells (SOECs) run at high temperatures and use the rare earth elements yttrium, lanthanum, and strontium. Their biggest issue is maintaining stability during repeated heating and cooling cycles. Tables 13 and 14 illustrate the needs of these critical materials for various electrolysers, mining and processing locations. Africa possesses almost all critical materials that are needed for electrolysers. The shift toward a H_2 economy depends on rapidly scaling electrolyser capacity from 0.2 GW in 2020 to around 1400 GW by 2050. However, this growth is limited by the availability of critical materials. Iridium stands out as the biggest constraint due to its extreme scarcity and low annual production, requiring major reductions in its use for future deployment. Among African countries, South Africa, the Democratic Republic of the Congo, Zimbabwe, Namibia and Madagascar possess significant percentages of rare earth elements required for green H_2 production technologies (electrolysers) as shown in Tables 13 and 14.

Table 13. Rare earth materials required for various electrolysers [141–143].

Technology	Critical Material	Function	Material Intensity (kg/MW)	Primary Supply Risk
AWE	Nickel (Ni)	Electrode, catalyst support	3500–4000	Competing demand; supply concentration
AWE	Zirconium (Zr)	Diaphragm stabiliser	Low	Supply mainly in Australia and South Africa
PEM	Platinum (Pt)	Cathode catalyst (HER)	0.2–0.5	Supply mainly in South Africa; high cost
PEM	Iridium (Ir)	Anode catalyst (OER)	0.3–0.5	Extreme scarcity; by-product dependency
SOECs	Yttrium (Y)	Electrolyte stabiliser (YSZ)	0.1–0.3	Mostly processed in China
SOECs	Lanthanum (La)	Air electrode (LSM)	0.1–0.2	Mostly processed in China
SOECs	Strontium (Sr)	Air electrode (LSM)	0.02–0.05	Lower risk; linked to REE supply chain

Table 14. Major mining and processing countries for rare earth materials [143–145].

Material	Electrolyser Type	Global Availability	Supply Risk	Key Producing Countries (with % of Global Production/Reserves)	Critical Issues
Iridium	PEMEL	Very low (7–8 t/yr annual production)	Very high	South Africa (~90% of global reserves); Zimbabwe (~5%); Russia (~3%); Canada (~1%); United States (~1%)	By-product of platinum mining. 89–97% demand reduction required.
Platinum	PEMEL	Low (170–200 t/yr annual production)	High	South Africa (~70% of global production); Russia (~12%); Zimbabwe (~8%); Canada (~4%); United States (~3%); Botswana (~2%)	Cost pressure; competition from automotive catalysts; concentration done in Southern Africa.
Nickel	AEL, SOEL	High (94 million tonnes of global reserves)	Medium	Indonesia (~42% of global production); Philippines (~12%); Russia (~7%); New Caledonia (~6%); Australia (~5%); Canada (~4%); China (~3%); Brazil (~2%)	Demand growth across multiple clean energy sectors (batteries, stainless steel); processed in China (35% of refined production).
Yttrium	SOEL	Moderate (6000 t/yr annual production)	Medium	China (~70% of global production); Australia (~15%); United States (~5%); Russia (~3%); Myanmar (~3%); Vietnam (~2%); Brazil (~2%)	Processed in China (over 85% of refining); limited substitution options; co-product of heavy rare earth mining.
Lanthanum	SOEL	Moderate (25,000–30,000 t/yr annual production)	Medium	China (~70% of global production); Australia (~12%); United States (~8%); Russia (~4%); Myanmar (~3%); Vietnam (~2%); Brazil (~1%)	Processed in China; co-produced with cerium and neodymium.

Table 14. *Cont.*

Material	Electrolyser Type	Global Availability	Supply Risk	Key Producing Countries (with % of Global Production/Reserves)	Critical Issues
Cerium	SOEL	Moderate (25,000–30,000 t/yr annual production)	Medium	China (~70% of global production); Australia (~12%); United States (~8%); Russia (~4%); Myanmar (~3%); Vietnam (~2%); Brazil (~1%)	Large-scale consumption in glass and polishing industries competes with electrolyser demand.
Zirconium	AEL, SOEL	High (70 million tonnes global reserves)	Low	Australia (~35% of global production); South Africa (~20%); China (~12%); Mozambique (~8%); Indonesia (~6%); Senegal (~5%); United States (~4%); Ukraine (~3%)	Diversified supply; low concentration risk; reserves distributed across multiple jurisdictions.
Scandium	SOECs (emerging)	Very low (15–20 t/yr annual production)	High	China (~40% of global production); Russia (~20%); Philippines (~15%); Ukraine (~5%); Kazakhstan (~5%); Australia (~3%); Canada (~2%)	Emerging material for SOEC interconnects; extremely limited supply; by-product of nickel, cobalt, or rare earth mining.
Cobalt	PEMEL (bipolar plates)	Moderate (8.3 million tonnes global reserves)	High	The Democratic Republic of the Congo (~70% of global production); Indonesia (~10%); Australia (~5%); Canada (~3%); Philippines (~2%); Russia (~2%); Morocco (~1%)	Mined in the DRC; competing demand from electric vehicle batteries.
Titanium	PEMEL (bipolar plates, frames)	High (800 million tonnes reserves)	Low	China (~35% of global production); Russia (~15%); Japan (~10%); Kazakhstan (~8%); Ukraine (~5%); United States (~4%); Australia (~3%); Canada (~2%)	Abundant reserves; diversified production; processing for high-purity grades is done in China and Japan.

At present, no African country is producing rare earth element refined products at a commercial scale. While African nations are developing mining projects, it is crucial to distinguish between mining (the extraction of raw ore) and processing (the separation of individual elements such as Lanthanum and Cerium). Most projects aim to conduct initial concentration in Africa; however, the final, high-tech separation step is currently planned for other countries. South Africa is the only nation on the continent making efforts to develop local separation capacity, yet it is not refining final products for electrolyser applications. The Steenkampskraal project intends to commission a separation plant to produce individual rare earth oxides (including Yttrium) starting in 2027. Other countries, like Angola, plan to ship their mixed rare earth carbonate to the UK for final processing, while Malawi intends to send material from the Songwe Hill project to Poland. The development initiative of Africa's rare earth sector is being driven by Western countries, particularly the US and EU, with the aim of reducing their reliance on imports from China, which currently holds over 85% of global refining capacity. This competition may lead to a new scramble for Africa, presenting both opportunities for economic development and risks of resource exploitation. Major rare earth element and critical mineral processing countries, along with their weighted shares and potential risks associated with rare earth materials, are illustrated in Figure 17.

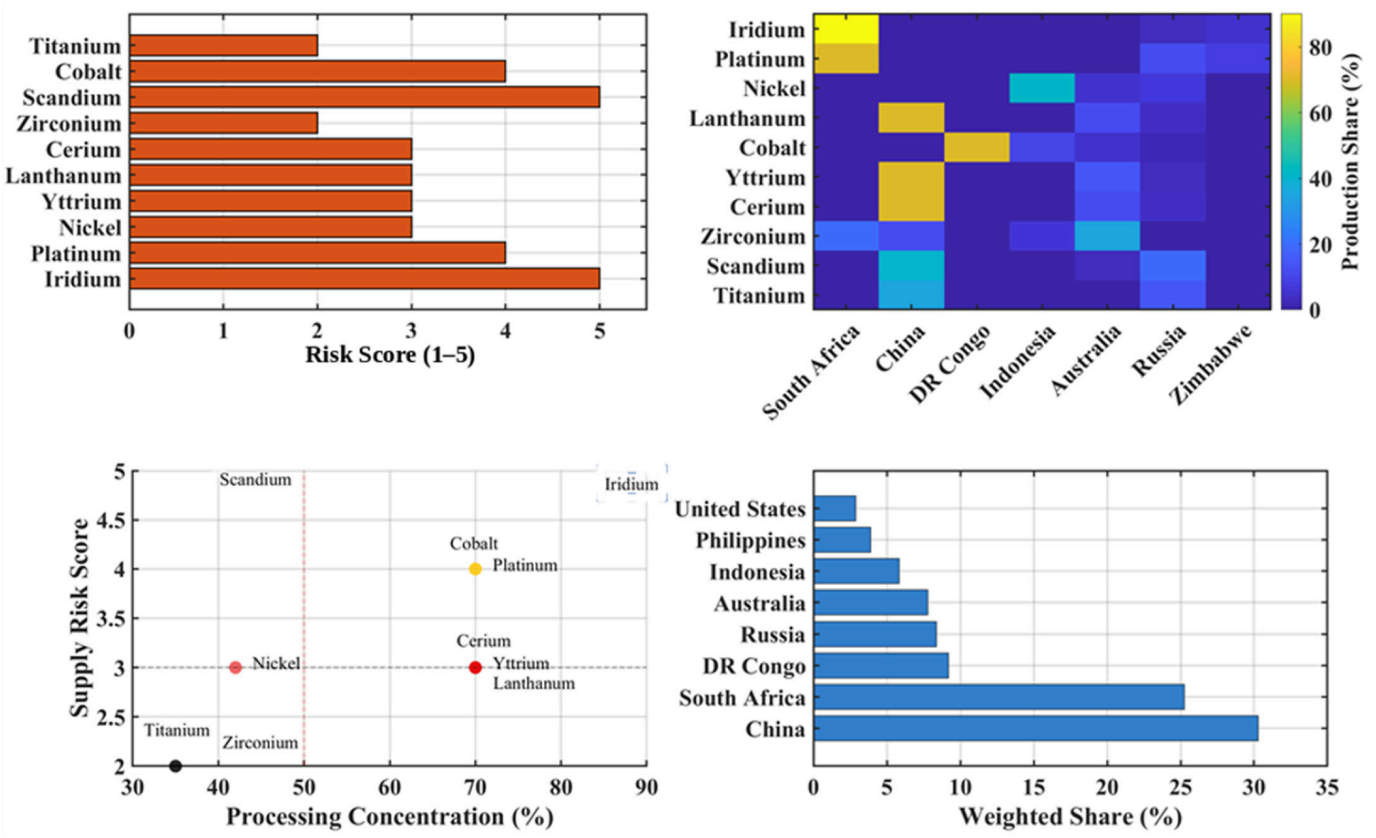


Figure 17. Processing countries, weighted share and potential risk of rare earth materials.

7. Green Hydrogen Strategy Roadmap for Africa Considering the Global Context

Until 2025, there were 1749 initiatives for green H_2 production globally, of which 510 were green H_2 projects valued at US$110 billion. From inception to production, green H_2 projects have an extremely low success rate [146]. The years 2025 and 2026 marked a significant "reality check" for the global green H_2 industry. After years of ambitious announcements and hype, a wave of project cancellations, delays, and strategic pullbacks swept across Europe, North America, Australia, Asia, and Africa. While China continues to invest heavily, it too is encountering significant challenges. Of the fifty-two (52) publicly announced cancelled projects between 2024 and 2025, thirty-eight percent (38%) cited market uncertainty due to high costs and the absence of clear policy as the primary reasons for cancellation [2]. Industry reports reveal the scale of green H_2 project failures, their geographic distribution, and the interconnected reasons behind them. According to the Global Hydrogen Review 2025 by the International Energy Agency (IEA) [2], while public funding for low-emission H_2 has decreased, a more pressing issue is that nearly 45% of announced production projects are aimed at export, yet these are the least likely to reach final investment decisions (FIDs). The International Hydrogen Council reported that at least fifty (50) green H_2 projects were cancelled in the eighteen (18) months leading up to early 2026, with 80% of these being early-stage green H_2 projects. A breakdown of significant green H_2 project failures by region is shown in Table 15. The global retreat from green H_2 is not attributable to a single factor but rather a convergence of structural and economic challenges.

Table 15. Selected failed and/or stalled projects in Europe, North America and Asia [2,147–150].

Region	Notable Failed/Stalled Projects	Primary Reasons
Australia	BP's US$36 billion AREH project; Stanwell's US$8.1 billion CQ-H2 project.	High costs; lack of off-takers; export model failure.
North America	PlugPower's six projects; ExxonMobil's Texas 'largest' project.	Economic viability; policy deadline (45 V credit); high costs.
Europe	Shell (Norway); Air Products (UK); E.ON (Germany); Equinor (Germany).	Cost; weak demand; regulatory uncertainty; gap between ambitious supply targets and actual demand.
China	8+ projects cancelled in early 2025; major state-owned projects scrapped.	High costs; market price drops; low returns.

There are four root causes considered to be the main reasons for the failure of large-scale green H_2 projects globally. These root causes are:

(a) Unbridgeable cost gap: The most critical factor is the prohibitive cost of green H_2 compared to its fossil-fuel-based alternative, grey H_2. According to data cited by the Chinese Petroleum and Chemical Industry, the production cost of green H_2 is roughly US$3.0 to US$4.4 per kilogram (kg) (CN¥22- CN¥32), but including storage and transportation within 200 km, the delivered cost can approach US$8.3 per kg (CN¥60) [147,151]. This is approximately three times the cost of grey H_2 [146]. In India, the situation is similar, with green H_2 costing between US$4.1 and US$5.9 per kg (INR 350-500), while grey H_2 is available for just US$1.8 to US$2.6 per kg (INR 150-220). As a senior executive from China's state-owned energy giant bluntly stated, a project was abandoned as the project's economics did not meet expectations and did not satisfy the group's requirements [149].

(b) Cause and effect conundrum: A recurring theme in project cancellations is the lack of a market. Many projects, particularly in Australia and Canada, were built on the speculative model of 'build it and they will come', but the buyers never materialised [147]. The IEA notes that over half of announced export-oriented projects are in developing economies, where affordable capital and export infrastructure may be limited [2]. For example, the Australian CQ-H2 project collapsed after its primary off-taker, Japan's Kansai Electric Power, withdrew due to costs being far higher than initial feasibility studies predicted [147]. ING Bank reported that only 3% of total government support globally is directed at creating demand, leading to a severe market imbalance [150].

(c) 'Policy dependency' trap: The green H_2 sector has shown a dangerous over-reliance on government subsidies and favourable regulations. When policies shift or fail to materialise, projects become unviable overnight. In the United States, changes to the 45 V tax credit under the 'One Big Beautiful Bill Act' created uncertainty and moved the construction deadline forward, squeezing developers and causing many to give up [149,150]. In the UK, Air Products cancelled a UK£2 (US$2.66) billion project, explicitly stating that the government failed to provide 'sufficient policy support and financial incentives' for its specific technology pathway [147]. The German energy association BDEW reported that regulatory, economic, and infrastructure risks have made investments too costly and uncertain, stalling the market despite strong corporate interest.

(d) High financing costs and investor scepticism: Green H_2 projects are capital-intensive infrastructure ventures with long payback periods. This clashes with the current high-interest-rate environment and capital markets' preference for quicker returns. According to the IEA, while thousands of kilometres of H_2 pipelines have been announced, less than 6% have reached a final investment decision (FID) [2]. The sector has reverted to a 'pilot phase', according to a 2026 analysis by ING Bank. The focus must be on moving projects toward FID,

which requires solid demand and secure financing—conditions that are currently absent in much of the Western world [150]. A recent report by the Hydrogen Council and McKinsey & Company revealed that approximately 27% of the projects cancelled encountered funding challenges linked to bankruptcy, as illustrated in Figure 18. The report concluded that only 10% of announced H_2 projects are expected to reach production [151]. Europe's green H_2 projects are focused on developing infrastructure and demand centres for H_2 imports instead of producing giga-scale renewable H_2 production capacity domestically. Most H_2 projects in Europe are not for renewable H_2 production as these projects are focused on electrolysis and methane reformation with carbon capture and storage (CCS) [151].

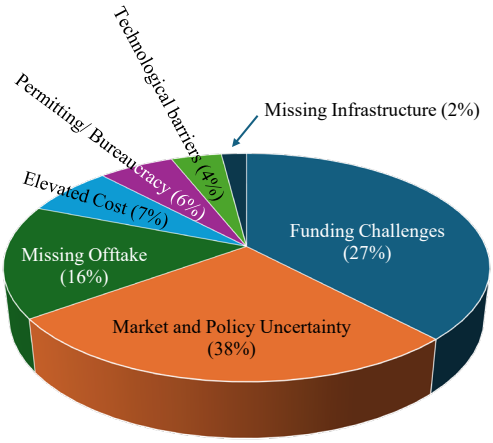


Figure 18. Reasons for announced project cancellations.

Despite current setbacks, H_2's significance in a low-carbon future is multifaceted. It has the potential to power road vehicles and trains using fuel cells, store surplus renewable energy for later use, and decarbonise hard-to-abate steel and fertiliser industries [152]. The green H_2 initiatives in Africa present a promising opportunity; however, realising this vision is fraught with substantial challenges that necessitate well-planned strategies tailored to the specific needs of individual countries and the continent as a whole. The primary challenges include considerable capital requirements, infrastructure development, long-term purchase commitments from foreign buyers, high costs associated with power and electrolysers, scarcity and cost of demineralised water, policy and regulatory gaps, acute skills shortages, and inequitable or non-beneficial foreign investment initiatives. To address these challenges, a comprehensive green H_2 strategy is essential for Africa. One such green H_2 strategy is proposed below.

Green H_2 Strategy for the Continent of Africa

To transition from a natural gas (CH_4), coal, and liquid fuel-based economy to a hydrogen (H_2) economy, developing nations in Africa and other regions face a series of challenges, notably the high financial costs associated with green H_2 production, storage, transmission, and utilisation. Consequently, a H_2 strategy for Africa must consider its financial capacity, energy availability, demand, usage, import and export capabilities, security, renewable electrification, and socioeconomic development. A comprehensive approach to developing a hydrogen economy should encompass various elements, including finance, technology, production capability, H_2 derivatives, storage, transport, safety, utilisation, distribution networks, logistics value chains, skills development, and socioeconomic benefits. These aspects should be integrated into a national and continental green H_2 strategy to effectively address the aforementioned challenges and reap socioeconomic and environmental benefits. Based on these criteria, a green H_2 strategy for Africa has been proposed, as illustrated in Figure 19.



Figure 19. Proposed green H_2 strategy for Africa.

The proposed strategy consists of six stages: (i) Observation and Analysis of Global Green H_2 Development; (ii) National Green Hydrogen Policy Formulation; (iii) Creating Conditions for the Domestic Green Hydrogen Market; (iv) Determination of National Green H_2 Demand; (v) Green Hydrogen Production for Local Use, Storage, Transportation, and Distribution; and (vi) Green Hydrogen in Africa for Local Use and Export. The figure also indicates a tentative time frame for each of the six stages. The action plan in each of the six stages is elaborated in detail.

Stage I: *Observation and Analysis of Global Green H_2 Development (Time Frame: 2026–2028)*

- Policies of developed and developing nations in other continents, especially Asian countries.
- New technology trials and efficacy (case studies from China, Europe, Australia, Americas).
- Green H_2 financing model(s) outside of Africa.
- Green energy economic viability for developing (especially the least developing) countries.

Stage II: *National Green H_2 Policy Formulation (Time Frame: 2029–2032)*

- Setting national vision, encompassing Africa's socioeconomic conditions and priorities.
- Green H_2 switching plans.
- Finance support schemes without compromising vital development activities. Priority should be given to attract concessional finance from African Development Bank (AfDB), World Bank, etc.
- Understanding the international green H_2 market (long-term buyers and export).

Stage III: *Creating Conditions for Domestic Green H_2 Market (Time Frame: 2033–2035)*

- Formulation of legislations and regulations for the green H_2 market and investment.

- Development of national standards for green H_2 value chain.
- Formulation of H_2 origin (colour) certification mechanism and procedure, aligned with the national and international standards.

Stage IV: *Determination of National Green H_2 Demand and Local Skills Development (Time Frame: 2036–2038)*

- Domestic green H_2 demand assessment.
- Green H_2 cost development (without subsidy) including cost calculation methods.
- Global H_2 production cost dynamics.
- Skilled workforce preparation for green H_2 economy and value chain through existing and/or support industries, establishing new engineering and vocational institutions.

Stage V: *Green H_2 Production, Storage and Transportation for Domestic Use and Export (Time Frame: 2039–2045)*

- Storage system development.
- Pipeline transportation network construction between production hub(s), major storage and distribution hubs and ports.
- Domestic surface and waterway transportation systems other than pipelines (truck, ship, rail).

Stage VI: *Application of Green H_2 in the Continent of Africa (Time Frame: 2046–2060)*

- Power grid stabilisation.
- Ammonia (fertiliser) production.
- Explosive for mining.
- Transport (especially shipping, rail and long haulage trucks, buses).
- Feedstock (heat) for industries including metal processing.
- Petrochemicals including refineries.
- Fully synchronised green H_2 logistics, value chain development.
- Surplus green H_2 for export.

To achieve the proposed six-stage green H_2 development strategic roadmap by 2060, several key components are essential. These include universal electrification across Africa, substantial financial investment (hundreds of billions of US dollars or equivalent), focused research and development efforts, innovation in homegrown technologies, dedicated infrastructure development, the preparation of a highly skilled workforce, and the establishment of markets within Africa for local use as well as for export outside the continent.

The proposed six-stage strategy can be sub-grouped into three main phases: (a) a primary or foundational phase (2026–2035), (b) a secondary or pilot phase (2036–2045), and (c) a tertiary or mature phase (2046–2060). A chronological technology outline is shown in Table 16.

A realistic time frame for Africa to become a leading global exporter of green H_2 is post-2050, with the potential to be a major force by 2060. However, the path is not simple. Instead of a single winner, the future market is projected to be multipolar, with Africa, China, Australia, and the Americas all playing significant but different roles. The competition is shaped less by who has the best green electricity generation, chief electrolyser technology, manufacturing bases, highly developed seamless value chains, or freshwater access, and more by who can secure the necessary low-cost financing and build infrastructure fastest. Africa's strategy is export-oriented with untapped renewable potential. The continent aims to become a major supplier of green H_2 to global markets, particularly Europe. The core challenge is moving from planning to execution. The strengths are excellent renewable resources (solar, wind). However, success hinges on overcoming high financing costs due to country and project risks. The Hydrogen Council notes that only 1% of Africa's

project pipeline has obtained a final investment decision, compared to 7% globally [153]. If Africa can capture around 15% of the global H_2 market, exports can rise from 1 million tonnes per annum (Mtpa) to 11 Mtpa by 2050 [153]. In contrast, China's green H_2 strategy, propelled by its domestic industry, primarily aims to decarbonise the extensive domestic sector. As the world's largest producer and consumer of H_2, its scale offers a considerable advantage. China possesses several strengths, including a mature manufacturing base, well-developed logistics and value chains, proactive government policy, a highly skilled workforce, and competitive capital costs. As of 2025, China is a global leader in green hydrogen (H_2) production, producing over 200,000 tonnes per year, while the rest of the world produces only 20,000 tonnes. By 2060, China aims to transition its entire hydrogen demand—exceeding 100 million tonnes per annum (Mtpa)—to green sources, utilising it in sectors such as steel, chemicals, and heavy transport. Initially focused on domestic needs, the International Renewable Energy Agency (IRENA) now projects that China will emerge as a leading exporter by 2050, propelled by its capacity to scale production and secure low-cost financing [154]. While the continent has the resources to be the cheapest producer on paper, higher financing costs currently make its projects more expensive to build than those in China. The potential for green H_2 to transform economies depends on a country's ability to embed it within a coherent industrial policy.

Table 16. Chronological technology roadmap for green H_2 in Africa: technology shifts, policy frameworks, and investment cycles as per the proposed green H_2 strategy roadmap.

Phase	Timeline	Technology Focus	Policy Framework	Capital Investment Billion US$	6-Stage Roadmap Alignment
Primary or Foundational Phase	2026–2035	Renewable electricity generation capacity development. AWE (TRL 9)—small-scale commercial application. PEM (TRL 8–9)—pilot-scale trial.	National H_2 strategy formulation. Mobilising funding for rapid expansion of renewable electricity generation. Mobilising public funding for pilot studies into green H_2 projects.	50–100	Stages I–III
Secondary or Pilot Phase	2036–2045	AWE (TRL 9)—commercial application. PEM scale-up (iridium reduction) AEM demo (TRL 7–8).	Cross-border green H_2 certification.	200–300	Stages IV–V
Tertiary or Mature Phase	2046–2060	AEM commercial application (TRL 9) SOEC commercial application (TRL 8–9)	H_2 trading. Circular economy. Integrated African market. Intercontinental market.	400–600	Stages V–VI and beyond

8. Discussion and Implication

Renewable energy presents an opportunity for Africa, potentially leading to socioeconomic prosperity and industrialisation for its people. However, these resources can also become burdensome if the benefits do not reach the African populace, instead favouring former colonial powers and primarily serving the interests of industrialised Western nations. Africa faces a dilemma: whether to prioritise renewable energy for direct electrification or to focus on green H_2 production. This is not a simple choice; it involves considerations of sequence, timing, scale, strategic interest, and development priorities. A favourable balance between electrification and green H_2 production is essential. Nevertheless, Africa should first prioritise renewable energy for direct electrification and grid development to enhance its people's socioeconomic prosperity. Nearly half of Africa's population currently lack access to electricity, making it a pressing moral and economic imperative to alleviate acute energy hunger and financial hardship. Produced from surplus power, green H_2 should be regarded as a primary, strategic domestic industry, particularly for applications such

as ammonia for fertiliser, steel production, refineries, and potassium nitrate for mining. It should also be considered a secondary, strategic, export-oriented industry built on a renewable energy foundation. The priority of green H_2 varies depending on the specific context of each country. Nations with good renewable resources—such as solar energy in the Sahel or wind energy in the Horn of Africa—can allocate additional renewable capacity beyond their domestic needs specifically for green H_2 production intended for export. The objective must be additionality, ensuring that power is not diverted from the grid without meeting consumer needs.

At present, the modes of green H_2 export from African countries pose a major obstacle. An economic analysis of hydrogen exports from Africa is vital for making green H_2 projects economically viable. It is important to recognise that Africa should not be viewed as a single energy market; rather, the continent features diverse attributes, including varying solar irradiance (particularly in the Sahel), substantial hydropower potential (especially in the Congo/DRC), established natural gas infrastructure (notably in North Africa and Nigeria), and differing levels of other related risks. The economic feasibility of green H_2 projects relies on the delivered cost of H_2, or its carriers, to importing markets such as the EU, Japan, and South Korea, expressed in US$/kg. A tiered economic breakdown of various export modes is presented in Tables 17 and 18, alongside a technical framework detailing the specifications and cost considerations for liquid H_2 (LH2) tankers.

Table 17. Carrier decision (ammonia vs. liquid hydrogen vs. LOHC) [155,156].

Carrier	Capex (Production)	Storage Cost	Transport Cost (per GJ)	End-Use Efficiency	Best Suited For
Liquid Hydrogen (LH2)	Highest (liquefaction consumes 30–35% of LHV)	Extreme (boil-off: 0.5–1.5% per day)	Moderate (high density, small ships)	High (direct use in fuel cells/industry)	Short-haul (Europe via North Africa) or high-value niche markets.
Ammonia (NH_3)	Lowest (Haber–Bosch at scale)	Cheap (ambient pressure, −33 °C or 10 bar)	Lowest (carries 1.7× more H2 per m^3 than LH2)	Low (requires cracking or direct combustion; 20–30% energy loss at reconversion)	Long-haul (Asia via Namibia/South Africa) and existing fertiliser infrastructure.
LOHC (e.g., Toluene/MCH)	Moderate	Cheap (ambient)	High (carrier is heavy; fewer tons of H_2 per ship)	Moderate	Regions with existing petrochemical refineries for dehydrogenation.

As shown in Table 17, from an economic perspective, ammonia emerges as the preferred option for nearly three-quarters of announced African projects, specifically in Mauritania, Namibia, and Egypt. This preference is due to several factors: a) it avoids a significant liquefaction energy penalty, which is crucial given the instability of Africa's power grid; b) it takes advantage of established global shipping standards, as the IMO IGF Code already permits ammonia; and c) it enables the utilisation of stranded renewable energy at a high capacity factor, with electrolysers operating continuously and ammonia storage acting as a buffer for output. In contrast, liquefied hydrogen (LH2) is only economically feasible for North African nations—namely Morocco, Algeria, and Egypt—that are targeting Southern Europe, where shipping distances are less than 2.5 days. At this range, the minimal boil-off (less than 1.5%) compensates for the high liquefaction costs by negating the need for ammonia cracking at the EU off-take point.

Table 18. Route decision (pipeline vs. sea routes) [155–157].

Route	Capex per km	Energy Loss per 1000 km	Economic Breakeven Distance	African Applicability
Pure H_2 Pipeline (New)	US$2–3 million/km (requires specialty steel)	~5% compression loss	<1500 km	Morocco to Spain; Algeria to Italy via existing gas pipeline retrofits (retrofit costs: $US0.5 million/km).
Ammonia Pipeline	US$1–1.5 million/km (standard carbon steel)	~2% pumping loss	<3000 km	DRC to Angola; Nigeria to coastal export hubs.
Sea Shipping ($LH2/NH_3$)	Capex on ships (US$250–350 million per large carrier)	Boil-off/N_2 purging losses	>3000 km	Namibia, South Africa, Kenya to Asia/Europe.

As indicated in Table 18, the economically optimal model for West/Central Africa seems to be the "pipeline-to-ship" hybrid mode.

(a) A dedicated ammonia pipeline should be constructed from the solar-rich interior, such as Mali, to a coastal floating terminal located in Guinea or Nigeria.
(b) This approach reduces the shipping distance for tankers by 2000 km and enables the pipeline to serve as buffer storage, thereby minimising the necessity for large onshore tank farms, which can be costly in high-risk coastal areas.
(c) Economic modelling indicates that for distances exceeding 400 km inland, a pipeline is more cost-effective than trucking or compressing ammonia into ISO containers for delivery to ports.

In relation to determining specifications and costs for liquid hydrogen (LH2) tanker vessels, if LH2 is considered viable—specifically for short-haul or premium green steel markets—an engineering–economic framework should be established to ascertain vessel specifications and associated costs.

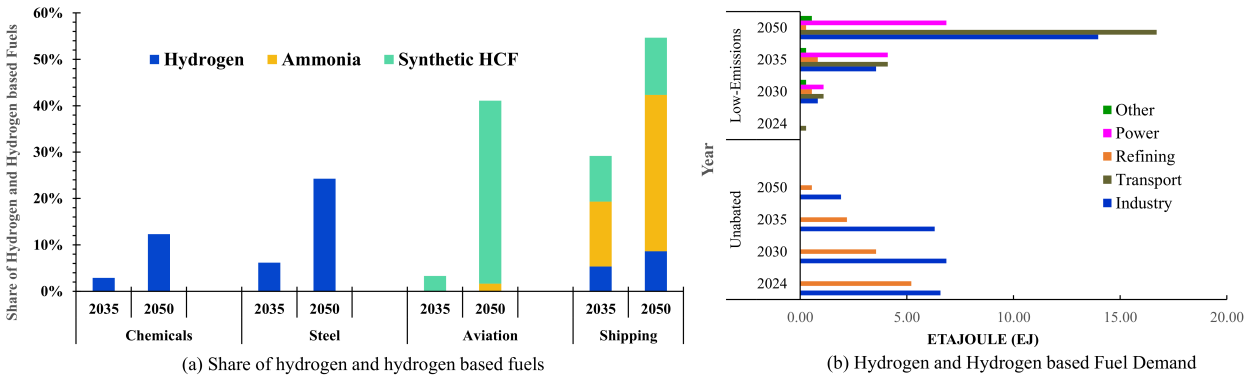
The economic calculations, which consider vessel capacity (cargo volume), boil-off and propulsion specifications; the costing framework (both capital and operational); and the final economic viability test (levelised cost of transport—LCOT) are as follows:

- For North Africa (Morocco, Egypt): Constructing hydrogen pipelines to Europe and retrofitting existing natural gas pipelines present the lowest LCOT. Utilising liquid hydrogen (LH2) exclusively for premium industrial off-takers (e.g., Germany) that do not accept ammonia appears more promising.
- For Southern Africa (Namibia, South Africa): Shipping ammonia instead of LH2 appears more viable; the 14-day voyage to Asia renders boil-off loss (BOR) economically unviable (>4% loss). Investing in "cracking-ready" terminals in Japan that can accept ammonia directly for co-firing in coal plants seems to be a favourable option.
- For West Africa (Nigeria, Mauritania): The "pipeline-to-ship" hybrid for ammonia is preferable. Constructing a 500 km pipeline from the high-wind coastal zone to a deep-water port, with the pipeline serving as dynamic storage, can reduce onshore tank capital expenditures (CAPEX).

For green H_2 to be produced in Africa competitively, it must be generated at a cost of less than US$2.50/kg at the electrolyser. This price point is crucial for any export model to be more favourable than grey H_2 in Europe or elsewhere. If the LCOH surpasses US$2.50/kg, even the prospect of free shipping can render the project economically unviable. Therefore, it is vital to focus on scaling up electrolysers and establishing a direct link to high-capacity-

factor solar or wind energy sources (with a capacity factor exceeding 45%) before optimising shipping logistics.

The alternative to export, at least for now, is to utilise green H_2 locally. Ammonia, currently produced from fossil fuels, primarily natural gas, is essential for Africa's agricultural and mining sectors. Decarbonising Africa's existing ammonia production with domestically produced renewable H_2 offers a path to emission reductions, although Africa's per capita CO_2 emissions are negligible compared to the per capita emissions of industrialised nations. Ammonia production plants located near renewable sources offer a stable, predictable market using appropriately sized electrolysis facilities powered by solar, wind, hydro or geothermal and supported by increased low-cost battery storage, directly replacing fossil-derived H_2 without the costly complexities associated with exports. Farmers in Africa and elsewhere rely heavily on ammonia-based fertilisers to boost crop productivity. Many African countries (South Africa, DRC, Angola, Namibia, and Mozambique) rely on mining, which requires ammonium nitrate explosives. Renewable H_2 can be used to produce ammonia nitrate locally with fewer carbon emissions. Transitioning to green H_2 at existing and future plants would significantly cut emissions, enhance energy security, and deliver stable employment without exposure to uncertain and highly competitive global green H_2 markets. Figure 20 shows the prospective use of green H_2 (a) and low-carbon H_2 (b) in various sectors in 2035 and 2050.



(a) Share of hydrogen and hydrogen based fuels

(b) Hydrogen and Hydrogen based Fuel Demand

Figure 20. Green and low-carbon H_2 demand and their application share from 2024 to 2050, adapted from [2].

Africa's planned green H_2 projects, totalling 216 gigawatts, and their technical and financial viability remain uncertain. The green H_2 from these projects is primarily targeted at exports to Europe, but the market is yet to be developed, and purchase agreements are yet to be signed. Limited funding and off-takers, unrealistic schedules, and technological difficulties are some of the severe headwinds that make these initiatives unlikely to be economically feasible, particularly in the context of competing priorities and the need for substantial investment in infrastructure to support green H_2 production. Furthermore, plans for financing massive projects are still a mystery. Europeans own 65% of Africa's potential green H_2 projects, while Africans own only 25%. Furthermore, much of the earnings from the H_2 value chain would go to the buyer; thus, if most of the green H_2 is exported, African countries would not benefit much from these initiatives. The prospect of becoming green H_2 hubs, exporting green H_2 and industrial feedstocks to Europe, has inspired H_2 projects in eleven African countries: Botswana, Djibouti, Egypt, Kenya, Mauritania, Morocco, Mozambique, Namibia, South Africa, The Gambia, and Western Sahara. The majority of the green H_2 infrastructure-building companies lack experience in building such large projects. Plans for future and current wind and solar capacity in some African countries far exceed current operating infrastructure, as shown in Figure 21.

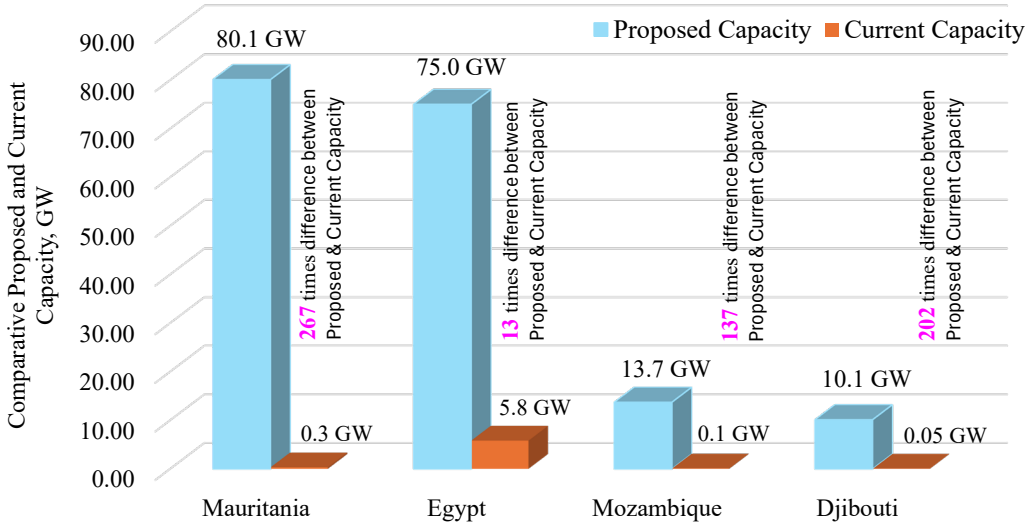


Figure 21. Proposed and operating wind and solar capacity in gigawatts (GW) for selected countries.

Analysing current market failures and project cancellations, it is apparent that specific policy changes are required to shift the green H_2 target towards industrial consumers, moving from a cycle of announcements to realistic, bankable, and profitable projects, especially in Africa, where the average per capita GDP is less than US$700 and over 40% of the population lacks access to electricity. Instead of building massive supply for a non-existent market, successful projects need to be smaller and anchored to existing demand. Green H_2 should specifically target industrial consumers, such as refineries and fertiliser plants. BP's only surviving projects are a 100 MW plant in Germany and a 25 MW plant in Spain, designed specifically to serve its refineries and local industrial customers [158] only. The proposed green H_2 production strategic roadmap offered in this study outlines specific steps at various stages over the next 35 years, unlike other published strategies for green H_2 production in Africa, as discussed in Section 7. Table 19 highlights some specific differences in the approaches to Africa outlined in this study, such as the emphasis on localised power production first and then the integration of renewable energy sources tailored and prioritised according to regional needs.

Table 19. Major green H_2 policy variation in the proposed green H_2 production strategy roadmap in this study.

Published Green H_2 Models	**Green H_2 Models for Africa in the Proposed Strategy Roadmap (This Study)**
(a) Diverting renewable power for H_2 production without providing universal electricity access to the population, businesses and industries in Africa.	• Ensure electrification for the nation first using renewable energy plus deficit power by conventional energy. • Only use leftover or surplus renewable power for green H_2 production.
(b) High-cost electricity for green H_2 generation.	• Firstly, use advanced technologies for renewable power generation for reducing the electricity cost (nearly 70% green H_2 cost due to electricity cost). • Secondly, use a low-cost electrolyser or commercially proven electrolyser to reduce H_2 production cost (the electrolyser constitutes nearly 25–27% of H_2 cost). • Harvest and use rainwater as it needs minimal purification. • Avoid seawater use as it is most expensive due to the purification required for H_2 production.

Table 19. *Cont.*

Published Green H_2 Models	Green H_2 Models for Africa in the Proposed Strategy Roadmap (This Study)
(c) No significant international market.	• Parity or comparable production cost with grey H_2 which is difficult to achieve at this moment. • African countries must not sign long-term contracts without securing subsidies from European and Asian buyers.
(d) Short-term, one-off grant programmes for low-cost technology development.	• Long-term (10–20 year) state support for technology development following the path of China as an example.
(e) No or negligible investment and financial support for storage, transportation and fuelling station networks.	• Significant public and private investment in storage, transportation and fuelling stations to develop complete H_2 supply and value chain.
(f) Mega ambition and mega H_2 projects.	• Small-scale project with minimal investment to generate green H_2 for use in hard-to-abate CO_2 intensive industries.
(g) Ambitious plans for global H_2 export.	• Develop within Africa market for NH_3 and other fertiliser uses to enhance food production and food security.
(h) Utilisation of high-cost and commercially unviable technologies.	• Wait and see for commercially viable and proven electrolyser technology.
(i) Heavily relying on foreign experts and workforce.	• Develop a homegrown skilled workforce with a long-term plan.
(j) National standards that conflict globally.	• Mutual recognition agreements for certification.

9. Conclusions, Recommendations and Limitations of the Study

This study investigated green H_2 projects along with renewable energy sources in Africa. The study evaluated the potential use of renewable energy for green H_2 production and electrification. Major findings and recommendations are summarised below:

(a) The levelised cost of green hydrogen (LCOH) generated from solar power in Africa ranges from US$6/kg to US$10/kg. The lowest cost of US$6/kg is primarily found in desert regions, except for Mauritania and Somalia. However, these desert areas experience significant water scarcity, which could ultimately drive up the LCOH. Countries in Africa with moderate solar irradiation face the highest LCOH for green H_2, reaching around US$10/kg.

(b) The levelised cost of green H_2 production from wind power varies significantly across different regions in Africa. The lowest LCOH is found at approximately US$5.5/kg in areas adjacent to the Arabian Sea, the Red Sea, and the Horn of Africa, where the wind capacity factor exceeds 40%. With the low wind capacity factor (~15%) in various parts of Southern Africa and central Eastern Africa, the LCOH ranges from US$8/kg to US$26/kg.

(c) Considering Africa's renewable energy potential, its resources, and the deficiencies in infrastructure, logistics, value chains, and skills development, along with the current status of global green H_2 projects and market conditions, this study proposes a six-stage roadmap for the green H_2 strategy from 2026 to 2060. This strategy aims to aid Africa's policymakers in producing green and low-carbon H_2 for use both within the continent in the short term and for export in the future. The strategy is anticipated to facilitate the effective and sustainable production and utilisation of green H_2, contributing to Africa's socioeconomic development, industrialisation, CO_2 emissions reduction, and the global transition to green energy.

(d) The proposed green H_2 strategy roadmap can be tailored to any developing or emerging nation, incorporating local needs, resources, and priorities. It is anticipated that the

proposed strategy will aid governments, policymakers, decision-makers, implementers, investors, researchers, and academics working in the renewable and H_2 energy sector.

(e) The priority for the continent of Africa should be universal electrification through renewable energy to achieve socioeconomic development, industrialisation, and employment creation, instead of focusing on green H_2 exports in the short term.

(f) Africa has attracted significant announced green hydrogen investment (~$293 billion across 16 countries), but the projects remain overwhelmingly nascent—most are at early or emerging stages and have yet to reach a final investment decision (FID). This gap is even more pronounced for large-scale projects, which lag well behind the global FID rate of ~10%. Thus, the policy- and decision-makers should focus on bankable benefits for the people of Africa and take a cautious approach before making commitments to green H_2 projects for exclusive exports.

(g) This study provides a continent-wide assessment of the prospects, challenges, costs, and strategic development of green hydrogen in Africa. The levelised cost of hydrogen (LCOH) analysis relies on a static annual techno-economic model instead of an hourly or sub-hourly chronological simulation. This approach utilises annual capacity factors and full-load-hour assumptions to estimate the availability of renewable electricity and hydrogen production. Therefore, the model does not adequately account for the temporal variability in solar and wind generation, including fluctuations that occur on an hourly, daily, and seasonal basis.

(h) The proposed six-stage strategic roadmap is based on currently available evidence regarding technology readiness, project development, market conditions, renewable-resource availability, infrastructure, and Africa's socioeconomic priorities. Long-term developments in hydrogen demand, international trade, carbon pricing, electrolyser technology, financing, policy, and competing decarbonisation technologies remain uncertain. Accordingly, the roadmap should be periodically reassessed as technologies, markets, and national development priorities evolve.

Author Contributions: Conceptualisation: F.A.; software: M.R. and S.A.; investigation: F.A., Y.J. and X.H.; methodology: F.A. and N.H.; visualisation: M.R. and S.A.; data curation: F.A., Y.J., X.H., M.R. and S.A.; original draft preparation: F.A. and N.H.; supervision: Q.A., N.H. and X.H.; reviewing and editing: F.A., I.T. and N.H.; validation: I.T., Q.A. and Y.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the conclusions of this article will be made available by the authors on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dagnachew, A.G.; Yalew, S.G.; Tesfamichael, M.; Okereke, C.; Abraham, E. A green hydrogen revolution in Africa remains elusive under current geopolitical realities. *Clim. Policy* **2025**, *25*, 291–302. [CrossRef]
2. International Energy Agency—IEA. *Global Hydrogen Review 2025*; IEA Publications: Amsterdam, The Netherlands, 2025. Available online: https://iea.blob.core.windows.net/assets/a6c466dd-b6f0-44bd-a60a-6940eccfb1c3/GlobalHydrogenReview2025.pdf (accessed on 26 December 2025).
3. Togni, L.; Fakhoury, R.; Deen, A.; Steki, J.; Schafer, F.; Babenhauserheide, N.; Zahn, M.; Steinbach, C. *Hydrogen on the Horizon: Ready, Almost Seto, Go? Working Paper: National Hydrigen Strategies*; World Energy Council: London, UK, 2021; pp. 1–13. Available online: https://wec-estonia.ee/working-paper-hydrogen-on-the-horizon-national-hydrogen-strategies/ (accessed on 25 September 2026).

4. Thunder Said Energy. Global Hydrogen Supply-Demand: By Region, by Use & Over Time? Available online: https://thundersaidenergy.com/downloads/global-hydrogen-supply-demand-by-region-by-use-over-time/ (accessed on 24 August 2024).
5. Chigbu, U.E.; Nweke-Eze, C. Green Hydrogen Production and Its Land Tenure Consequences in Africa: An Interpretive Review. *Land* **2023**, *12*, 1709. [CrossRef]
6. Puliti, R. *Putting Africa on the Path to Universal Electricity Access*; World Bank: Washington, DC, USA, 2022. Available online: https://blogs.worldbank.org/energy/putting-africa-path-universal-electricity-access (accessed on 20 June 2023).
7. Sadik-Zada, E.R.; Gatto, A.; Schäfer, N. African green hydrogen uptake from the lens of African development and European energy security: A blessing or curse? *Technol. Forecast. Soc. Change* **2025**, *215*, 123974. [CrossRef]
8. Baskaran, G.; Coste, S. Achieving Universal Energy Access in Africa amid Global Decarbonization, Centre for Strategic and International Studies (CSIS). 2024. Available online: https://www.csis.org/analysis/achieving-universal-energy-access-africa-amid-global-decarbonization (accessed on 21 January 2026).
9. International Energy Agency—IEA. *Where Does Australia Get Its Electricity?* IEA: Paris, France, 2024. Available online: https://www.iea.org/countries/australia/electricity (accessed on 10 January 2026).
10. KfW; GIZ; IRENA. *The Renewable Energy Transition in Africa Powering Access*; Resilience and Prosperity: Frankfurt am Main, Germany, 2021. Available online: https://www.giz.de/en/downloads/Study_Renewable%20Energy%20Transition%20Africa-EN.pdf (accessed on 25 May 2026).
11. Warchold, A.; Pradhan, P.; Kropp, J.P. Variations in sustainable development goal interactions: Population, regional, and income disaggregation. *Sustain. Dev.* **2021**, *29*, 285–299. [CrossRef]
12. Alola, A.A.; Ozturk, I.; Bekun, F.V. Are clean energy prosperity and technological innovation rapidly mitigating sustainable energy-development deficit in selected sub-Saharan Africa? A myth or reality. *Energy Policy* **2021**, *158*, 112520. [CrossRef]
13. Cantarero, M.M.V. Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. *Energy Res. Soc. Sci.* **2020**, *70*, 101716. [CrossRef]
14. International Energy Agency—IEA. *World Energy Outlook 2023*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/world-energy-outlook-2023 (accessed on 11 March 2026).
15. Kalt, T.; Simon, J.; Tunn, J.; Hennig, J. Between green extractivism and energy justice: Competing strategies in South Africa's hydrogen transition in the context of climate crisis. *Rev. Afr. Political Econ.* **2023**, *50*, 302–321. [CrossRef]
16. Msweli, N.; Nnachi, G.U.; Richards, C.G. A Review of Green Hydrogen Technologies and Their Role in Enabling Sustainable Energy Access in Remote and Off-Grid Areas Within Sub-Saharan Africa. *Energies* **2025**, *18*, 5035. [CrossRef]
17. Egli, F.; Schneider, F.; Leonard, A.; Halloran, C.; Salmon, N.; Schmidt, T.; Hirmer, S. Mapping the cost competitiveness of African green hydrogen imports to Europe. *Nat. Energy* **2025**, *10*, 750–761. [CrossRef]
18. Uhrorakeye, T.; Ruet, J.; Cloete, B.; Bani, J.; Miram, L. *African Green Hydrogen Report*; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ): Eschborn, Germany, 2025; pp. 1–198. Available online: https://ptx-hub.org/wp-content/uploads/2025/06/African-Green-Hydrogen-Report-2025.pdf? (accessed on 23 February 2025).
19. Tiktas, A.; Hepbasli, A. Africa's green hydrogen trajectory: A multidimensional review of technology, economics, infrastructure, and social justice. *Int. J. Hydrogen Energy* **2026**, *225*, 154321. [CrossRef]
20. Lahnaoui, A.; Aniello, G.; Barberis, S.; Agbo, S.N.; Kuckshinrichs, W. Assessing the feasibility of a green hydrogen economy in selected African regions with composite indicators. *Int. J. Hydrogen Energy* **2025**, *101*, 1387–1405. [CrossRef]
21. Medinilla, A.; Dekeyser, K. *Green Hydrogen: The Future of African industrialisation?* ECDPM: Maastricht, The Netherlands, 2024. Available online: https://ecdpm.org/work/Green-hydrogen-the-future-of-African-industrialisation (accessed on 14 December 2025).
22. Agyekum, E.B. Is Africa ready for green hydrogen energy takeoff? A multi-criteria analysis approach to the opportunities and barriers of hydrogen production on the continent. *Int. J. Hydrogen Energy* **2024**, *49*, 219–233. [CrossRef]
23. Costa, P.M.; Duarte, A.; Tomé, P.; Bento, N.; Fontes, M. Technological Innovations in Decarbonisation Strategies: A Text-Mining Approach to Technological Readiness and Potential. *Energies* **2024**, *17*, 6479. [CrossRef]
24. Wei, X.; Sharma, S.; Waeber, A. Comparative life cycle analysis of electrolyzer technologies for hydrogen production: Manufacturing and operations. *Joule* **2024**, *8*, 3347–3372. [CrossRef]
25. Pinsky, R.; Sabharwall, P.; Hartvigsen, J.; O'Brien, J. Comparative review of hydrogen production technologies for nuclear hybrid energy systems. *Prog. Nucl. Energy* **2020**, *123*, 103317. [CrossRef]
26. International Renewable Energy Agency-IRENA. Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5 °C Climate Goal. 2020. Available online: https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction (accessed on 12 April 2026).
27. Al-Mandhari, M.; Cowdall, O.; Ghosh, A. Challenges and Advancements in Direct Solar PV to Water Electrolyser Technology for Hydrogen Production. *Sustainability* **2026**, *18*, 2089. [CrossRef]

28. Schneider, L.P.C.; Dhrioua, M.; Ullmer, D.; Egert, F.; Wiggenhauser, H.J.; Ghotia, K.; Kawerau, N.; Grilli, D.; Razmjooei, F.; Ansar, S.A. Advancements in hydrogen production using alkaline electrolysis systems: A short review on experimental and simulation studies. *Curr. Opin. Electrochem.* **2024**, *47*, 101552. [CrossRef]
29. Roeder, T.; Rosenstiel, A.; Monnerie, N.; Sattler, C. Impact of expected cost reduction and lifetime extension of electrolysis stacks on hydrogen production costs. *Int. J. Hydrogen Energy* **2023**, *95*, 1242–1251. [CrossRef]
30. Krishnan, S.; Koning, V.; de Groot, M.T.; de Groot, A.; Mendoza, P.G.; Junginger, M.; Kramer, G.J. Present and future cost of alkaline and PEM electrolyser stacks. *Int. J. Hydrogen Energy* **2023**, *48*, 32313–32330. [CrossRef]
31. Kumar, S.S.; Lim, H. Recent advances in hydrogen production through proton exchange membrane water electrolysis—A review. *Sustain. Energy Fuels* **2023**, *7*, 3560–3583. [CrossRef]
32. Arun, M.; Giddey, S.; Joseph, P.; Dhawale, D.S. Challenges and mitigation strategies for general failure and degradation in polymer electrolyte membrane-based fuel cells and electrolysers. *J. Mater. Chem. A* **2025**, *13*, 11236–11263. [CrossRef]
33. Wortmann, B.; Stolten, D.; Heinrichs, H. Critical Iridium Demands arising from future Expansion of Proton Exchange Membrane Electrolysis (Version 1). *arXiv* **2025**. [CrossRef]
34. Zong, S.; Zhao, X.; Jewell, L.L.; Zhang, Y.; Liu, X. Advances and challenges with SOEC high temperature co-electrolysis of CO_2/H_2O: Materials development and technological design. *Chem. Eng. J.* **2025**, *507*, 160620. [CrossRef]
35. Yoon, K.J.; Lee, S.; Park, S.-Y.; Minh, N.Q. Advances in high-temperature solid oxide electrolysis technology for clean hydrogen and chemical production: Materials, cells, stacks, systems and economics. *Prog. Mater. Sci.* **2025**, *154*, 101520. [CrossRef]
36. Ruiz, K.; Judez, X.; Fantova, M.; García-Martín, S.; García-Alvarado, F.; Ciaurriz, P.; Aguado, M.; Garbayo, I. Current market status of solid oxide hydrogen technology: From starting materials to system level. *Energy Rep.* **2026**, *15*, 109091. [CrossRef]
37. Bernat, R.; Milewski, J.; Dybinski, O.; Martsinchyk, A.; Shuhayeu, P. Review of AEM Electrolysis Research from the Perspective of Developing a Reliable Model. *Energies* **2024**, *17*, 5030. [CrossRef]
38. Mustapha, F.; Guilbert, D.; Gross, B. Advancements in anion exchange membrane electrolysers: From catalysts to life cycle assessment. *Int. J. Sustain. Energy* **2025**, *44*, 2520812. [CrossRef]
39. Curcio, E. Techno-economic analysis of hydrogen production: Costs, policies, and scalability in the transition to net-zero. *Int. J. Hydrogen Energy* **2025**, *128*, 473–487. [CrossRef]
40. Al-Mahmodi, M.; Ayadi, O.; Wang, Y.; Al-Halhouli, A. Sensitivity-based techno-economic assessment approach for electrolyzer integration with hybrid photovoltaic-wind plants for green hydrogen production. *Int. J. Hydrogen Energy* **2025**, *97*, 904–919. [CrossRef]
41. Park, J.; Kim, S.; Kim, H.; Lee, J.H. Strategies for achieving a techno-economic threshold of 1 USD/kg for green hydrogen. *Chem. Eng. J.* **2025**, *521*, 167069. [CrossRef]
42. Mendler, F.; Garcia, J.F.; Kleinschmitt, C.; Voglstätter, C. Global optimization of capacity ratios between electrolyser and renewable electricity sources to minimize levelized cost of green hydrogen. *Int. J. Hydrogen Energy* **2024**, *82*, 986–993. [CrossRef]
43. IRENA. *Analysis of the Potential for Green Hydrogen and Related Commodities Trade*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2025. Available online: https://www.irena.org/Publications/2025/Jun/Analysis-of-the-potential-for-green-hydrogen-and-related-commodities-trade (accessed on 15 June 2026).
44. Katebah, M.; Al-Rawashdeh, M.; Linke, P. Analysis of hydrogen production costs in Steam-Methane Reforming considering integration with electrolysis and CO_2 capture. *Clean. Eng. Technol.* **2022**, *10*, 100552. [CrossRef]
45. Odenweller, A.; Ueckerdt, F. The green hydrogen ambition and implementation gap. *Nat. Energy*, 2025; *Advance online publication*. [CrossRef]
46. Alex-Oke, T.; Bamisile, O.; Cai, D.; Adun, H.; Ukwuoma, C.C.; Tenebe, S.A.; Huang, Q. Renewable energy market in Africa: Opportunities, progress, challenges, and future prospects. *Energy Strategy Rev.* **2025**, *59*, 101700. [CrossRef]
47. Oni, A.O.; Anaya, K.; Giwa, T.; Di Lullo, G.; Kumar, A. Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Convers. Manag.* **2022**, *254*, 115245. [CrossRef]
48. IRENA. Hydrogen: A Renewable Energy Perspective. This Report Explicitly Compares Present and Future Hydrogen Costs as Renewable-Electricity and Electrolyser CAPEX Decline. For Example, it Considers Alkaline Electrolyser Investment Falling from about $840/kW to $200/kW and Demonstrates the Resulting Reduction in LCOH. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf (accessed on 26 June 2026).
49. McKinsey. Global Energy Perspective 2023: Hydrogen Outlook. This provides Useful Support for Comparisons Among Green, Blue and Grey Hydrogen. It Projects Increasing Competitiveness of Green Hydrogen as Renewable and Electrolyser Costs Decline and Projects Green Hydrogen to Account for 50–65% of Global Hydrogen Supply by 2050 Across Its Scenarios. Available online: https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-hydrogen-outlook (accessed on 9 February 2026).
50. International Energy Agency—IEA. *Global Hydrogen Review 2024*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/global-hydrogen-review-2024.

51. Santana, L.; dos Santos, G.; Santos, A.; Marinho, C.; Bispo, A.; Villardi, H.; Pessoa, F. Evaluating the economic influence of water sources on green hydrogen production: A cost analysis approach. *Int. J. Hydrogen Energy* **2024**, *89*, 353–363. [CrossRef]
52. Havukainen, J.; Ahola, J. Dynamic mass and energy balance model of a 50-kW proton exchange membrane electrolyzer system. *Int. J. Hydrogen Energy* **2025**, *97*, 904–919.
53. Martinez-Lopez, V.A.; Ziar, H.; Haverkort, J.W.; Zeman, M.; Isabella, O. Dynamic operation of water electrolyzers: A review for applications in photovoltaic systems integration. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113407. [CrossRef]
54. International Energy Agency—IEA. *Africa Energy Outlook 2022*; IEA Publications: Amsterdam, The Netherlands, 2022. Available online: https://iea.blob.core.windows.net/assets/220b2862-33a6-47bd-81e9-00e586f4d384/AfricaEnergyOutlook2022.pdf (accessed on 27 December 2025).
55. International Energy Agency—IEA. *World Energy Outlook 2025*; IEA Publications: Amsterdam, The Netherlands, 2025. Available online: https://www.iea.org/reports/world-energy-outlook-2025 (accessed on 27 December 2025).
56. African Energy Chamber. *The State of African Energy 2025 Outlook Report*; African Energy Chamber: Johannesburg, South Africa, 2025. Available online: https://energychamber.org/wp-content/uploads/The-State-of-African-Energy-2025_digital.pdf (accessed on 27 December 2025).
57. Global Solar Atlas. Available online: https://globalsolaratlas.info/map (accessed on 26 October 2025).
58. IRENA; CPI. *Global Landscape of Energy Transition Finance 2025*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2025. Available online: http://www.irena.org/publications (accessed on 26 December 2025).
59. DNV. Energy Transition Outlook. 2025. Available online: https://www.dnv.com/energy-transition-outlook/2025/ (accessed on 27 December 2025).
60. Sulikova, S.; Rojon, I.; Schwalm, M.; Englert, D. *Morocco to Fuel Global Shipping's Energy Transition*; World Bank Blogs: Washington, DC, USA, 2026. Available online: https://blogs.worldbank.org/en/arabvoices/morocco-to-fuel-global-shipping-s-energy-transition (accessed on 28 September 2026).
61. Eze, M. Moroccan Ports Poised to Become Green Hydrogen Hubs—World Bank. *The Electricity Hub*, 8 January 2026. Available online: https://theelectricityhub.com/moroccan-ports-poised-to-become-green-hydrogen-hubs-world-bank/ (accessed on 12 September 2026).
62. African Energy Chamber. Namibia's Quest for Energy Diversification: From Orange Basin Oil to Green Hydrogen and Nuclear. 18 February 2026. Available online: https://energychamber.org/namibias-quest-for-energy-diversification-from-orange-basin-oil-to-green-hydrogen-and-nuclear/ (accessed on 1 August 2026).
63. Kavitha. Egypt's 100MW Green Hydrogen Project Begins Exports to Europe and US, Solar Quarter. 14 January 2026. Available online: https://solarquarter.com/2026/01/14/egypts-100mw-green-hydrogen-project-begins-exports-to-europe-and-us/ (accessed on 23 June 2026).
64. Mauritania is Poised to Become a Leading Producer of Green Hydrogen in Africa. Economic and Commercial Office, Embassy of the Islamic Republic of Mauritania, Beijing, China. 9 December 2025. Available online: https://investgo.cn/article/gb/fxbg/202512/821828.html (accessed on 22 February 2026).
65. Groenendaal, B. KAHRE Announces 20 GW Net Zero Industrial Corridor in South Africa, Green Building Africa. 15 February 2026. Available online: https://www.greenbuildingafrica.co.za/kahre-announces-20gw-net-zero-industrial-corridor-in-south-africa/ (accessed on 23 July 2026).
66. The Extractor. Clean Energy's Hydrogen Dune—How Walvis Bay Became Namibia's First Green Hydrogen Hub. 24 September 2025. Available online: https://theextractormagazine.com/2025/09/24/cleanergys-hydrogen-dune-how-walvis-bay-became-namibias-first-green-hydrogen-hub/ (accessed on 10 February 2026).
67. Yohannes-Kassahun, B. *Technology Primer Africa's Solar Power Potential—A Realistic Overview, Office of the Special Adviser on Africa (OSAA)*; United Nations: New York, NY, USA, 2025. Available online: https://www.un.org/osaa/sites/default/files/2026-05/policy_brief_technical_primer_solar_power_in_africa_2026.pdf (accessed on 30 September 2026).
68. African Energy Commission. *Key Africa Energy Statistics 2024*; African Energy Commission: Algiers, Algeria, 2024. Available online: https://au-afrec.org/sites/default/files/2025-02/Digital%20KEY%20AFRICA%20ENERGY%20STATISTICS%20EN%20A5%20.pdf (accessed on 13 February 2026).
69. Alam, F.; Jin, Y.; Hu, X. Current Status and Future Prospects of Commercial Wind Power Generation. *Energies* **2025**, *18*, 6068. [CrossRef]
70. Reul, J.; Mpinga, L.; Härter, S.; Zink, C.; Häckner, B. *Opportunities for Renewable Hydrogen Development in Africa: Insights from an Innovative Country Clustering Analysis*; H2Global Foundation: Hamburg, Germany, 2025. Available online: https://h2-global.org/wp-content/uploads/2025/06/H2Global-White-paper-Country-Clustering-FINAL.pdf (accessed on 30 December 2025).
71. Global Wind Energy Council—GWEC. *Global Wind Report 2025*; GWEC: Lisbon, Portugal, 2025. Available online: https://26973329.fs1.hubspotusercontent-eu1.net/hubfs/26973329/2.%20Reports/Global%20Wind%20Report/GWEC%20Global%20Wind%20Report%202025.pdf (accessed on 14 April 2026).

72. Global Wind Energy Council—GWEC. *The Status of Wind in Africa*; GWEC: Lisbon, Portugal, 2023. Available online: https://26973329.fs1.hubspotusercontent-eu1.net/hubfs/26973329/2.%20Reports/Africa/Status-of-Wind-in-Africa-Report.pdf (accessed on 15 December 2025).
73. National Renewable Energy Laboratory—NERL. *Land-Based Wind Resource Classes*; NERL: Research Triangle Park, NC, USA, 2026. Available online: https://atb.nlr.gov/electricity/2025/land-based_wind (accessed on 10 October 2026).
74. IRENA and Bluerisk. *Water for Hydrogen Production*; International Renewable Energy Agency, Bluerisk: Abu Dhabi, United Arab Emirates, 2023. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Dec/IRENA_Bluerisk_Water_for_hydrogen_production_2023.pdf (accessed on 12 March 2026).
75. Global Wind Atlas—Technical University of Denmark (DTU)/World Bank Group. 2024. Available online: https://globalwindatlas.info/en/ (accessed on 10 April 2026).
76. Food and Agriculture Organization—FAO. *AQUASTAT Global Water Information System (2025)*; FAO: Rome, Italy, 2026. Available online: https://www.fao.org/aquastat/en/ (accessed on 10 April 2026).
77. World O Meter African Population. Available online: https://www.worldometers.info/world-population/africa-population/ (accessed on 23 December 2025).
78. Statistics Times. 2025. Available online: https://statisticstimes.com/demographics/africa-population.php (accessed on 23 December 2025).
79. United Nations Sustainable Development Group. Decoding Africa's Energy Journey: Three Key Numbers. 2025. Available online: https://unsdg.un.org/latest/stories/decoding-africa%E2%80%99s-energy-journey-three-key-numbers (accessed on 18 February 2026).
80. The World Bank Solar Mini Grids Could Sustainably Power 380 Million People in Africa by 2030—If Action is Taken Now. 2023. Available online: https://www.worldbank.org/en/news/press-release/2023/02/26/solar-mini-grids-could-sustainably-power-380-million-people-in-afe-africa-by-2030-if-action-is-taken-now (accessed on 24 May 2026).
81. Weyers, M. 600 Million People Without Power: Africa's Dilemma & The Renewable Energy Solution. 2022. Available online: https://www.anavo.com/learn/600-million-people-without-power-africas-dilemma-the-renewable-energy-solution (accessed on 27 August 2026).
82. *African Economic Outlook 2025*; African Development Bank: Abidjan, Côte d'Ivoire, 2025. Available online: https://www.afdb.org/sites/default/files/documents/publications/afdb25-01_aeo_highlights_english_020625.pdf (accessed on 27 December 2025).
83. *Africa Market Outlook for Solar PV 2025–2028*; Global Solar Council: Washington, DC, USA, 2025. Available online: https://www.globalsolarcouncil.org/resources/africa-market-outlook-for-solar-pv-2025-2028/ (accessed on 27 December 2025).
84. BP Energy Outlook. 2025. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2025.pdf (accessed on 24 December 2025).
85. US Energy Information Administration (EIA). *International Energy Outlook 2023*; EIA: Washington, DC, USA, 2023. Available online: https://www.eia.gov/outlooks/ieo/ (accessed on 14 November 2025).
86. OPEC. *World Oil Outlook 2050*; OPEC: Vienna, Austria, 2025. Available online: https://www.opec.org/assets/assetdb/woo-2025.pdf (accessed on 11 February 2026).
87. International Energy Agency—IEA. *World Energy Investment*; IEA Publications: Amsterdam, The Netherlands, 2025. Available online: https://iea.blob.core.windows.net/assets/1c136349-1c31-4201-9ed7-1a7d532e4306/WorldEnergyInvestment2025.pdf (accessed on 27 December 2025).
88. Shurov, N.I.; Andriyashin, S.N. Fuel cells as a future of automotive industry: A review of current developments. *J. Phys. Conf. Ser.* **2021**, *2061*, 012002. Available online: https://iopscience.iop.org/article/10.1088/1742-6596/2061/1/012002/pdf. [CrossRef]
89. Ember. Global Electricity Review 2025. 8 April 2025. Available online: https://ember-energy.org/latest-insights/global-electricity-review-2025/ (accessed on 25 February 2026).
90. *Statistical Review of World Energy*, 74th ed.; Energy Institute: London, UK, 2025; pp. 1–73. Available online: https://www.energyinst.org/statistical-review (accessed on 30 August 2026).
91. World Bank Group. Electric Power Consumption (kWh per Capita). Available online: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC (accessed on 2 January 2026).
92. World Bank Data on Energy and Mining. Available online: https://data.worldbank.org/topic/energy-and-mining (accessed on 27 November 2025).
93. Our World in Data. *Total Electricity Generation Per Person in 2024*; Our World in Data: Oxford, UK, 2026. Available online: https://ourworldindata.org/grapher/per-capita-electricity-generation (accessed on 26 March 2026).
94. Schmidt, M.; Moradi, A. Community effects of electrification: Evidence from Burkina Faso's grid extension. *J. Dev. Econ.* **2026**, *178*, 103556. [CrossRef]

95. Ramstein, C.; Hallegatte, S. *Connecting 300 Million People to Electricity and Building a Resilient Future in Africa, Development and a Changing Climate*; World Bank Blogs: Washington, DC, USA, 2025. Available online: https://blogs.worldbank.org/en/climate-change/connecting-300-million-people-to-electricity-and-building-a-resi (accessed on 17 January 2026).
96. Alare, T. Energy as a Major Determinant of Economic Growth: Technological Advancements and Policy Implications. Authorea. 2025. Available online: https://www.authorea.com/doi/full/10.22541/au.174102447.72814846 (accessed on 28 August 2026).
97. Ahsan, S.; Ahmmed, T.; Alam, F. The COVID-19, power generation and economy—Case study of a developing country. *Electr. J.* **2022**, *35*, 107145. [CrossRef]
98. Khandker, S.R.; Barnes, D.F.; Samad, H.A. Welfare Impacts of Rural Electrification: A Panel Data Analysis from Vietnam. *Econ. Dev. Cult. Change* **2013**, *61*, 659–692. [CrossRef]
99. Dinkelman, T. The Effects of Rural Electrification on Employment: New Evidence from South Africa. *Am. Econ. Rev.* **2011**, *101*, 3078–3108. [CrossRef]
100. World Bank. *World Development Report 1994: Infrastructure for Development*; World Bank: Washington, DC, USA, 1994. [CrossRef]
101. World Bank. *An Evaluation of the World Bank Group's Support to Electricity Access in Sub-Saharan Africa, 2015-24*; World Bank: Washington, DC, USA, 2025. [CrossRef]
102. Muritala, T.A. Electricity Access, Renewable Energy Investment, and Industrial Output in West Africa. *Wukari Int. Stud. J.* **2025**, *9*, 273–288. [CrossRef]
103. Overo, K.; Orubu, C.; Ezi, C.T. Transport and Electricity Infrastructures and Economic Growth and Development in Selected Sub-Saharan African Countries. *Afr. J. Econ. Sustain. Dev.* **2024**, *7*, 114–130. Available online: https://abjournals.org/ajesd/wp-content/uploads/sites/4/journal/published_paper/volume-7/issue-2/AJESD_LWFOH6O8.pdf.
104. Burke, P.J.; Stern, D.I.; Bruns, S.B. The impact of electricity on economic development: A macroeconomic perspective. *Int. Rev. Environ. Resour. Econ.* **2018**, *12*, 85–127. [CrossRef]
105. Magbondé, K.G.; Thiam, D.; Wagner, N. Impact of access to electricity on the well-being of rural households in Senegal. *J. Dev. Eff.* **2025**, *17*, 318–341. [CrossRef]
106. McKenna, E. *List of African Countries by Area*; Britannica: Chicago, IL, USA, 2026. Available online: https://www.britannica.com/topic/list-of-African-countries-by-area (accessed on 16 March 2026).
107. World Population Review Population by Continent. 2026. Available online: https://worldpopulationreview.com/continents (accessed on 20 August 2026).
108. AFSA. *Africa's Land Is Not Empty: New Report Debunks the Myth of "Unused Land" and Calls for a Just Future for the Continent's Farmland*; Alliance Food Sovereignty in Africa: Kampala, Uganda, 2025. Available online: https://afsafrica.org/africas-land-is-not-empty-new-report-debunks-the-myth-of-unused-land-and-calls-for-a-just-future-for-the-continents-farmland/ (accessed on 18 July 2026).
109. Hall, R. Land rights and land tenure are changing in Africa. In *How is the Answer of 'Good Land Governance' Framed and Contested?* PLAAS, Institute for Poverty, Land and Agrarian Studies: Cape Town, South Africa, 2026. Available online: https://plaas.org.za/land-rights-and-land-tenure-are-changing-in-africa-how-is-the-answer-of-good-land-governance-framed-and-contested/ (accessed on 26 August 2026).
110. Boratyn, K. Africa's Abandoned 'Nobody's Land' That is Completely Empty with no Country Claiming It. *Express*, 11 February 2025. Available online: https://www.express.co.uk/news/world/2013106/africa-abandoned-nobody-land-bir-tawil-egypt-sudan (accessed on 10 April 2026).
111. Gerges, A. Bir Tawil: The Stateless Land of Many and No Rulers. *Egyptian Streets*, 20 July 2023. Available online: https://egyptianstreets.com/2023/07/20/bir-tawil-the-stateless-land-of-many-and-no-rulers/ (accessed on 10 April 2026).
112. Nkurunziza, M. UNECA Calls for Fairer Global Systems to Unlock Africa's Land Potential. *The New Times*, 10 November 2025. Available online: https://www.newtimes.co.rw/article/31148/news/economy/uneca-calls-for-fairer-global-systems-to-unlock-africas-land-potential/amp (accessed on 19 August 2026).
113. Zamchiya, P. *Globalised Extractive Territorialisation and Changing Land Uses in Africa*; PLAAS, Institute for Poverty, Land and Agrarian Studies: Cape Town, South Africa, 2026. Available online: https://plaas.org.za/globalised-extractive-territorialisation-and-changing-land-uses-in-africa/ (accessed on 19 March 2026).
114. Donglin, H. Africa Is Catching up with the Development Opportunities of the Green Hydrogen Industry, CRI Online. *Economic Daily*, 11 October 2025. Available online: https://big5.cri.cn/gate/big5/ge.cri.cn/20251011/d6393ba5-df56-bb43-3a67-df7fbc4b2135.html (accessed on 23 June 2026).
115. Bega, S. Abandoned Coal Mines Could Power South Africa's Solar Future. *Mail and Guardian*, 27 June 2025. Available online: https://mg.co.za/the-green-guardian/2025-06-27-abandoned-coal-mines-could-power-south-africa-s-solar-future/#1 (accessed on 5 May 2026).
116. Kaandorp, C.; van de Giesen, N.; Abraham, E. The water use of heating pathways to 2050: Analysis of national and urban energy scenarios. *Environ. Res. Lett.* **2021**, *16*, 055031. [CrossRef]

117. Beswick, R.R.; Oliveira, A.M.; Yan, Y. Does the green hydrogen economy have a water problem? *ACS Energy Lett.* **2021**, *6*, 3167–3169. [CrossRef]
118. Kumar, P.; Date, A.; Mahmood, N.; Das, R.K.; Shabani, S. Freshwater supply for hydrogen production: An underestimated challenge. *Int. J. Hydrogen Energy* **2024**, *78*, 202–217. [CrossRef]
119. International Energy Agency—IEA. *Renewable Energy Opportunities for Mauritania*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/renewable-energy-opportunities-for-mauritania (accessed on 26 August 2026).
120. Smith, T. Developing Green Hydrogen Economy in Africa Still Way off, ESI Africa. 2024. Available online: https://www.esi-africa.com/business-and-markets/developing-green-hydrogen-economy-in-africa-still-way-off/ (accessed on 25 July 2026).
121. Modern Power Systems. EU H2 Projects Are 'Being Stalled by Financing and Demand Gaps. 17 February 2026. Available online: https://www.modernpowersystems.com/news/eu-h2-projects-are-being-stalled-by-financing-and-demand-gaps/ (accessed on 21 March 2026).
122. International Energy Agency (IEA). Global Hydrogen Review 2025—Trade and Infrastructure. 2025. Available online: https://www.iea.org/reports/global-hydrogen-review-2025/trade-and-infrastructure (accessed on 15 August 2026).
123. Food and Agriculture Organization—FAO. *Africa—Regional Overview of Food Security and Nutrition 2023: Statistics and Trends*; FAO: Accra, Ghana, 2023. [CrossRef]
124. African Export Impot Bank. *Food Imports and Food Security in Africa*; African Export Impot Bank: Cairo, Egypt, 2024. Available online: https://media.afreximbank.com/afrexim/Food-Imports-and-Food-Security-Addressing-the-Challenges.pdf (accessed on 25 December 2025).
125. African Union. Africa Pledges to Triple Fertilizer Production and Distribution to Empower Small Farmers. 2024. Available online: https://au.int/en/pressreleases/20240521/africa-pledges-triple-fertilizer-production-distribution-empower-farmers (accessed on 12 December 2025).
126. Malpass, D. A Transformed Fertilizer Market Is Needed in Response to the Food Crisis in Africa. 2022. Available online: https://blogs.worldbank.org/en/voices/transformed-fertilizer-market-needed-response-food-crisis-africa (accessed on 25 December 2025).
127. Alam, F.; Watkins, S.; Jin, Y.; Hu, X. Passenger Car Aerodynamic Drag, Thermal Cooling: A Perspective for Energy Saving and Improving Environment. *Energies* **2025**, *18*, 6433. [CrossRef]
128. US Department of Energy-DOE. Fuel Cell Electric Vehicles. 2026. Available online: https://afdc.energy.gov/vehicles/fuel-cell (accessed on 24 January 2026).
129. Our World in Data. *Per Capita Electricity Demand, 2025*; Our World in Data: Oxford, UK, 2026. Available online: https://ourworldindata.org/grapher/per-capita-electricity-demand (accessed on 27 March 2026).
130. Guan, Q. Analysis of the Current Situation and Prospects of the Hydrogen Energy Vehicle Market. 11 December 2025. Available online: https://www-lf.dongchedi.com/article/7582534014557553177 (accessed on 26 August 2026).
131. Market Research. Global Hydrogen Fuel Powered Commercial Vehicles Market 2025 by Manufacturers, Regions, Type and Application, Forecast to 2031. 2026. Available online: https://www.marketresearch.com/GlobalInfoResearch-v4117/Global-Hydrogen-Fuel-Powered-Commercial-42984339/ (accessed on 12 August 2026).
132. Luo, Y.; Wang, Y.; Cai, D.; Shao, Z. The Development of Hydrogen Energy Transportation Needs to Face the Three Major Pain Points of "Expensive Hydrogen, Expensive Cars, and Expensive Stations. *Sinopec Magazine*, 19 December 2025. Available online: http://www.sinopecnews.com.cn/xnews/content/2025-12/19/content_7138916.html (accessed on 28 June 2026).
133. Ding, D.; Wu, X.Y. Hydrogen fuel cell electric trains: Technologies, current status, and future. *Appl. Energy Combust. Sci.* **2024**, *17*, 100255. [CrossRef]
134. Schmalz, S.; Schneidemesser, L.; Xu, H. An emerging 'China-threat-corporatism'? CRRC's acquisition of a German locomotive company and its impact on labour relations. *Eur. J. Ind. Relat.* **2024**, *31*, z187–z208. [CrossRef]
135. TradingView. CRRC: 2025 Revenue up 10.79% and Net Profit Up 6.40%, with Robust R&D and 50% Dividend Payout. 29 March 2026. Available online: https://www.tradingview.com/news/urn:summary_document_report:quartr.com:3187052:0-crrc-2025-revenue-up-10-79-and-net-profit-up-6-40-with-robust-r-d-and-50-dividend-payout/ (accessed on 20 July 2026).
136. Xu, L.; Li, Y.; Zhang, W.; Ma, T.; Jing, X. Safety Analysis of Hydrogen-Powered Train in Different Application Scenarios: A Review. *Energies* **2025**, *18*, 1743. [CrossRef]
137. Xinhua News Agency. Chinese Company to Launch 250 km/h Hydrogen-Powered Train by 2025. 16 July 2025. Available online: https://english.news.cn/20250716/1b86c44a2bce4c828d17198403220b37/c.html (accessed on 11 July 2026).
138. Fuel Cells Works. Fuel Cell Shortage Forces German Hydrogen Train Pioneer Back to Diesel. 14 August 2025. Available online: https://fuelcellsworks.com/2025/08/14/fuel-cells/fuel-cell-shortage-forces-german-hydrogen-train-pioneer-back-to-diesel (accessed on 8 March 2026).
139. Stephens, B. Canadian Pacific's Hydrogen-Powered Locomotive Makes First Revenue Run, TrainsPRO. 6 August 2025. Available online: https://www.trains.com/pro/mechanical/locomotives/canadian-pacifics-hydrogen-powered-locomotive-makes-first-revenue-run/ (accessed on 13 August 2026).

140. Precedence Research, 2025, Green Hydrogen Market Size, Share and Trends 2026 to 2035. Available online: https://www.precedenceresearch.com/green-hydrogen-market (accessed on 26 December 2025).
141. International Energy Agency—IEA. *The Role of Critical Minerals in Clean Energy Transitions, revised version*; IEA: Paris, France, 2022. Available online: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (accessed on 12 January 2026).
142. Sahu, A.K.; Rufford, T.E.; Ali, S.H.; Knibbe, R.; Smart, S.; Jiao, F.; Bell, A.T.; Zhang, X. Material needs for power-to-X systems for CO_2 utilization require a life cycle approach. *Chem. Sci.* **2025**, *16*, 5819–5835. [CrossRef]
143. Xun, D.; Liu, M.; Hao, H.; Sun, X.; Geng, Y.; You, F.; Dou, H.; Li, H.; Dong, Z. Sustainable supply of critical materials for water electrolysers and fuel cells. *Commun. Earth Environ.* **2025**, *6*, 627. [CrossRef]
144. Eikeng, E.; Makhsoos, A.; Pollet, B.G. Critical and strategic raw materials for electrolysers, fuel cells, metal hydrides and hydrogen separation technologies. *Int. J. Hydrogen Energy* **2024**, *71*, 433–464. [CrossRef]
145. Greitzer, M. Iridium and platinum availability for electrolyser production up to 2030. In *Powerfuels*; Springer Nature: Cham, Switzerland, 2025; pp. 257–279. [CrossRef]
146. Ecofin Agency. For Africa's Green Hydrogen Dreams, a Reality Check on Scale and Buyers. 20 January 2026. Available online: https://www.ecofinagency.com/news/2001-52073-for-africa-s-green-hydrogen-dreams-a-reality-check-on-scale-and-buyers (accessed on 10 April 2026).
147. Huaxia Energy Network. The Enthusiasm of Oil and Gas Giants Has Subsided, and the Global Green Hydrogen Has Encountered "Cold Wind and Rain" Beijing, China. 26 January 2026. Available online: https://news.qq.com/rain/a/20260121A01MMO00 (accessed on 20 March 2026). (In Chinese)
148. Wright, K.; Ong, S.Y.; Mathis, W.; Wade, W. *The $147 Billion Green Hydrogen Bubble That BP Helped Burst*; Bloomberg: New York, NY, USA, 2025. Available online: https://www.bloomberg.com/news/articles/2025-07-29/the-147-billion-green-hydrogen-bubble-that-bp-helped-burst (accessed on 27 May 2026).
149. Xinyu, C. In-Depth Analysis of the Phenomenon of "Halving" of Green Hydrogen Projects: The Economic Crossroads Faced by the Global Hydrogen Energy Industry, SMM Information & Technology. 21 November 2025. Available online: https://new-energy.smm.cn/content/15003/103634008 (accessed on 20 March 2026).
150. Hieminga, G.; Zhang, C. *Hydrogen Stuck in the Pilot Phase*; ING: Singapore, 2026. Available online: https://think.ing.com/articles/energy-hydrogen-stuck-in-the-pilot-phase/ (accessed on 31 March 2026).
151. Lamba, S.; Chang, J. *Global Hydrogen Compass 2025*; Hydrogen Council: Brussels, Belgium, 2025. Available online: https://compass.hydrogencouncil.com/ (accessed on 27 December 2025).
152. Barnard, M. Major Project Cancellation Exposes Fatal Flaws in Australia's Hydrogen Export Strategy. 16 July 2025. Available online: https://reneweconomy.com.au/project-cancellation-exposes-fatal-flaws-in-australias-hydrogen-export-strategy/ (accessed on 27 December 2025).
153. Hydrogen Council and McKinsey & Company. The Africa Hydrogen Opportunity. 1–10 March 2024. Available online: https://hydrogencouncil.com/en/the-africa-hydrogen-opportunity/#jupiterx-main (accessed on 10 March 2025).
154. Fuel Cell Works. IRENA: US, China, Australia, and Latin America to Dominate Global Green Hydrogen Export Markets by 2050. 9 July 2025. Available online: https://fuelcellsworks.com/2025/07/09/news/irena-us-china-australia-and-latin-america-to-dominate-global-green-hydrogen-export-markets-by-2050 (accessed on 25 July 2026).
155. Patonia, A.; Poudineh, R. *Global Trade of Hydrogen: What is the Best Way to Transfer Hydrogen Over Long Distances?* OIES PAPER: ET16; The Oxford Institute for Energy Studies: Oxford, UK, 2022; pp. 1–23. Available online: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/08/Global-trade-of-hydrogen-what-is-the-best-way-to-transfer-hydrogen-over-long-distances-ET16.pdf (accessed on 19 May 2026).
156. Patonia, A.; Lenivova, V.; Poudineh, R.; Nolden, C. *Hydrogen Pipelines vs. HVDC Lines: Should We Transfer Green Molecules or Electrons?* OIES Paper: ET, No. 27; The Oxford Institute for Energy Studies: Oxford, UK, 2023. Available online: https://www.econstor.eu/bitstream/10419/280134/1/1869396030.pdf (accessed on 23 July 2026).
157. Agyekum, E.B.; Ampah, J.D.; Uhunamure, S.E.; Shale, K.; Onyenegecha, I.P.; Velkin, V.I. Can Africa Serve Europe with Hydrogen Energy from Its Renewables? Assessing the Economics of Shipping Hydrogen and Hydrogen Carriers to Europe from Different Parts of the Continent. *Sustainability* **2023**, *15*, 6509. [CrossRef]
158. Eren, E. Hydrogen Project Collapse: Why Mega-Scale Ambitions Stalled in 2026. 2026. Available online: https://enkiai.com/bp-hydrogen-initiatives-for-2025-key-projects-strategies-and-partnerships/ (accessed on 29 March 2026).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.