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Solar Photovoltaic-Based Green Hydrogen in West Africa: Pathways, Potential, and Prospects

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ABSTRACT

Solar photovoltaic-based green hydrogen offers a strategic pathway for transitioning West Africa towards a low-carbon and sustainable energy system. This review offers a region-specific evaluation of PV-based hydrogen production and integrating renewable resources, electrolyser technologies, and techno-economic performance into a single framework. The paper reviews the global and regional literature on production pathways, system integration, deployment opportunities, and complementary hydrogen pathways. Results show that Nigeria, Mali, Senegal, and Cape Verde have high potential for competitive hydrogen production with the levelised cost of hydrogen (LCOH) of about USD 2.0-2.6/kg due to their high solar irradiance. Broader analyses indicate costs ranging from USD 3.60-6.70/kg in large-scale systems and small-scale systems ranging over USD 20/kg. Electrolyser efficiencies are 60-85%, and PV capacity factors range from 20-28%, indicating the significance of technology choice and system design. Decentralised PV-electrolysis systems are a viable solution to industrial decarbonisation and expansion of energy access. The review key priorities include hybrid renewable integration, long-term hydrogen storage, lifecycle environmental assessment, and new electrolysis technologies. The result reveals West Africa as a potential low-cost hydrogen site with great potential to contribute to energy security and industrial development.

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1. Introduction

The global energy system has been facing increasing challenges due to climate change, rising energy demand, fossil fuel scarcity, and enduring energy access disparities, especially in developing nations. The energy sector is globally one of the areas that contributes approximately three-quarters of greenhouse gas emissions, underscoring the urgency of shifting to low-carbon alternatives [1], [2], [3]. Africa remains under-represented, with more than 600 million people without electricity and an overwhelming reliance on traditional biomass and imported fossil fuels [4], [5], [6]. Hence, solar energy has become the most rapidly developing renewable technology with an installed photovoltaic (PV) capacity of over 1,800 GW by 2024. Africa has some of the highest solar irradiance levels on Earth, yet the proportion of global installed photovoltaic capacity is less than 1%, and only about 18 MW is documented. West Africa mirrors this contradiction. Despite vast solar potential, deployment remains uneven and largely confined to small-scale, grid-constrained systems, with about 1,500 MW installed, representing less than 8% of Africa's reported solar capacity [7], [8]. The fact that off-grid solar is systematically undercounted is also a great concern, as mini grids, solar home systems, rooftops, telecom, and agricultural installations are not fully captured in formal reporting systems. These systems are decentralised, privately operational, often informal, and rarely regulated or owned by the utility. Projects funded by donors and NGOs are often considered social infrastructure rather than energy assets, and upgrades and replacements are not logged. Inadequate national energy data systems continue to keep Africa blind on paper, even as it operates millions of active watts day to day [9], [10], [11], [12]. In addition to data gaps, scale is hindered by structural issues. Intermittency, grid inflexibility, limited storage, and poor transmission infrastructure, underscoring the need for complementary solutions that convert on-site variable solar energy into dispatchable and storable energy carriers [13], [14], [15], [16], [17]. Measurement, formalisation, and system integration are the principal limiting factors, as they are being addressed by IRENA, the African Union Department of Energy, AREI, SE4ALL, ECREEE, ACEC, Rural Electrification Agencies, NREA, the Renewable Energy Association of Ghana, and REEEA, for inclusion in national energy planning.

The global solar installed capacity by region as of the end of 2025, as reported by International Renewable Energy Agency [18], and as shown in Figure 1, illustrates a market dominated by Asia, which holds a massive 63.99% share, while Europe and North America follow as significant contributors at 17.05% and 9.64%, respectively; in contrast, regions such as Africa (0.93%) and Central America (0.30%) represent minimal portions of the total, highlighting a substantial geographic disparity in solar energy adoption.

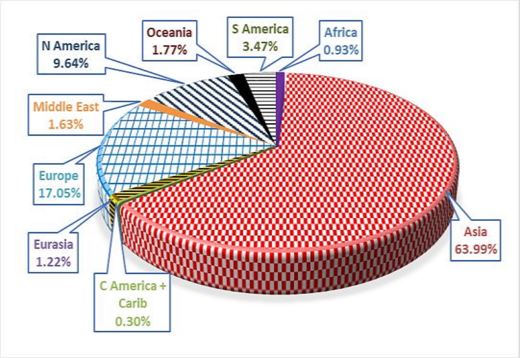

Figure 1. Global distribution of installed solar capacity by region [18]

As solar energy becomes the most widely used renewable technology worldwide, there is growing interest in green hydrogen as a strategic direction to capitalise on excess solar energy generation, enhance energy security, and advance deep decarbonisation goals [19], [20], [21]. Hydrogen has become one of the key vectors of energy in the global shift towards low-carbon energy systems, and it can be utilised in power generation, industrial processes, transportation, and heating, becoming a crucial element of the overall energy strategy [22], [23], [24]. Energy systems are starting to realise the value of hydrogen not just as a fuel but as a versatile energy storage and transportation medium, as well as a cross-sectoral integration medium. The mounting energy transition worldwide is driven by ambitious climate goals, including the Paris Agreement and net-zero commitments by 2050, which require massive reductions in greenhouse gas emissions. Hydrogen, especially green hydrogen using renewable electricity, is viewed to be critical to these targets due to its ability to decarbonise those areas that are difficult to electrify directly, such as steel, cement, chemicals, and aviation, as it is technically difficult or not economical to directly electrify them [25], [26], [27], [28]. Current research shows that green hydrogen generated through water electrolysis powered by renewable energy can have near-zero carbon-emission lifecycles, especially when combined with low-cost solar or wind sources [29], [30], [31].

The world has increased investments in hydrogen technologies, with over 70 national hydrogen strategies released globally, and major private-sector investments in the sector have amounted to over USD 500 billion by 2030 [32], [33]. Electrolysers have now grown in capacity, driven by technological advances in alkaline, proton exchange membrane (PEM), Anion Exchange Membrane (AEM), and solid oxide electrolysis (SOE), making them cheaper and more flexible to operate. In addition, hydrogen-based alternatives such as green ammonia and methanol are now in the limelight as means of energy storage and international trade, offering countries with abundant renewable sources new export opportunities [34], [35], [36]. Although its potential is promising, the global hydrogen economy encounters significant challenges, such as the high cost of production, scarcity of infrastructure, integration of supply chain, and uncertainty relating to the regulation of the hydrogen industry, and capacity utilisation is a major determinant of cost-effective production [37], [38]. Furthermore, techno-economic modelling indicates that these processes should be supported by joint policies, investment incentives, and international cooperation to overcome initial risks and market fragmentation and achieve global scale-up [39], [40], [41]. Hence, hydrogen is being positioned as a transformative energy carrier that will support global objectives of decarbonisation and renewable integration, as well as provide a source of sustainable domestic energy that can support local development and potential export energy commodity, in both West Africa and across the globe, in line with global climate goals [42], [43]. Figure 2 presents the hydrogen value chain as a three-layer structure. The initial layer classifies hydrogen production by carbon intensity: green hydrogen is produced by renewable sources, and grey hydrogen by fossil fuels. The second layer depicts hydrogen as a core energy carrier that provides energy for transportation, buildings, and industry. The third layer introduces the most important system outcomes, such as emission reduction, sector coupling, and system flexibility, which enable a stable and decarbonised energy system.

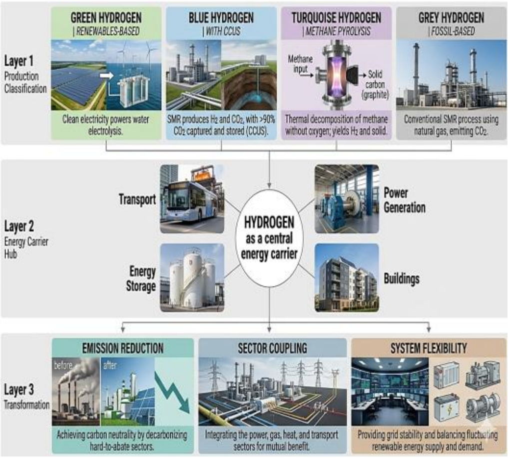

Figure 2. Overview of hydrogen production pathways and system applications [44]

Green hydrogen can be described as hydrogen generated through the process of electrolysis of water using renewable electricity sources, preferably solar PV, wind power, water power, or hybrid renewable energies. Unlike other hydrogen production pathways, like grey hydrogen that reforms methane in the steam process and blue hydrogen that includes carbon capture and storage, green hydrogen is characterised by almost no direct greenhouse gas emissions during its production phase, so it is the most climate-compatible type of hydrogen route that can be deployed on a large scale [45], [46]. Three related imperatives underpin the strategic rationale for green hydrogen in the present-day power system: deep decarbonisation, power system flexibility, and long-term energy security. However, green hydrogen is well known as a vital decarbonisation enabler across hard-to-abate sectors with technical limitations to direct electrification or economies of scale in producing ammonia and fertilisers, cement, refineries, maritime transportation, and long-haul aviation. The peer-reviewed literature shows that such applications of hydrogen-based pathways can significantly minimise the lifecycle emissions, especially when the hydrogen is generated using renewable electricity [47], [48]. Furthermore, green hydrogen can also be an effective way to generate extra flexibilities and resilience in renewable dominated electricity systems because too much renewable energy is likely to be curtailed because of intermittence in solar PV and wind production, which can be remedied by having electrolysers that can be operated as controllable and demand responsive loads to absorb excess renewable generation and convert it into hydrogen, and therefore provide long-duration and seasonal energy storage [49], [50]. Figure 3 presents a comparative analysis of key hydrogen production pathways and their characteristics.

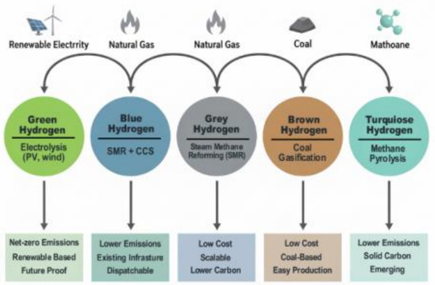

Figure 3. Comparative hydrogen production routes and key characteristics [44]

Hydrogen storage has proven to be a more scalable energy source than the electrochemical battery, thanks to its long-term storage capacity and broad array of potential energy applications [51]. Similarly, green hydrogen contributes to the sustainability of energy and economic diversification by adding a new layer of scalability to the long-term storage of the product and the diversification of its use across various sectors. This factor is especially relevant to the developing world, where volatile fuel prices and a lack of foreign exchange negate the affordability of energy and macroeconomic stability, and green hydrogen can be exported or derived as a product (e.g., green ammonia), building novel industrial-oriented value chains and job opportunities [52], [53], [54]. Assessments of related studies show that countries with high solar irradiation and land availability can achieve competitive hydrogen production costs over time, particularly when electrolyser learning rates and the falling costs of PVs are factored in [30], [55].

It is important to note that, despite its conceptual benefits, green hydrogen is constrained by techno-economic and resource constraints. The main elements influencing the current production cost are the price of renewable electricity, the capital cost of the electrolyser, the operating efficiency, and the capacity utilisation factor. Moreover, the issues of water use, land utilisation, and lifecycle environmental impacts, such as embodied emissions in the manufacturing process of equipment, are particularly sensitive in arid and infrastructure-connected areas [56], [57], [58]. These challenges highlight why geographically specific evaluations are necessary rather than global assumptions about green hydrogen. In West Africa, the region's high solar PV potential, increasing electricity demand, and decarbonisation targets are reflected in national and ECOWAS energy policies. Solar PV-based electrolysis is considered the most technically advanced and locally suitable route due to abundant solar resources, declining photovoltaic system prices, and the scalable nature of electrolyser systems within an organisation [59], [60], [61]. Hence, the current review considers green hydrogen, which is based on solar photovoltaic electrolysis, as its central method of studying production pathways, techno-economic performance, and deployment prospects in West Africa. ECOWAS, with a highly dynamic environment based on renewable energy sources, a fast-growing population, and an upsurging industrial base, is strategically placed in the global energy transition because of its substantial solar irradiance of approximately 350-6,000 kWh/m^2/year, spread throughout the region. The ECOWAS member states have one of the largest solar energy resources in the world, especially in the Sahelian and coastal regions, which offer the most promising prospects for large-scale implementation of solar PV for green hydrogen production [20], [60], [62]. This resource endowment, along with robust wind and hydropower potential, makes West Africa a viable option for establishing competitive, low-carbon hydrogen supply chains as a component of domestic and export markets. ECREEE reports that electrification rates are 40% in rural regions and 70% in urban centres, and that biomass and fossil fuels are mostly used in West Africa for cooking and generating power [63], [64]. The production of green hydrogen is a coordinated step to diversify the energy base, enhance energy security, and broaden the socio-economic foundation. For example, solar PV-powered electrolyser systems could meet energy-related requirements in industries and remote rural regions [57], [65]. Also, ammonia, methanol, or fuel cell production can create a local value chain and open up employment opportunities and lessen greenhouse gas emissions across the West Africa region, which is also well-positioned geopolitically to play a role in the emerging hydrogen market globally. The presence of potential exports to European demand centres and existing ports in Ghana, Senegal, and Côte d’Ivoire makes regional integration in the economic market, and makes West Africa a source of green energy [66], [67]. Cross-border cooperation in ECOWAS is essential in aligning regulatory frameworks, combining renewable energy, and coming up with mutually beneficial infrastructure, which decreases the risk of investment and raises the viability of projects [61], [68]. Besides, policy frameworks, such as the

ECOWAS Green Hydrogen Policy and Strategy Framework, provide strategic guidance to scale production, establish hydrogen clusters, and promote private-sector inclusion. These policy frameworks align with regional long-term development objectives and incorporate the priorities of the energy transition, climate action, industrialisation, and sustainable development [43], [63]. Through technical potential, enabling policies, and regional collaboration, ECOWAS is well placed to position solar PV-driven green hydrogen production as one of the pillars of its low-carbon energy policy. Solar PV-based electrolysis systems can not only address domestic energy and climate issues but also help West Africa become part of potential international hydrogen markets, which offer a path to sustainable economic development and to integrating the region into the global energy system [42], [69].

This review offers a detailed, region-focused assessment of green hydrogen production in West Africa via solar PV-driven electrolysis, filling major gaps in the current literature that are mostly global or country-specific. It combines the evaluation of renewable resources, electrolysis technology, and techno-economic performance within a single regional approach. The paper provides an in-depth review of green hydrogen technologies, focusing on PV-integrated electrolysis, resource potential, and large-scale production capacity, and critical techno-economic considerations, including efficiency, cost, storage, and transportation. Moreover, it provides comparative information on the levelised cost of hydrogen across various West African countries, highlighting the cost competitiveness in high-irradiance regions. The review also finds major enablers and constraints, such as infrastructure preparedness, policy frameworks, and water resource availability, and defines both the decentralised and export-based development pathways. This work has provided a systematic foundation on which policymakers, investors, and researchers can build to develop a sustainable and competitive green hydrogen industry in West Africa, integrating technological, economic, and policy lenses.

2. Review of related literature

The recent growth in the literature on green hydrogen is indicative of its status as a major focus in global decarbonisation policies and a key facilitator of the incorporation of variable renewable energy into low-carbon energy systems. Still, the traditional hydrogen production remains fossil-fuel based, and more than 95% of the global supply is based on grey and blue hydrogen generated through either natural gas or coal, rather than aligning with the global climate ambitions, even with net-zero commitments in place in Europe, Asia, and some parts of Africa [70], [71]. However, green hydrogen, or renewable hydrogen, generated via the electrolysis of water using low-carbon electricity sourced from solar and wind resources, has almost zero lifecycle emissions and further increases the flexibility of the energy system [54], [72]. Therefore, green hydrogen is currently seen as a necessity across many areas of decarbonisation, including hard-to-abate industries such as steelmaking, chemicals, aviation, shipping, and long-distance transport, which are directly electrified due to technical or economic limits.

Green hydrogen has undergone a global trend over the past two decades, driven by the development of renewable energy, specific policy priorities, and advances in electrolyser technology [73], [74]. Early research was more focused on mature alkaline electrolysis and experimental thermochemical pathways, but this has gradually shifted to flexible, modular, and renewable integrated electrolysers capable of operating on lineable power feeds. PEM electrolysers have become popular for their rapid dynamic response and ability to integrate with intermittent solar and wind generation, and newer AEM systems aim to balance the price benefits of alkaline electrolysis with the operational flexibility of PEM technologies. Bibliometric and thematic analyses show that the number of scholarly works increases exponentially; the leading research areas include hydrogen production pathways, techno-economic performance, storage optimisation, system integration, and policy frameworks [75], [76]. International roadmaps and initiatives organised by IRENA and the Africa Green Hydrogen Alliance, also at the policy level, emphasise the significance of green hydrogen for net-zero goals and position regions with strong renewable endowments as future exporters of clean energy carriers [77], [78].

Electrolysers are central to net-zero energy systems to facilitate the conversion of renewable electricity into a flexible, zero-carbon energy carrier, whether to meet short-term system demands, to provide grid balancing when renewable electricity grids require large parts of their generation, or to minimise renewable curtailment or provide grid balancing services [28], [79]. Long-term storage of green hydrogen generated by electrolysis is compatible with a wide variety of end-use applications, including industry, transport, power generation, and seasonal energy storage, which cannot be decarbonised by simple direct electrification [66]. The wide range of technologies of electrolyser, varying among alkaline, PEM, AEM, and solid oxide, creates significant trade-offs in performance, operating temperature, purity of water needed, capital costs, and system integration opportunity, which supports the fact that technology should be chosen depending on local resources and strategic use of the system.

Several studies have been conducted at a global scale to analyse the potential of renewable resources and the cost dynamics of large-scale green-hydrogen implementation. Bouzida et al. [80] show that optimised solar chimney power plant turbine designs greatly enhance solar energy conversion efficiency, with design-sensitive gains in power output, underscoring the role of aerodynamic optimisation in improving the performance of solar-based renewable energy systems. This view supports the broader concept that the efficiency improvement in solar energy technologies is not confined to photovoltaic systems but also extends to other solar-driven conversion pathways that can supplement renewable-based hydrogen production systems.

Wu et al. [81] report a more advanced spatial assessment model using the Global Renewable-energy Exploitation Analysis Platform, indicating that the potential for hydrogen production is closely linked to the technical potential of wind and solar resources. Notably, their results show that there is no linear correlation between the costs of renewable electricity and hydrogen production, which supports the need to consider them as a system and to apply multi-objective optimisation. To complement this system's view, Ghosh [82] summarises solar-based hydrogen generation through water electrolysis, underlining the emissions and cost benefits of solar PV-electrolyser integration as well as current challenges of intermittency, competition of land use against other applications, material limitations, and long-term stability of electrolyser during sun-varying conditions.

On the technology scale, recent review articles have investigated not only developments but also limitations in the fields of electrolysis and solar-driven electrochemical processes, including innovations in electrocatalysts, electrode structures, and electrolyser design, such as decoupled, hybrid, and seawater electrolysers. Although technical studies have advanced, Zhu et al. [83] identify durability, material availability, and the complexity of the manufacturing process as barriers to commercial-scale deployment, and show how techno-economic considerations can be used to determine the relative preference for centralised, single-product or decentralised, multi-product system deployment.

Modelling and simulation investigations have enabled an increasing number of studies to evaluate photovoltaic-driven hydrogen generation under realistic climatic and operating conditions, such as the analysis of small- and large-scale PV-driven PEM electrolysis systems by Guerrero-Rodríguez et al. [84] in tropical regions based on dynamic modelling and real meteorological data, and have found strong economies of scale and that the levelised cost of hydrogen is significantly reduced with large system sizes. Their results further indicate significant reductions in carbon emissions and the efficacy of PV-electrolysis routes for clean energy switches in tropical areas. There are also similar findings by Rhimi et al. [85], who report the high potential for photovoltaic-based solid oxide electrolysis, achieving energy and exergy efficiencies of 88% and 78%, respectively, via optimised thermal integration and autonomous operation under variable solar conditions.

In addition to the traditional system setups, new studies investigate digitalisation and other pathways to the production of hydrogen. Joshua et al. [86] show that combining artificial intelligence, Internet of Things, and machine learning can greatly increase the forecasting accuracy, fault detection, and overall system performance in solar hydrogen systems, thus improving the efficiency and stability of the whole system. Conversely, Bio-based hydrogen production through dark fermentation of organic waste is suggested by Snousy et al. [87] as an option of low-carbon alternative production that minimises the use of freshwater, rare materials, and complicated infrastructure, which is especially relevant to the setting of African and other developing regions where grid connectivity and political security might be insufficient. The emerging literature across the African continent, and West Africa in particular, is increasingly emphasising renewable resource evaluation, techno-economic viability, and a strategic development path towards green hydrogen within the country, although the short-term domestic market remains limited. According to Bhandari [59], Niger has significant solar potential, and one of the promising long-term prospects is export-oriented green hydrogen production with international collaboration, despite the country's currently small domestic demand. Asare-Addo [88] uses a geospatial multi-criteria model to evaluate the solar and wind potential of Ghana and finds that a large percentage of land is technically feasible, but that only grid connectivity and population density will impede the large-scale grid-first potential of high-potential areas in the north. Idriss et al. [89] present a comparative economic evaluation of hydrogen production based on solar energy in selected urban centres in Africa and show that the levelised cost of hydrogen is dominated by the costs of electricity and the electrolyser, and that it also reveals a substantial environmental impact through reduced carbon emissions.

Collectively, the reviewed literature shows significant advances in green hydrogen technologies worldwide and rising awareness of Africa's strategic significance, particularly West Africa, due to its rich renewable resources. Recent reports highlight that the world energy transition and environmental sustainability debate have been heightened, placing hydrogen as a key pillar in future low-carbon energy systems. The hydrogen economy is becoming a widely accepted decarbonization route, and green hydrogen produced by renewable-based electrolysis is the most environmentally friendly alternative to blue and grey hydrogen. The current trends in global deployments show that there is a large-scale momentum with more than 180 hydrogen transport projects, 60 distribution projects, 80 storage projects, 30 terminal and port projects, and more than 220 production projects being developed globally that are indicative of high international investment and commitment to policy in the hydrogen-based systems [90].

However, there are still major gaps, especially in region-specific system integration, preparedness of system infrastructure, water availability, policy coherence, and comparative assessment, which depend on West African socio-economic and environmental conditions. Numerous studies available take a global view or focus on individual countries, providing limited integration of photovoltaic-based hydrogen approaches across West Africa. This review addresses these gaps by integrating state-of-the-art knowledge, critically comparing solar PV-based pathways for producing green hydrogen, and offering a cogent, regionally dependent framework to guide policy, investment, and future research in West Africa.

3. Technical and resource foundations for solar PV-based green hydrogen production

This section explores renewable resource-based electrolyser technology, infrastructure needs, and regional evidence to support the creation and implementation of solar photovoltaic-based green hydrogen facilities.

3.1 Renewable energy resources for electrolysis-based hydrogen production

3.1.1 Solar photovoltaic resource potential in West Africa

West Africa has some of the best solar photovoltaic sources on the planet, with an average daily solar insolation and global horizontal irradiance in the region alternating between approximately 4.5 to 6.5 kWh/m2 per day [43], [57], [91]. Africa: countries like Niger, Mali, Burkina Faso, and northern Nigeria have significant solar irradiance and vast land areas, making them good locations to deploy large-scale PV to produce hydrogen via electrolysis [7], [69]. Figure 4 shows the solar power potential in West Africa.

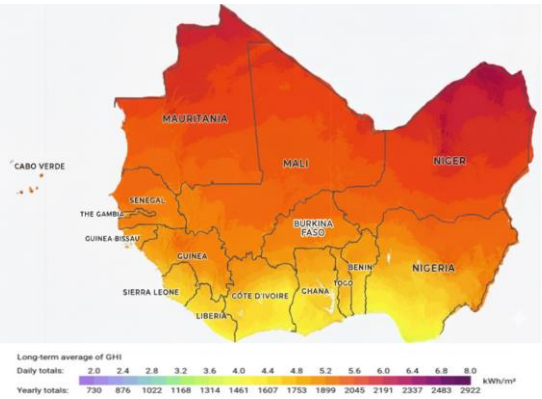

Figure 4: Solar installed capacity across West African countries [69]

Solar PV with electrolysers enables scalable, modular hydrogen generation, ranging from small, decentralised systems to support local energy access to large, utility-scale, export-oriented generation facilities [88], [92]. The high solar potential and the falling PV costs further enhance the techno-economic appeal of solar-driven green hydrogen, which may be offset by intermittency and seasonal fluctuation with battery storage, desalination, or a hybrid renewable system, but land use, panel performance, and long-term maintenance are very important factors [93], [94], [95].

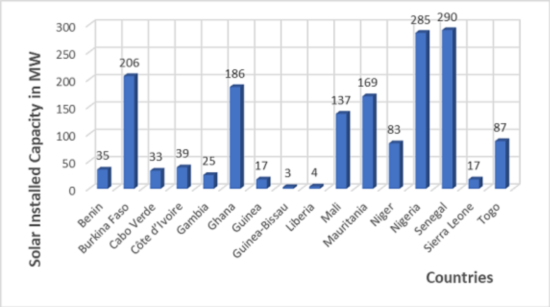

Figure 5. Solar installed capacity across West African countries [18]

Figure 5 illustrates regional inequalities in solar installed capacity in West African countries as of the end of 2025, based on data from the International Renewable Energy Agency [18]. The highest capacities are registered in Senegal and Nigeria at 290MW and 285MW, respectively, followed by Burkina Faso at 206MW. Conversely, other countries, such as Guinea-Bissau and Liberia, are still in the initial stages of deployment, with capacities of 3MW and 4MW, respectively, indicating uneven development of renewable energy in the region.

3.1.2. Wind and hybrid renewable contributions

Although solar PV dominates the renewable potential in West Africa, in certain coastally located and Sahelian zones, especially in Senegal, Mauritania, Ghana, and Cape Verde, also known as Cabo Verde, where wind speeds of 80 m hub height with average values of between 5 and 8 m/s have been recorded, wind energy sources have an important complementary value [69], [96]. Hybrid solar-wind systems can boost capacity factors, lower the levelised cost of hydrogen, and facilitate stable, continuous hydrogen production by activating wind resources, complementing electricity supply and hydrogen demand, and decreasing the percentage of intermittency [49], [97], [98]. Even though wind potential has higher spatial constraints and capital intensity than solar, it can be used strategically to enhance the effectiveness and resilience of systems, though it must be properly assessed on a case-by-case basis with respect to technological-economic factors and long-term maintenance.

3.1.3. Water availability and environmental constraints:

Electrolysis requires significant amounts of water, especially in arid and semi-arid areas of West Africa, where the idea of electrolysis occupies a considerably small portion of the volume of water in comparison to agricultural or industrial use [99], [100]. Constraints can be addressed by using desalination in coastal locations, though at a cost. Environmental factors, such as land-use competence, ecosystem sensitivity, and access to infrastructure, can further influence whether a site is selected as sustainable [101], [102].

3.2 Technology and performance characteristics of electrolysis.

Electrolysis remains the primary method of green hydrogen production, particularly when combined with renewable electricity sources such as solar PV, wind, or hydropower. This is because it can convert electricity into hydrogen with minimal carbon emissions, thus being the core of the energy transition in West Africa [19], [103]. There are various types of electrolysis, each with its own characteristics, advantages, and drawbacks. The most commonly implemented systems are Alkaline Electrolysis (AEL) and PEM electrolysers, but some new technologies, such as AEM and SOE, are gaining public attention.

3.3 Electrolysis technologies and performance characteristics

Electrolysis remains the backbone of green hydrogen production, especially when paired with renewable electricity sources such as solar PV, wind, or hydropower. This is because it can convert electricity into hydrogen with minimal carbon emissions, thus being the core of the energy transition in West Africa [19], [37], [103]. Different types of electrolysis are available, and each possesses unique properties, merits, and shortcomings. The most commonly implemented systems are AEL and PEM electrolysers, but some new technologies, such as AEM and SOE, are gaining public attention.

3.3.1. Alkaline electrolysis

The most developed and commonly deployed hydrogen production technology is AEL, which uses a liquid alkaline electrolyte, either potassium hydroxide or sodium hydroxide, and has proven to be very reliable in large-scale, continuous production of hydrogen. AEL systems have comparatively low capital requirements and moderate efficiency of about 60-70%. Although the reaction time to variable renewable power contributions, including intermittent solar PV, is slower than that of modern technologies [104], [105]. The demand for high-purity water and the generation of low-pressure hydrogen require additional compression and purification steps, which affect the overall flexibility and integration of the system when using PV off-grid or in a decentralised West African installation.

3.3.2 Proton exchange membrane electrolysis

PEM electrolysers feature a solid polymer electrolyte to exchange protons, and this enables compactness and modularity of the system, with fast dynamic response, which is particularly appealing to integrate a variable renewable energy source, e.g., solar PV, common in West Africa. PEM has a higher current density, provides more efficient performance (up to 70-80%) and purer hydrogen production than alkaline systems [106], [107]. PEM technology can be strategically used in off-grid and hybrid PV-hydrogen systems due to higher CAPEX, operational flexibility, rapid ramp-up, and the potential to deploy these systems in a distributed format.

3.3.3 Anion exchange membrane electrolysis

AEM electrolysers are a newer technology that combines the strengths of AEL and PEM systems, using a solid polymer membrane that transports hydroxide ions, allowing the electrolyser to be operated with less expensive non-noble catalysts and with moderate water purity levels. AEM systems are flexible for variable PV-powered operation and can achieve efficiencies similar to PEM (≈65-75%). Since they remain at a pilot or demonstration stage, they offer lower capital and operating costs than PEM [108], [109]. AEM electrolysers can be applied in decentralised solar-hydrogen projects where cost reduction, material availability, and ability to respond to intermittent solar generation are important factors.

3.3.4 Solid Oxide electrolysis

SOE operates at high temperatures (approximately 700-1000ºC) using a ceramic electrolyte and is more thermodynamically efficient (up to 80-90%), as it uses both heat and electricity. SOE systems are specifically compatible with concentrated solar thermal energy or industrial waste heat, thereby improving overall energy efficiency, but the technology itself is at the pilot stage due to high CAPEX, material degradation, and operational complexity [19], [110]. In West African contexts, SOE may enable large-scale industrial or centrally located hydrogen generation where there are sources of high-temperature heat, but the high cost, durability, and technical expertise required for implementation are currently limiting its overall application.

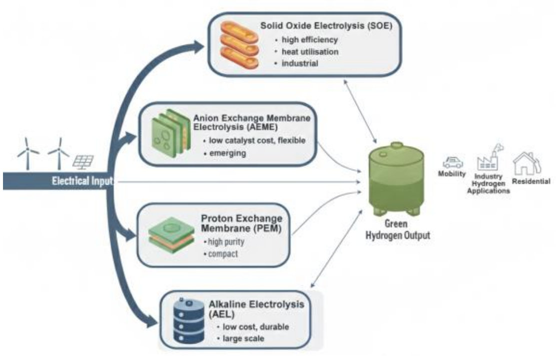

Figure 6. Water electrolysis technologies and key performance advantage [31]

Figure 6 shows four main electrolysis routes for sustainably producing green hydrogen: AEL, PEM, AEM, and SOE. The flow indicates the functional strengths of the individual technologies, such as AEL, with its affordability and large-scale durability, and SOE, with its efficiency in converting industrial heat into green hydrogen for mobility, industry, and residential use.

Table 1 provides a comparative analysis of major electrolysis technologies for generating green hydrogen in West Africa, using techno-economic and technical parameters, alongside PV integration. AEL is a low-cost technology available at large-scale centralised PV sites, but with low flexibility to variable solar input. PEM electrolysers are highly flexible with variable solar input, but have a high CAPEX cost. New AEM electrolysers are capable of lower cost, moderate purity water operation, and SOE systems have the highest efficiency in high-temperature operation, but are pilot-scale and expensive, allowing the table to report levels of

Table 1. Comparative techno-economic and technical performance of electrolysis technologies for West Africa [106], [111], [112], [113], [114], [115]

Electrolysis Technology	Electrical Efficiency (% LHV)	CAPEX (USD/kW)	LCOH Range (USD/kg)	Capacity Factor (PV) (%)	Lifetime (years)	Water Purity Requirement	Dynamic Response	TRL	Suitability for West Africa
Alkaline Electrolysis	60–70	800–1,200	3.0–4.0	20–25	60,000–80,000 h (~15–20 yrs)	Deionized water	Slow	9	Mature, low-cost; suitable for large centralised PV sites; limited flexibility for variable solar inputs
Proton Exchange Membrane Electrolysis	65–75	1,200–1,800	2.8–3.5	22–28	50,000–70,000 h (~12–18 yrs)	High-purity water	Fast	8–9	Highly suitable for dynamic PV integration; applicable for grid and off-grid systems; higher CAPEX
Anion Exchange Membrane Electrolysis	60–70 (projected)	900–1,400	2.7–3.3 (projected)	20–28	40,000–60,000 h (~10–15 yrs)	Moderate-purity water	Medium	6–7	Emerging technology; lower material cost; suitable for decentralised PV applications
Solid Oxide Electrolysis	75–85 (high-temp)	2,000–3,500	3.0–4.5 (projected)	Thermal dependent	30,000–50,000 h (~8–12 yrs)	Deionized water or steam	Slow/thermal lag	5–6	High efficiency with heat integration; suitable for large-scale industrial applications; high complexity and cost

Technology Readiness Level (TRL) of the technologies to guide the selection of technology based on local conditions of solar availability, operational flexibility, and economic constraints.

3.4 Infrastructure requirements for solar PV–Green hydrogen systems

The availability and integration of supporting infrastructure in electricity supply, hydrogen logistics, and water resources are key conditions in the deployment of solar photovoltaic-based systems in West Africa to produce green hydrogen, as compared to conventional power systems, which need a multi-sector approach to infrastructure planning to be technically reliable, economically feasible, and environmentally sustainable [58], [69], [116]. PV-based hydrogen systems are based on the generation and integration of electricity into power systems. The solar PV systems may be off-grid, grid-connected, or hybrid, depending on the strength of the grid, electricity availability, and the size of the proposed project. Grid-connected designs allow export of excess electricity and grid backup when the sun goes down, enhancing the utilisation of electrolysers and lowering the levelised cost of hydrogen in most countries in the West African region [117], [118], [119], [120]. But grid-dependent designs are hampered by weak transmission networks, limited grid coverage, and frequent grid outages in most West African countries. As a result, off-grid and mini-grid PV-electrolysis is now practical, particularly in industrial clusters, remote areas, and coastal export centres. Hybridisation with battery storage or other complementary renewable sources, such as wind, makes power availability even more stable, reduces solar intermittency, and enables PV systems to be more adaptable to operational changes [43], [121], [122]. Recent integrated energy system research has shown that biomass- and solar-based multi-generation systems that integrate hydrogen generation, cooling, desalination, and power generation can be designed with up to 82.4% energy efficiency, sufficient to justify the concept of hybrid infrastructure for resilient energy systems [123].

Hydrogen storage, transport, and distribution infrastructure has a significant impact on the cost and scalability of the system; compressed gaseous hydrogen storage is the most established and widely used to date in small- and medium-scale applications because it is operationally simple but has a low volumetric energy density [124], [125]. Liquid hydrogen storage is more energy-dense and can be applied for long-range transport and export markets, but it is associated with significant energy penalties and capital costs of liquefaction [77]. Metal hydrides and liquid organic hydrogen carriers under research are new technologies that are potentially safer and more energy-dense but are currently at an early stage of commercial applicability [74]. In West Africa, hydrogen was originally intended to be delivered by tanker trucks on roads, and only when large-scale production and high density around industrial zones and port systems became the norm would pipeline infrastructure become a possibility [78], [126].

3.5 Existing green hydrogen studies in Africa and other developing regions

The recent works on green hydrogen in West Africa have been more about the techno-economic viability and optimisation of the systems under high solar irradiance conditions, studies have been conducted in Ghana, Niger, Senegal and Nigeria, all emphasising the potential of solar PV-based electrolysis to be used in on-and off-grid applications, assessing Levelised Cost of Hydrogen (LCOH), system efficiency, and scalability [59], [88], [89], [127]. The main results highlight that scale economies in the deployment of PV systems, along with either PEM or AEL electrolysers, can be used to cut costs and fill energy access gaps. Other factors to consider for successful implementation include water availability, grid reliability, and policy frameworks.

Research in Southern and Eastern Africa and regions with comparable climatic conditions, such as the Middle East and Latin America, is useful for providing benchmarks for the adoption of PV-based hydrogen, especially in areas with poor grid infrastructure [82], [85], [86]. Experience in these areas has shown that integrating the system, operating dynamically under variable solar conditions, and selecting electrolyser technology (PEM, SOE) are the main ways to enhance operational efficiency and lower production costs.

Comparing evidence from Africa and other similar regions offers important lessons for scaling up hydrogen production using PV-based methods in West Africa. The economies of scale, effective water utilisation, and the electrolyser's flexible operation are the main success factors. Policy support, financing mechanisms, and capacity-building are also required to scale up the pilot projects. Combining local solar power and modular PV-electrolysis infrastructure provides a flexible, dependable, and cost-effective avenue to sustained energy transformation to aid local decarbonisation prospects and export potential, as demonstrated in Figure 7, which features the integrated green hydrogen value chain, such as storage, transport, and applications in industry, power, and mobility.

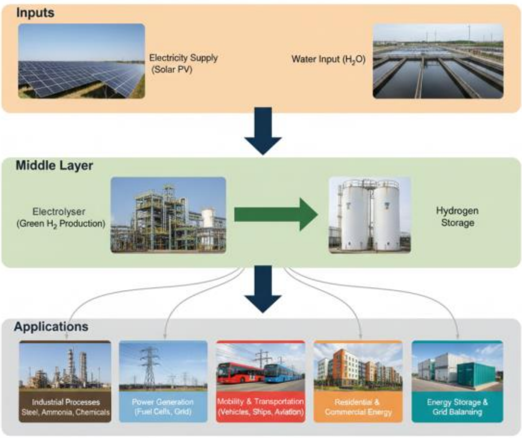

Figure 7. Integrated green hydrogen value chain and applications [133]

4. Status of solar photovoltaic–based green hydrogen development in West Africa

The development of solar-based photovoltaic green hydrogen in West Africa is moving along a clear trajectory of scale, ambition, and institutional maturity, encompassing large-scale export projects, pilot projects, and establishment-building projects. The interaction among renewable resource abundance, policies, and investment maturity is a trend in the region. Mauritania is becoming the obvious regional leader, and the second tier of nations is advancing to pilot- and medium-scale developments; Mauritania is supported by several large-scale, export-based projects combining solar PV and wind generation to provide electrolyser clusters on an industrial scale. The flagship Aman Project is one example that incorporates about 12 GW of solar PV and 18 GW of wind energy, for a total of 30 GW of hybrid renewable energy. It is projected to produce about 1.7 million tonnes of green hydrogen and 10 million tonnes of green ammonia, transforming Mauritania into a global producer [7], [20], [26]. To scale it up, the Megaton Moon Project will install about 6 GW of electrolysis capacity with 6.3 GW of solar PV and 6.8 GW of onshore wind, and will be introduced in phases with projected initial quantities of green ammonia produced by 2029, and full-scale operation by the early 2030s. Other concepts of multi-gigawatts are also being considered, which only enhances the leadership of Mauritania. Hence, solar PV is an affordable and predictable source of power, and the Saharan solar potential enhances the system's capacity, operational predictability, and economic feasibility when used in conjunction with wind. This technological trend can be facilitated by institutional development, in particular by introducing a Green Hydrogen Code that provides regulatory certainty, incentives for investors, and compatibility with international hydrogen and ammonia markets.

A second level of development is evident in Senegal, where solar PV is at the heart of early-stage hydrogen development, on a path from pilot to commercialisation. The proposed Green Hydrogen and Renewable Hub integrates solar and wind generation, with an initial 100 MW of renewable capacity, and plans to expand to about 500 MW. This project, though smaller than the efforts of Mauritania, can be viewed as one of the most developed hydrogen projects in the area beyond the country. Such a phased approach can be described as one of the pragmatic strategies of this region, with hybrid renewable systems demonstrating technical and economic feasibility. The capacity can be increased as policy frameworks, funding models, and offtake agreements evolve. In the demonstration stage, Ghana and Nigeria are developing solar-linked hydrogen projects that focus on skills development, technical education, and system integration, with the GH2GH pilot project in Tema being one of the few actually running in the region, and it can serve as a testbed for later scaling up. In Nigeria, proposed solar-to-hydrogen pilot projects and conceptual hubs, there is emerging interest in adopting PV-based hydrogen, but, given financing, grid strength, and regulatory development, large-scale application of this technology is still pending.

Other West African nations, such as Burkina Faso and Togo, are also focusing on feasibility studies, research pilots, and capacity-building programmes, which are usually sponsored by international development partners, with the aim of testing electrolysis performance under local climatic conditions and determining its economic feasibility. In countries like Guinea, Liberia, Sierra Leone, Benin, Niger, and Guinea-Bissau, solar PV is currently being central and strategic in various renewable energy plans and strategies. The solar-to-hydrogen initiatives are primarily in the concept phase, although these renewable technologies are essential for subsequent green hydrogen systems. Low-cost solar electricity is a key driver of competitive production of hydrogen in West Africa because of the abundance of solar resources, modular deployment capability, and decreasing costs, which place PV as the most economically and geographically viable option of hydrogen generation [42], [43], [57], [62], [128]. Recent techno-economic data on distributed photovoltaic systems show that on-grid and hybrid systems have levelised electricity costs of 0.041 USD/kWh and 0.1066 USD/kWh, respectively, supporting the economic viability of scalable renewable energy deployment pathways [129]. Consequently, Mauritania is the breakthrough level that features several multi-gigawatt, solar-integrated hydrogen projects that aim at export markets; Senegal, Ghana, and Nigeria are pilot and phased commercial-level; and other West African countries are preparing the technical, policy, and renewable energy infrastructure that will be used to deploy solar PV-based green hydrogen in the future.

4.1 Techno-Economic performance and cost of hydrogen in West Africa

The quality of renewable resources, the technology used to select the electrolyser, the scale of the system, the availability of infrastructure, and policy support play a critical role in determining the techno-economic performance of solar photovoltaic-based green hydrogen systems in West Africa. Due to high solar irradiance in most areas, the cost of electricity produced at utility-scale PV is among the lowest in the world, which makes the LCOH depend on the capital invested in electrolysers and other balance-of-plant components, as well as on storage infrastructure and other funding conditions. Recent techno-economic evaluations show that there is a massive cost difference among locations and project configurations. Research in Ghana, Niger, and Senegal has shown that the cost of hydrogen production diminishes substantially with scale, hybridisation, and better utilisation of electrolysers, as large PV-electrolyser installations have significantly lower LCOH than small, decentralised systems. Electricity and electrolyser capital costs are recurrently the most significant cost drivers, significantly impacting the economics of hydrogen production, along with the system structure. The sensitivity analysis further reveals that reductions in PV module and electrolyser costs, and in the weighted average cost of capital, have a compelling impact on overall system economics. Grid-connected or hybrid PV systems typically perform better than fully off-grid systems, as they can operate at a higher capacity factor and incur less curtailment, but the reliability of grids in some areas of West Africa may offset these benefits. New and emerging electrolyser technologies, specifically PEM and AEM systems, offer sufficient operational flexibility for variable solar input, but at a higher capital cost than the mature alkaline electrolysers. As a result, there is a trade-off among efficiency, flexibility, and the initial investment in the technology. Nonetheless, regional and country-specific analyses indicate that the medium- and long-term cost of hydrogen can be internationally competitive in West Africa, at least for large export projects in high-irradiance areas. Further reduction in the cost of solar PV and electrolysers, conducive policy frameworks, infrastructure development, and availability of cheap finance are likely to further enhance techno-economic performance and make West Africa a potential source of low-cost green hydrogen.

4.2 Regional disparities and country-specific readiness

The evolution of solar PV-based green hydrogen in West Africa is characterized by a high level of regional dispersion, as the accreditation of differences in solar resources availability, the maturity of infrastructure, policy frameworks, and institutional capacity. Some countries have the advantage of rich solar irradiance, like Mauritania and Senegal, access to ports on their coastlines to support the logistics of exporting their products, and an enabling regulatory environment, and so become the leaders in the region in pilot and industrial-scale hydrogen projects. Conversely, other countries, such as Burkina Faso, Togo, Niger, and Guinea, are more preoccupied with feasibility, capacity building, and the expansion of renewable energy, which will form the basis for future deployment. Inequality also exists in grid infrastructure and water resource availability, which determines the technical feasibility and operation design of the PV-electrolysis systems. Whereas certain regions can support large export projects, others are better suited to decentralised or hybrid strategies to meet local energy access needs for large-scale green hydrogen production. These differences underscore the need to plan country-specific policies and align local infrastructure investments to ensure that each region

Table 2. Country-level readiness assessment for solar PV-based green hydrogen development in West Africa [66], [69], [70],[100]

Country	Solar Resources Potential	Wind Resources Complementarity	Grid Infrastructure Strength	Hydrogen Project Maturity	Water Availability Constraint	Export Potential	Overall Readiness Level
Mauritania	Very high (Sahara irradiance)	High (coastal wind corridors)	Moderate	Industrial scale (Aman, Megaton Moon)	Moderate (desert water stress)	Very high	Very high
Senegal	High	High wind (coastal wind)	Moderate	Pilot to early commercial (Green Hydrogen Hub)	Moderate	High	High
Ghana	High	Moderate	Relatively strong	Pilot (GH2GH and related studies)	Moderate	Medium	Moderate to high
Nigeria	High (North), Moderate (south)	Moderate	Weak to moderate	Early pilot stage	High constraint in arid zone	Medium	Moderate
Niger	Very high	Low to moderate	Weak	Feasibility and export concept stage	High constraint	Medium	Moderate
Mali	Very high	Low	Weak	Conceptual stage	High constraint	Medium	Moderate
Burkina Faso	High	Low	Weak	Feasibility and pilot studies	Moderate to high constraint	Low to medium	Moderate
Cape Verde	High	Very high (offshore wind advantage)	Moderate	Pilot scale renewable hydrogen concepts	Moderate	High (island export niche)	High
Côte d'Ivoire	High	Moderate	Relatively strong	Early-stage planning	Moderate	Medium	Moderate to high
Togo	Moderate	Low	Weak	Conceptual stage	Moderate	Low	Low to moderate
Benin	Moderate	Low	Weak	Conceptual stage	Moderate	Low	Low to moderate
Guigui	High	Low	Weak	Early planning stage	High	Low	Moderate
Sierra Leone	Moderate	Low	Weak	Very early stage	High	Low	Low
Liberia	Moderate	Low	Weak	Very early stage	High	Low	Low
Guinea-Bissau	Moderate	Low	Weak	Very early stage	High	Low	Low

is ready to produce green hydrogen on a scalable, economical basis.

Table 2 presents a comparative readiness analysis of West African nations for solar PV-based green hydrogen development, incorporating resource availability, infrastructure strength, and project maturity. It shows a distinct regional gradient with Mauritania and Senegal being at the forefront, Ghana and Nigeria in the middle stages, and some of the inland nations still in the initial conceptual stages.

Figure 8 presents a green hydrogen readiness heatmap of West Africa, categorising countries into three levels. Mauritania and Senegal are highly ready, owing to robust solar power and the development of the project. Nigeria, Ghana, and Niger are moderately prepared, and the rest are in the emerging category. The figure highlights key enabling factors, such as solar potential, infrastructure capacity, and access to export markets, all of which are important for promoting regional decarbonisation initiatives.

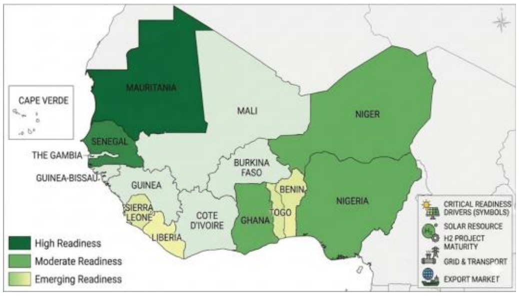

Figure 8: West African green hydrogen readiness heatmap [69]

5. Discussion

The review identifies solar PV-based green hydrogen as a strategically important avenue for the future energy transition in West Africa, where the region's solar potential is coupled with new electrolytic methods. Globally, the development of green hydrogen has accelerated over the last 20 years, driven by the migration of mature alkaline electrolysis and experimental thermochemical reactions towards flexible, modular, and renewable-integrated systems, especially PEM and newly developed AEM [73], [74]. The development of solid oxide electrolysis and hybrid PV-thermochemical technologies highlights that the world is becoming increasingly prepared to deploy them, and AI and IoT integration illustrates how operations can be optimised and more predictively controlled [86]. In West Africa, the review finds a distinct gradient of development with Mauritania in the lead with multi-gigawatts, export focused projects like the Aman and the Megaton Moon projects which combine solar PV and wind to enable industrial level electrolysis, Senegambia comes next with pilot-to-medium-scale projects such as the Green Hydrogen and Renewable Hub and Ghana and Nigeria are bringing up demonstration platforms with a focus on skills development, system integration, and technical validation [59], [88], [130]. Pilot research, feasibility studies, and renewable energy expansion initiatives in other nations are slowly facilitating future PV hydrogen implementation routes, but solar PV is the most predictable, modular, and least expensive source of electricity for both pilot and large-scale use. Techno economic forecasts also suggest that the levelised cost of hydrogen in the area is quite variable with a range of about USD 3.60 to USD 6.70/kg in large scale high resource designs and inefficient or small-scale systems may be over USD 20/kg, which is highly sensitive to system scale, infrastructure preparedness, and operation efficiency [85], [90], [131], [132]. Electrolyser CAPEX, solar PV performance, and grid or hybrid integration strategies primarily determine system costs, whereas operational flexibility and storage solutions may alleviate intermittency and enhance capacity utilisation. Although there is significant potential, differences between regions persist. It faces grid constraints, water scarcity, and underdeveloped policy frameworks, which require regional strategies. The most promising countries for encouraging investment in and developing hydrogen production are those with strong institutional and regulatory frameworks, significant solar and wind power, and access to the coast. Hybrid renewable hydrogen systems combining 1.2 MWp solar PV, 800 kW wind turbines, and a 1 MW PEM electrolyser are capable of a 71% capacity factor, yielding 55.8 tonnes of hydrogen per year at a levelised cost of 5.82 €/kg, with the ability to operate the grid independently and avoid transport sector emissions by a significant margin [132], [133].

Nations with limited infrastructure or financing can use decentralised or hybrid PV-to-hydrogen systems. Collectively, the review highlights that the potential of PV-based green hydrogen in West Africa is huge, although achieving this potential requires comprehensive planning across technology, infrastructure, policy, and financing. The transformation of resource abundance into economically and sustainably viable hydrogen production requires strategic investments in grid integration, electrolyser deployment, water management, and regional coordination. Figure 9 depicts the critical perspective of solar PV-based green hydrogen, where the key barriers and strategic enablers interact, with the key barriers being constrained resources like high capital cost and regulatory uncertainties, and the key enablers being diminishing PV cost, availability of solar resources, and emerging policy and storage solutions.

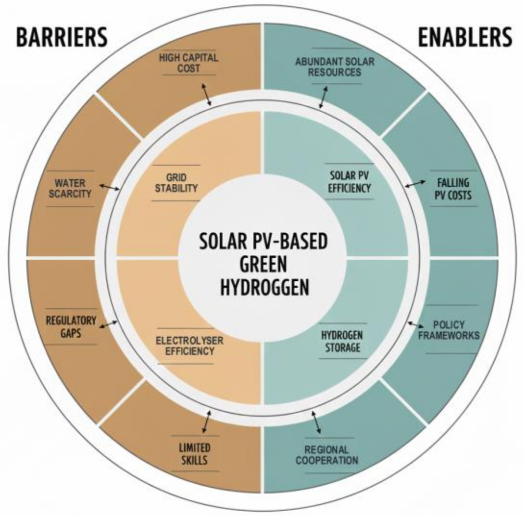

Figure 9: Key barriers and enabling factors influencing solar PV–based green hydrogen deployment in West Africa. [34]

6. Conclusion

This review confirms solar PV-based green hydrogen as an important strategic direction of energy transition in West Africa, which is backed by the strong solar resources, land, and increasing institutional interest. Analysis shows that hydrogen production can be cost-competitive at USD 2.02.6/kg in high-resource sites; however, system costs are cost-sensitive to scale, infrastructure preparedness, and financing. The use of decentralised PV-electrolysis systems can provide viable options to rural electrification and local decarbonisation of industries, whereas large-scale systems have a high potential to export hydrogen and its derivatives like ammonia and methanol. To realise this potential, there must be a concerted effort to invest in electrolysers, grid integration, water supply, and hydrogen transport infrastructure, with stable regulatory frameworks. In spite of these opportunities, there are still challenges in the integration of hybrid renewable, long-term storage, lifecycle environmental impacts, and water resource management. New technologies in electrolysis are efficient and cost-effective, but are still in their infancy. The paper is limited by the use of secondary data, limited region-specific data, and future uncertainties in cost and policy development. The priority of future studies should be country-level modelling, pilot-scale validation, water-energy nexus optimization, and integration of hybrid systems in the real world.

Nomenclature

AEL	Alkaline Electrolysis
AEM	Anion Exchange Membrane
CAPEX	Capital Expenditure (USD/kW)
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
DCF	Discounted Cash Flow
ECREEE	ECOWAS Centre for Renewable Energy and Efficiency
EV	Electric vehicle
FCEV	Fuel Cell Electric Vehicle
GHI	Global Horizontal Irradiance ($kWh/m^2/day$)
H	Hour
H_2	Hydrogen
IRR	Internal Rate of Return (%)
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized Cost of Energy (USD/kWh)
LCOH	Levelized Cost of Hydrogen (USD/kg)
MW	Megawatt
MWp	Megawatt-peak
NPV	Net Present Value (USD)
O&M	Operation and Maintenance
PEM	Proton Exchange Membrane
PV	Photovoltaic
PR	Performance Ratio
SCPP	Solar Chimney Power Plant

SOE	Solid Oxide Electrolysis
TRL	Technology Readiness Level (TRL)
USD	United State Dollar
η	Efficiency (dimensionless)
^{o}C	Degree Celsius
€/kg	Euro per kilogram
$/kg	US dollar per kilogram
$/kW	US dollar per kilowatt
%	Percentage
m/s	Meters per second
m^2	Square meter

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