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Review

Development of the Hydrogen Market and Local Green Hydrogen Offtake in Africa

Chidiebele E. J. Uzoagba [1,2], Princewill M. Ikpeka [3], Somtochukwu Godfrey Nnabuife [4], Peter Azikiwe Onwualu [1], Fayen Odette Ngasoh [1] and Boyu Kuang [4,*]

1 Centre for Climate Change Adaptation and Mitigation Studies (C3AMS), African University of Science and Technology (AUST), Abuja 900107, Nigeria; cuzoagba@aust.edu.ng (C.E.J.U.); aonwualu@aust.edu.ng (P.A.O.); fngasoh@aust.edu.ng (F.O.N.)
2 Department of Petroleum and Energy Resources Engineering, African University of Science and Technology (AUST), Abuja 900107, Nigeria
3 Division of Global Challenges and Transdisciplinary Studies, Brunel University, London UB8 3PH, UK; princewill.ikpeka@brunel.ac.uk
4 Faculty of Engineering and Applied Science (FEAS), Cranfield University, Bedfordshire MK43 0AL, UK; g.nnabuife@cranfield.ac.uk
* Correspondence: neil.kuang@cranfield.ac.uk

Abstract

Creating a hydrogen market in Africa is a great opportunity to assist in the promotion of sustainable energy solutions and economic growth. This article addresses the legislation and regulations that need to be developed to facilitate growth in the hydrogen market and allow local green hydrogen offtake across the continent. By reviewing current policy and strategy within particular African countries and best practices globally from key hydrogen economies, the review establishes compelling issues, challenges, and opportunities unique to Africa. The study identifies the immense potential in Africa for renewable energy, and, in particular, for solar and wind, as the foundation for the production of green hydrogen. It examines how effective policy frameworks can establish a vibrant hydrogen economy by bridging infrastructural gaps, cost hurdles, and regulatory barriers. The paper also addresses how local offtake contracts for green hydrogen can be used to stimulate economic diversification, energy security, and sustainable development. Policy advice is provided to assist African authorities and stakeholders in the deployment of enabling regulatory frameworks and the mobilization of funds. The paper contributes to global hydrogen energy discussions by introducing Africa as an eligible stakeholder in the emerging hydrogen economy and outlining prospects for its inclusion into regional and global energy supply chains.

Keywords: Africa; hydrogen offtake agreement; hydrogen policy; green hydrogen; clean energy; climate change

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1. Introduction

In recent times, hydrogen has emerged as an energy carrier for future energy systems, to support electricity demand in a potential "hydrogen economy", primarily produced from fossil fuels, renewables, nuclear power, or even in situ hydrocarbon reservoirs [1–3]. It can be used in clean energy production, emissions-free power generation, and industrial applications [4]. The transition to a hydrogen-based economy requires developing infrastructure, extending life cycle of existing hydrocarbon assets through hydrogen applications [5], and the understanding of the various hydrogen production pathways, including greenhouse gas (GHGs) emissions and energy efficiencies (EE), to be able to achieve low-carbon energy production [6]. In Africa, hydrogen has been identified as a clean energy carrier towards transition to sustainable energy systems, and it is increasingly seen as a better transition fuel than natural gas in the decarbonization process [7]. The continent's huge renewable energy resources, such as solar, wind, and hydropower, provide a strong background for developing the green hydrogen market and potentially positioning it as a global hydrogen hub [4,8,9]. Currently, Southern Africa (made up of 16 countries) has the potential to become a major global supplier of green hydrogen, aiming to produce ~500 kilotons of hydrogen annually by 2030 [9,10]. Also, a significant number of countries in Africa face challenges in implementing hydrogen technologies, largely due to socio-economic, technical, and policy barriers [9,11]. To realize their hydrogen potential, African nations need to develop implementable policy, regulatory, and legal frameworks [9,12], develop mechanisms to address financing issues, and align with global decarbonization goals and strategies [7,8]. These policies, legal and regulatory frameworks, should address hydrogen energy development in African regions, nations, and sub-nationals, creating structures to build confidence and attract investment. The current energy sector regulations are still largely based on traditional market models and do not account for hydrogen's role as a flexible energy vector. Additionally, despite a growing global discourse on hydrogen power, there is a profound shortage of focused academic and applied research that responds specifically to Africa's policy, regulatory, and infrastructural shortcomings, inhibiting the development of Africa's green hydrogen industry. This study aims to fill this gap through the incorporation of local dynamics into internationally accepted best practices, thus providing policymakers, investors, and stakeholders with practical suggestions. This way, it not only contributes to scholarly understanding of Africa's place in the hydrogen economy but also offers practical steps towards accelerating an equitable and sustainable transition towards a low-carbon economy in Africa [13].

To address this, strategies should consider the principles of good regulation, embracing flexibility to respond to technological, societal, and economic changes. This will enable policymakers to create a well-functioning hydrogen market that supports energy sovereignty and climate neutrality goals while fostering business competitiveness and long-term sustainability [14,15]. The motivation for this review stems from Africa's vast renewable energy (RE) potential and the growing demand for green hydrogen as a clean energy source. Establishing local offtake agreements (LOA) which is a contractual arrangement between green hydrogen producers and buyers for specified volumes over a period to guarantee demand and attract investment [11], and developing a hydrogen market can drive sustainable economic growth, energy security, and environmental sustainability, positioning Africa as a hub in the global energy transition. Local green hydrogen offtake in Africa also refers to industries such as fertilizers, steel, transportation, etc., sourcing green hydrogen domestically rather than relying on exports. A comprehensive analysis with a focus on the Southern African Development Community (SADC) member states found that there were no policies related to hydrogen energy. While there are general renewable energy plans, none of the SADC countries have targeted hydrogen policies other than South Africa. Lack of policy framework prevents green H_2 development and commercialization within the region [9].

Researcher [16] examined the hydrogen value chain in Africa and its production activities, transport networks, and application processes. The study examined the future role of Africa by considering its rich renewable energy resources and also highlighting the need for legislative support and infrastructure investment to focus on H_2 consumption. Obanor et al. [17] also highlighted the African green hydrogen challenges facing the region, which encompass having unclear legal and regulatory standards, technology being costly, and other development purposes. They create investors' uncertainty and curtail the development of the hydrogen sector. The study [18] used a multi-criteria decision-making method in ranking opportunities and challenges to the production of hydrogen in Africa. It demonstrated the continent's ability to join the ranks of key producers of green hydrogen, as well as identifying challenges such as financial barriers, lack of infrastructure, and legislative shortcomings.

Whereas there is so much potential for Africa to produce green hydrogen owing to it being endowed with so many abundant renewable energy sources, various inhibitive factors prevent the development thereof. Closing gaps in policy and regulation, evolving appropriate infrastructure, accessing finance, and aligning development objectives are all essential pieces of propelling Africa toward an effective, sustainable hydrogen economy. This research answers the following questions: What are the critical drivers and barriers for green hydrogen market development in Africa? How can local green hydrogen offtake mechanisms be structured to accelerate domestic adoption, regional and national trade? And what regulatory, legal, and policy frameworks are needed to successfully align Africa's hydrogen potential with global best practices?

Therefore, this study aims to assess Africa's potential in developing a green hydrogen market by analyzing policy frameworks, infrastructure needs, and market opportunities. It explores the role of local green hydrogen offtake agreements in supporting energy transition, economic growth, and sustainability. By comparing global best practices, the study highlights pathways for Africa to integrate into the global hydrogen economy and foster clean energy development.

2. Research Methodology

A systematic qualitative review methodology was used to examine the hydrogen market development and local green hydrogen offtake in Africa. The study identified, screened, and synthesized hydrogen-related studies on current policies, strategies, market developments, and case studies using systematic literature review techniques guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart (Figure 1). The analyses focused primarily on English-language sources. Other limitations of this study are limited empirical data on African hydrogen projects, requiring extrapolation from global case studies, and rapidly evolving policy dynamics. The data collections were primarily from peer-reviewed journal articles between 2014 and 2025, Government reports, white papers, policy briefs from African nations, international agencies such as multilateral development banks (MDAs), International Energy Agency (IEA) etc., and from the official hydrogen strategies of global leaders such as European Union (EU), Japan, Australia. Also, there were Scopus, Google Scholar, and industry databases searches. Keywords were used such as "Green hydrogen in Africa," "hydrogen policy frameworks," "hydrogen offtake agreements," "hydrogen market development," "hydrogen strategies Africa," "renewable hydrogen projects.". For the data analyses, collected documents were analyzed thematically to identify recurring patterns, challenges, policy recommendations, and opportunities relevant to Africa's hydrogen landscape, followed by comparative assessment between Africa's hydrogen development trajectory and leading hydrogen economies such as EU, Japan, and Australia was conducted to identify best practices Africa could emulate. Selected case studies (e.g., Boegoebaai Green Hydrogen Project, Hyphen Hydrogen Energy Project) were used to illustrate successful off-take agreements, financing mechanisms, and local market strategies.

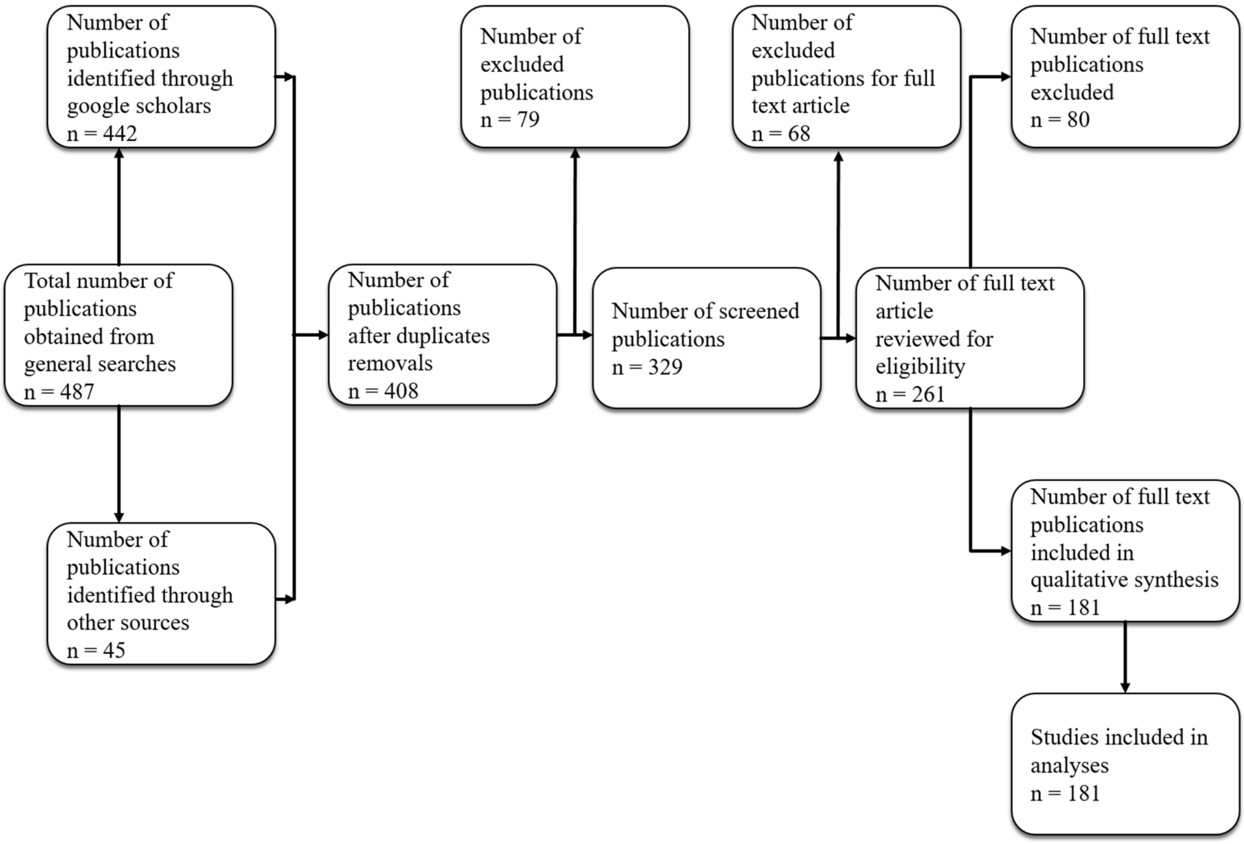

Figure 1. Systematic literature selections and reviews.

Although this paper presents a general outline of the potential for developing the hydrogen market in Africa, it is necessary to recognize the constraints that come with accessing localized empirical data. Specifically, some dimensions of the analysis, like levelized cost of hydrogen (LCOH) projections, were determined partly through extrapolated global benchmarks because of the limited availability of periodically reported country-specific African datasets. To understand the varied climatic, socioeconomic, and infrastructural status of the continent, we have incorporated initial empirical data from representative African nations, such as Egypt, Morocco, Nigeria, Namibia, South Africa, and Kenya, to contextualize the regional variation in hydrogen production costs. For instance, LCOH varies between $2.20 and $4.20/kg in Egypt with high solar irradiation and grid readiness, and $6.00 and $9.50/kg in Nigeria, where infrastructural and regulatory issues remain. This variability illustrates the heterogeneity of cost conditions among African markets. To make broader extrapolations, there is still a lack of fully coordinated, long-term datasets for the continent. The way forward has to be in conducting high-resolution, country-specific techno-economic analysis and sensitivity studies, particularly on key variables such as renewable resource availability, capital costs, water availability, and policy support mechanisms. These enhancements will continue to expand the relevance and potency of hydrogen development approaches in the African context.

3. Results and Discussion

3.1. The Global Hydrogen Landscape

The global hydrogen market is experiencing significant growth as nations and subnationals seek to decarbonize their energy systems [19]. Recent studies have focused on improving production methods categorized by color codes Figure 2, storage, and transportation techniques to enhance efficiency and reduce costs [20,21]. The more widely recognized colors include black, brown, gray, blue, and green hydrogen; however, other lesser-known color spectra exist, such as purple, red, white, aqua, pink, and turquoise.

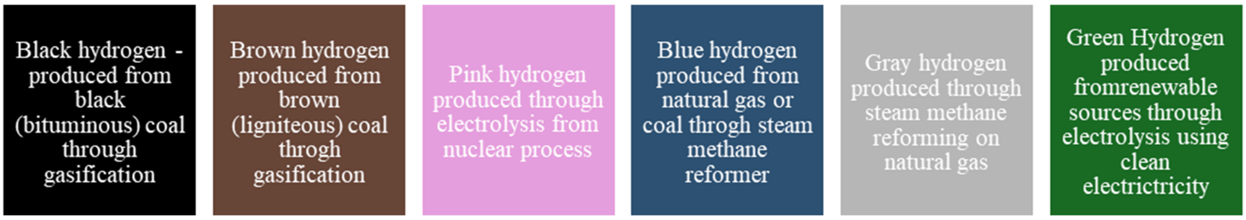

Figure 2. Hydrogen color codes.

Investments are ramping up in hydrogen energy development, with a particular emphasis on "green" hydrogen production, although this technology is still in its early stages and heavily reliant on government support [19]. In the Middle East and North Africa (MENA) region, opportunities to transition from natural gas exports to blue hydrogen production have been explored as a stepping stone towards green hydrogen [22]. As the hydrogen market expands, international cooperation will be required for its widespread adoption [21]. A study has shown that by 2050, hydrogen could meet ~2% of global energy needs, primarily in the transport sector [23]. To achieve this, significant scaling of production is required, with estimates suggesting 660 million metric tons of low-carbon hydrogen will be needed annually, accounting for 22% of global energy demand [24]. Also, a study analyzed 789 hydrogen projects across 61 countries, revealing trends in production technologies and end-use sectors up to 2038 [25]. The transition to hydrogen-based energy systems will require huge investments in renewable power, electrolysis capacity, and CO_2 sequestration infrastructure [24].

The EU, Japan, and Australia have implemented various policies to foster hydrogen market growth [26]. The EU and Japan have set ambitious targets for hydrogen production and integration into their energy systems, supported by substantial budgets for grants and incentives [27]. A study showed that Australia has also set ambitious targets for domestic hydrogen use and export, leveraging its abundant renewable energy resources [28]. Japan has been particularly proactive in promoting the hydrogen economy, with policies aimed at creating new opportunities in sectors such as fuel cells, heat supply, and transportation [26]. These countries have emphasized the importance of steady hydrogen supply, infrastructure development, job creation, and international partnerships [26,29]. While hydrogen offers potential benefits in energy security and environmental impact, it is important to compare it with alternative technologies before advancing policies [30]. EU studies highlight the industrial sector as a key driver for large-scale hydrogen value chains, with transport becoming crucial in the long term. Renewable-powered and natural gas-based hydrogen production with carbon capture and sequestration (CCS) requires coordinated planning and public support [31].

3.2. The Role and Challenges of Hydrogen in Africa's Energy Transition

Hydrogen presents a promising solution for Africa's energy transition, offering opportunities for clean energy access, decarbonization, and economic development [4,32]. Africa possesses significant comparative advantages in the generation of clean hydrogen. It possesses world-class renewable energy sources (RES) for economical energy generation, essential for attaining competitive clean hydrogen production costs (see Figure 3). Numerous countries in Northern and Southern Africa benefit from an advantageous combination of solar and wind resources [33]. Other nations in Central Africa possess the capacity for hydroelectric power expansion, while the East African Rift Valley region holds promise for geothermal development. The wind and solar capacity factors of certain African nations may surpass those of numerous other emerging producer regions worldwide, with only a few regions in Australia, Chile, and China exhibiting superior wind and solar capacity factors. The capacity factors of Mauritania, Namibia, and Morocco, some of the premier locations in Africa, are around 20% superior to those of Iberia, Canada, and the Middle East, which have gained considerable traction in developing hydrogen hubs [34]. Moreover, the sites for affordable renewable energy sources in Africa frequently see reduced rivalry for alternative applications, hence diminishing implementation obstacles in comparison to certain other regions (e.g., Europe).

Despite Africa's increased use of local renewable energy sources for hydrogen production, the overall contribution will remain a minor fraction of the continent's renewable energy development potential. For instance, even with 1% land utilization, Africa's solar power potential is roughly eight terawatts (TW), while its wind power is 0.5 TW. 2; therefore, establishing a hydrogen export initiative at this location would not negatively affect the domestic energy supply. Moreover, it may yield beneficial spillover effects on the domestic power supply. Hydrogen production serves as a reliable off-take for renewable energy and promotes the expansion of renewable energy sources on a broader scale [34]. Local entities can acquire expertise in the hydrogen production sector and subsequently apply their talents to meet local energy needs. In areas with limited freshwater resources, seawater can frequently be desalinated to provide a source for electrolysis. In such instances, the discharge of salt brine into the ocean must be executed meticulously to avert disruption of the surrounding ecosystem.

Sub-Saharan Africa faces challenges in accessing modern energy resources due to its heavy reliance on fossil fuels, contributing to greenhouse gas emissions [35–37]. Despite abundant renewable and non-renewable energy resources, the continent struggles to provide reliable energy services to its population [36,38,39]. Electrification rates vary widely, with some countries like Ghana and Cape Verde achieving higher access, while others lag [35]. RE sources are growing but face obstacles such as weak technologies, insufficient funding, and inadequate policies [35]. Energy cooperation and integration across Africa are hindered by various factors, including market conditions, geography, and governance [40]. However, climate financing instruments and increased foreign investment present opportunities for accelerating energy sector development and addressing the continent's energy challenges [40].

The transition to a low-carbon energy mix, including the integration of green hydrogen produced from RE sources, could play an important role in decarbonizing Africa's economy, while meeting its growing energy demands [4,38]. These would require huge investments in infrastructure and regional cooperation to address challenges such as intermittency and grid integration [36,37]. The continent's potential for hydrogen production ranges from 366 to 2738 Giga tons per annum for various sources [41]. Several African countries, such as South Africa, Egypt, Morocco, and Namibia, are emerging as key players in green hydrogen production [32]. Hydrogen technology offers potential benefits for the continent's economy and electrification coverage [42]. The development of hydrogen economies can support decarbonization efforts, enable clean energy access, and create export opportunities [18,41]. Technological solutions, such as cost-effective transportation systems and hybridization with fuel cells, are being explored to overcome these obstacles [41,42]. Overcoming barriers such as legal, regulatory, and policy challenges through regional cooperation and policy development will boost Africa's hydrogen potential realization [18].

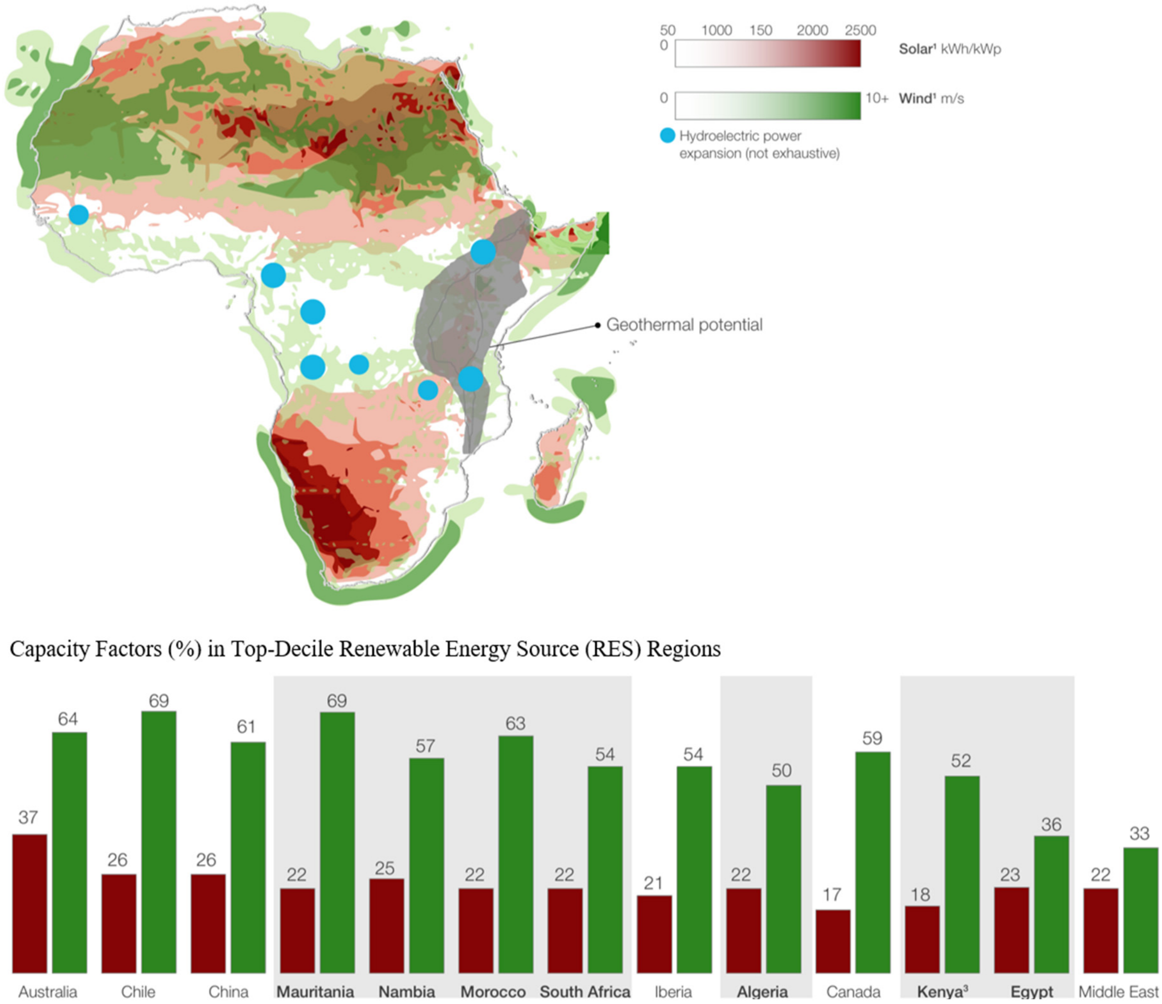

Figure 3. Map of renewable energy potential. 1. Solar energy potential (in kWh/kWp) and wind energy potential at 100 m above ground level (m/s). 2. Ranking of countries based on a 50:50 weighted average of capacity factors for the top 10% solar power [34,43].

3.3. Strengthening the Policies and Regulatory Frameworks in Hydrogen Market Development

While some regions, like Southern Africa, are reviewing existing policies to address these barriers [9], others, such as the Economic Community of West African Countries (ECOWAS), currently do not have official Hydrogen Energy policies [12]. Nigeria has developed a local green hydrogen offtake study as well as a policy and regulation framework for the build-up of a hydrogen market in Nigeria [44,45]. Hydrogen presents opportunities for socio-economic development and sustainable growth in Africa [32]. To capitalize on these prospects, African nations need to strengthen their regulatory frameworks, align policies, and foster regional cooperation to overcome barriers and facilitate the transition to a green hydrogen economy [9,12,18]. Table 1 captures current regulatory challenges for Hydrogen implementation across Africa and the corresponding opportunities to strengthen the policies.

The development of an integrated hydrogen policy for Africa requires an analysis that goes beyond the assessment of the solo effectiveness of individual policy instruments, including their interrelatedness [9]. Economic incentives in the form of grants and tax credits, for example, will only catalyze investment if preceded by credible regulatory guidance and reliable infrastructure. Subsidy programs aimed at incentivising hydrogen production, for example, will be ineffective at attracting developers if certification regimes, streamlined permitting procedures, or grid access are not in place [46]. Similarly, land-use policy reforms are needed to enable the widespread construction of solar or wind facilities necessary for green hydrogen generation; yet their effectiveness relies on parallel investments in hydrogen transportation and storage infrastructure. International cooperation plays a double role: the co-regulation of safety and environmental standards, as well as the provision of concessional finance and risk mitigation for investors. However, in the absence of coordinated regional regulatory frameworks, such cooperation may give rise to fragmented markets. Policy design should therefore be underpinned by a systems-based approach that acknowledges the interdependent economic, regulatory, technological, and social conditions necessary to catalyze a robust and scalable hydrogen economy in Africa [17].

Table 1. Regulatory challenges and policy reforms in hydrogen market development.

Challenges	Descriptions	Opportunities for Policy Reforms
Energy Sector Regulations	Existing regulations in the energy sector often favor traditional fossil fuels, with minimal provisions for hydrogen. The regulatory frameworks are outdated and do not recognize hydrogen as a viable energy source [47].	Integrating hydrogen as part of the energy mix in the energy sector regulations.
		Defining hydrogen's role in decarbonization strategies.
		Establishing clear hydrogen standards for production, distribution, and use.
Land-Use Policies	Land-use restrictions and zoning laws hinder the establishment of hydrogen production and storage facilities. Hydrogen production, especially green hydrogen, requires significant land for renewable energy sources like solar and wind farms [48].	Revising land-use policies to allow for the development of hydrogen-related infrastructure.
		Implementing flexible zoning laws for hydrogen facilities in industrial zones.
		Encouraging multi-use land policies that integrate renewable energy production with hydrogen generation.
Investment Barriers	High capital costs and long payback periods discourage private investment in hydrogen projects. Financial support mechanisms such as subsidies or tax incentives for hydrogen are either limited or non-existent [49].	Offering investment incentives such as grants, subsidies, and tax credits for hydrogen projects.
		Establishing public–private partnerships (PPPs) to lower risk for private investors.
		Creating green financing mechanisms, including green bonds, specifically for hydrogen development.
Infrastructure	Limited infrastructure for hydrogen storage, transportation, and refueling stations, particularly in emerging markets. This slows the scaling up of hydrogen use across industries [50].	Encouraging infrastructure investments through public funding and international collaboration.
		Supporting the creation of hydrogen corridors for transportation and distribution.
		Promoting research and development (R&D) in hydrogen storage and distribution technologies.
Safety and Environmental Regulations	Lack of harmonized safety standards and environmental regulations for hydrogen handling, storage, and transport increases risks and deters investment [51].	Developing clear, global standards for hydrogen safety and environmental impact.
		Harmonizing hydrogen safety regulations across jurisdictions to promote cross-border trade.

Table 1. *Cont.*

Challenges	Descriptions	Opportunities for Policy Reforms
Permits and Licenses	Hydrogen projects face lengthy and complex permitting and licensing processes, leading to delays in development. Regulatory approvals for hydrogen-related infrastructure can take years [52,53].	Streamlining permitting and licensing processes for hydrogen projects.
		Implementing fast-tracked approval mechanisms for low-carbon energy projects, including hydrogen.
Fragmented Regulatory Landscape	Regulatory frameworks for hydrogen vary significantly between regions, creating barriers for cross-border trade and market integration. This lack of coordination complicates hydrogen market development [52,54].	Promoting regional and international cooperation on hydrogen regulations.
		Creating common regulatory frameworks and standards for cross-border hydrogen markets, particularly in Africa.

3.4. Comparative Analysis of Best Global Practices

This paper contrasts Africa's new hydrogen policy frameworks with those laid down in the European Union, Japan, and Australia [55] (See Table 2).

Table 2. Comparative analysis of global best practices.

Region	Key Policies	Financial Incentives	Market Structure	Notable Best Practice
EU	Green Deal, Hydrogen Strategy	Large-scale subsidies and funding calls	Liberalized, cross-border cooperation	Integrated EU Hydrogen Backbone
Japan	Basic Hydrogen Strategy	Direct government R&D funding	Public–private partnerships	Early commercialization focus
Australia	National Hydrogen Strategy	State and federal grants	Competitive, export-driven market	Federal-state coordination
Africa	Nascent national policies	Limited	Fragmented, emerging	Opportunity to integrate best practices

The conclusions are that Africa's policies are fragmented relative to the integrated policy blueprints being followed elsewhere. As Africa's policy environment evolves, global leaders have instituted comprehensive blueprints, strong fiscal incentives, and visionary market liberalization.

Among the most effective strategies that have been found are aggressive deregulation of the hydrogen market, transparent legislative templates, and organized fiscal incentives.

Emulating these strategies will render Africa competitive in the international hydrogen economy. The Australian federal-state model, the European Union monetary models, and the private sector initiatives of Japan provide especially useful ideas in regards to shaping Africa's shift to hydrogen [56].

3.5. Developing a Green Hydrogen Offtake Strategy in Africa

3.5.1. Strategies for Local Green Hydrogen Offtake Development

Studies indicate that solar-based hydrogen production outperforms wind-based systems in most African countries, with the levelized cost of hydrogen (LCOH) ranging from \$4.60 to \$7.31 per kg for solar and \$5.60 to over \$20.00 per kg for wind systems [57]. Its development in Africa could boost economic growth, stimulate investment, and create jobs, while contributing to CO_2 reduction targets [8,32]. The development of hydrogen infrastructure requires strategic planning and collaboration between the public and private sectors. Kim et al. (2022) [58] highlight the importance of utilizing existing industrial facilities and government subsidies to expand hydrogen production and distribution. Public–private partnerships (PPPs) have emerged as a popular strategy for infrastructure development, and there is a need for a framework to assess their effectiveness [59]. Mohtavipour et al. (2024) [60] introduced a reliability contract method to ensure a stable hydrogen supply for sustainable transportation, dividing networks into zones to manage outages effectively. Scholten (2012) [61] suggests that organizational structures are crucial for reliable renewable energy systems, especially in the transition to hydrogen as a motor fuel, as different technical characteristics necessitate corresponding organizational structures. The transportation sector, including light-duty and heavy-duty fuel cell electric vehicles, represents a major opportunity for hydrogen demand growth [62]. Power generation and industrial applications like ammonia production and metals refining are also promising sectors for hydrogen utilization [62,63]. The EU aims for hydrogen to fulfill 20–50% of transportation demands and 5–20% of industrial needs by 2050 [63]. Power-to-Hydrogen and Hydrogen-to-X technologies are crucial for integrating renewable energy sources with hydrogen production and utilization [63]. To support typical industrial plants, hydrogen facilities of several hundred to a few thousand megawatts (MW) capacity are necessary, highlighting the potential for significant local demand creation [64].

Localized data on solar hydrogen production costs across Africa reveals a lot of diversity. The variation is because of the quality of the solar resources, the age of the infrastructure, and the availability of financing. In Egypt, the levelized cost of hydrogen (LCOH) is expected to be between USD 2.20 and USD 4.20 per kilogram of H_2 by 2030. This variation is because of the country's high solar irradiation and grid capacity [65]. The LCOH for Morocco is between USD 2.50 and USD 4.50 per kilogram of hydrogen. The country has a well-established solar sector and trade relations with the EU. However, expenditures are still higher in South Africa, ranging from USD 4.60 to USD 7.31 per kilogram of hydrogen, because of grid bottlenecks and high capital expenditures [41].

In addition, densely populated West Africa, which is faced with energy poverty, does not yet have large green hydrogen projects because of policy, infrastructure, and investment-readiness deficits. However, some countries, such as Nigeria, have begun developing policy and regulatory frameworks for facilitating the build-up of hydrogen markets [66]. The recent [44] is the first step in the direction of hydrogen development in the region. The Economic Community of West African States (ECOWAS) does not yet have a shared hydrogen strategy, highlighting the need for policy convergence to enable future investment and deployment within the sub-region.

In Nigeria, the estimated LCOH is USD 6.00–USD 9.50/kg H_2 because of problems including not enough water, not enough solar energy being used, and not enough rules in place [18]. On the other hand, Mauritania and Namibia, which have a lot of land and solar potential, want to export hydrogen on a massive scale for USD 2.00 to USD 3.00 per kilogram through the AMAN and Hyphen Hydrogen Energy Projects [18]. Kenya plans to use geothermal energy as a backup source of energy and expects to produce USD 3.80–USD 5.00/kg H_2, which will help keep the grid stable and grow the local market. Profiles of each country show how important it is to have tailored investment and policy plans. To make a long-lasting hydrogen market in Africa [57], it is important to build on the comparative advantage of each country, whether that be solar or geothermal power, water, being ready to export, or having a lot of demand at home [67].

If Africa could gain a stake of approximately 15% of global trade in clean hydrogen and derivatives through being competitively priced and sourcing diverse imports, then it would translate to exporting 1 million tons equivalent of hydrogen by 2030, 5 million tons by 2040, and 11 million tons by 2050. In addition to this, the supply of hydrogen fuels in high-seas shipping lanes could be a 2 million ton opportunity by 2050. To build an African economy of this scale using hydrogen, more than USD 400 billion of additional investment would be needed. In addition, bunkering of hydrogen fuels at major shipping routes would offer a 2 Mtpa opportunity in 2050. To enjoy such an African hydrogen economy, there would be an additional total amount of capital of over USD 400 billion required (see Figure 4). The industry would generate a combined 13 million new job-years by the year 2050, covering jobs related to the installation and operation of renewable facilities, hydrogen production plants, conversion factories, and export facilities. Collectively, all the exports of hydrogen products would contribute over USD 15 billion annually to African export value in 2050. Investment within the industry is expected to increase in the years ahead, with over 90% of the investments happening after 2030. In 2050, 75% of Africa's hydrogen use could be allocated to chemicals, refining, and transport, contributing to a total usage of 6.5 Mtpa and resulting in additional local economic gains.

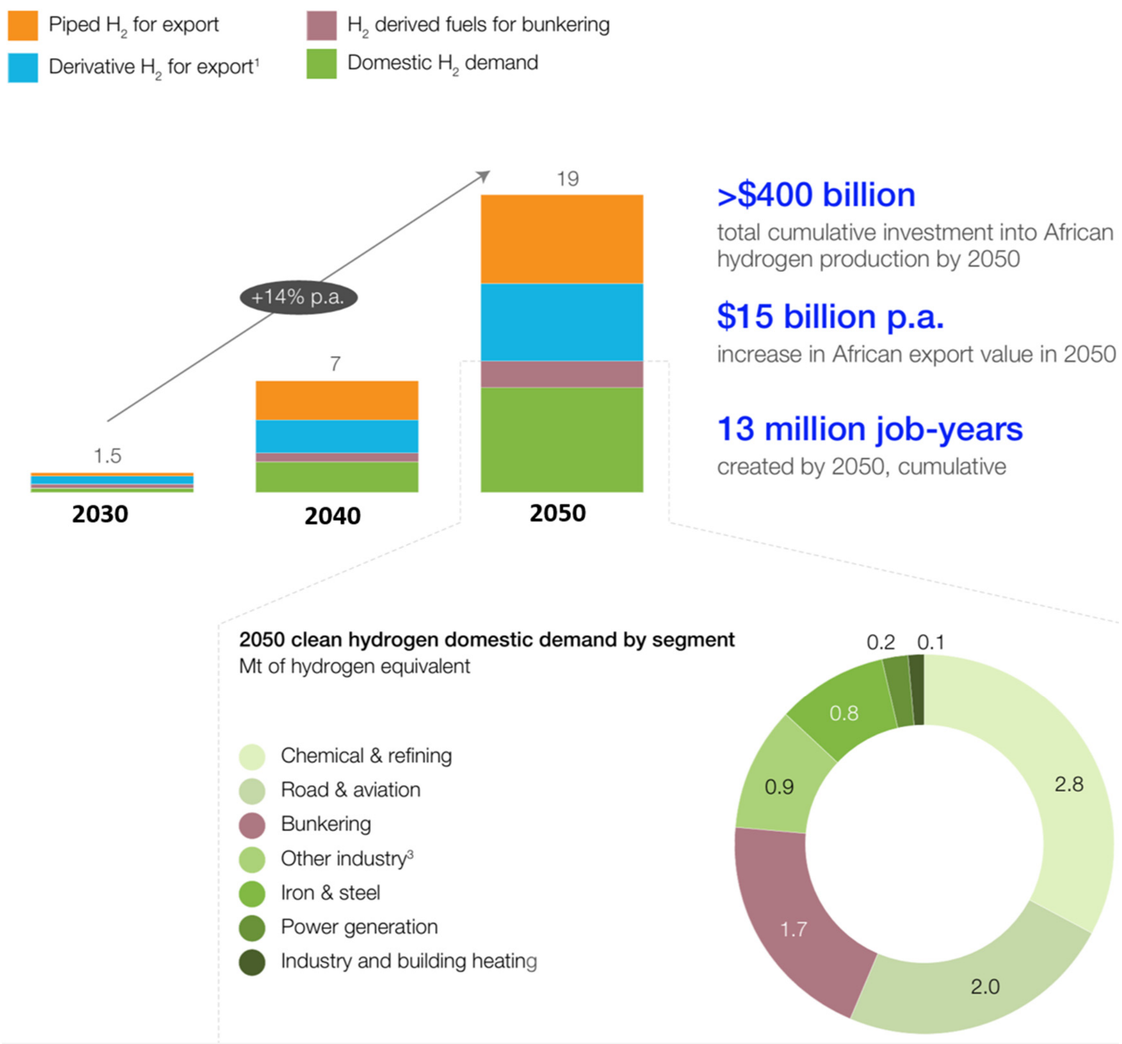

Figure 4. Potential H_2 production in Africa (Mtpa) [68].

3.5.2. Case Studies of Green Hydrogen Offtake Agreements

The case studies provide illustrative examples to validate findings from the systematic review and practical insights into how hydrogen offtake strategies are structured in real-world African and global projects. Other nations in the African continent, except for South Africa and Namibia, are leading innovations in green hydrogen offtake. In Egypt, Fertiglobe uses hydrogen from the Suez Green Hydrogen Project to produce ammonia domestically for industrial decarbonization [69]. In Kenya, the KenGen Pilot, through geothermal-powered electrolysis, targets industrial utilization and heavy transport, advancing energy security [70,71].

These are examples of a blend of plans: HEVO's Ammonia Project targets ammonia export (Fusion Fuel & Vitol), while Morocco Green Hydrogen Alliance is outlining plans for chemical and local fertilizer industries in later stages [72]. The Mauritanian AMAN Project targets local power and industrial consumption initially, followed by full exporting [72]. The Tunisian National Hydrogen Program targets the transport sector and decarbonization of steel in an initial phase, followed by EU export in a later stage [73].

These case studies reflect various models of use, including the following: captive industrial (Egypt, Kenya), hybrid local/export (Morocco, Mauritania), and phased domestic-first (Tunisia). They also refer to context-related drivers such as energy security, trading partners, and sectoral priorities.

It is crucial that policymakers and investors recognize this strategic diversity: successful hydrogen market expansion will have to be adapted to the unique economic models and decarbonisation goals of each country.

This involves modernizing plans for under-represented areas such as West Africa, where plans are nascent but with tremendous potential thanks to industrial demand, population density, and unexploited renewable resources. African hydrogen planning that is more representative will have to deliberately involve under-represented foreign-investment-supported areas, and the emphasis will have to be not only on export-focused hydrogen clusters but also on native energy sovereignty and security.

The thematic findings from the case studies support broader policy recommendations. Green hydrogen offtake agreements are contractual arrangements to buy hydrogen from a producer, often guaranteeing stable demand [74]. Examples are illustrated with case studies from South Africa—Boegoebaai project, Namibia—Hyphen Hydrogen Energy, etc. (see Table 3). Historical case studies of integrated hydrogen systems across multiple countries highlight the need for experience and operating data to make hydrogen a competitive energy carrier [75]. Research shows that incorporating hydrogen storage with RE sources can significantly increase operational revenues, with potential gains of up to 51% [74]. Green hydrogen offtake agreements are important for advancing the energy transition [74]. A pilot-scale demonstration in a commercial building revealed that off-site green hydrogen supply could extend fuel cell operation time and reduce CO_2 emissions to zero adequately [76]. These studies collectively highlight the growing importance of green hydrogen in sustainable energy systems.

Table 3. Case studies of green hydrogen offtake in Africa and the world.

Case Study	Region/ Country	Description	Offtake Partners	Ref.
Boegoebaai Green Hydrogen Project	South Africa	A large-scale green hydrogen production facility powered by RE sources, primarily solar and wind.	Sasol and the Industrial Development Corporation (IDC)	[18,77]
Hyphen Hydrogen Energy Project	Namibia	The first large-scale green hydrogen production plant in Namibia, using wind and solar to produce green hydrogen.	Various European partners (incl. the German government) for export to Europe	[78]

Table 3. *Cont.*

Case Study	Region/ Country	Description	Offtake Partners	Ref.
Nigeria Hydrogen Policy Framework	Nigeria (West Africa)	A strategic national policy initiative focusing on local market development and hydrogen readiness, targeting industrial decarbonization.	National pilot stakeholders; regulatory framework in development	[44,68]
Morocco Green Hydrogen Alliance (MGHA)	Morocco	Initiative aimed at developing a national green hydrogen production strategy using the country's vast renewable resources.	European Union partners and international corporations for hydrogen export	[32,79]
The AMAN Green Hydrogen Project	Mauritania	The massive renewable energy project is aimed at producing 10 million tons of green hydrogen annually for export.	CWP Global and European energy markets (offtake partners to be finalized)	[80]
Suez Green Hydrogen Project	Egypt	Focused on producing green hydrogen from solar and wind energy for use in local ammonia production and export.	Fertiglobe (Orascom), Scatec, and Egyptian Sovereign Fund	[81]
KenGen Green Hydrogen Pilot	Kenya	A pilot project to produce green hydrogen using geothermal energy from KenGen's existing geothermal power plants.	Local industrial and transportation sectors (offtake partners in negotiation)	[70]
HEVO Ammonia Morocco Project	Morocco	A large-scale facility to produce green hydrogen for ammonia production, aiming to export ammonia globally.	Fusion Fuel and Vitol (for ammonia offtake)	[82]
Anglo American Green Hydrogen Initiative	South Africa	Green hydrogen production to power hydrogen fuel cell trucks for mining operations, reducing reliance on diesel.	Anglo American (internal offtake for mining operations)	[83]
Tunisia Green Hydrogen Strategy (National Program)	Tunisia	Developing green hydrogen infrastructure and capacity for local industrial use and potential export to Europe.	European Union partners (export offtake agreements being developed)	[84]
HyDeal Ambition	Europe (Spain, France)	A large-scale green hydrogen initiative aiming to deliver hydrogen at fossil fuel parity. Expected to supply 3.6 million tons of green hydrogen by 2030.	Industrial partners across Europe	[85,86]
Western Green Energy Hub (WGEH)	Australia	A proposed hub focused on producing green hydrogen for export to international markets, leveraging renewable energy. The project aims to produce up to 50 GW of energy.	Asian and European countries	[87,88]
NEOM Hydrogen Project	Saudi Arabia	A $5 billion project focused on producing green hydrogen for both local and international consumption. Expected to produce 650 tons of hydrogen daily from 2026.	ACWA Power, Air Products, NEOM	[89–91]

Table 3. *Cont.*

Case Study	Region/ Country	Description	Offtake Partners	Ref.
Port of Rotterdam Green Hydrogen Offtake	Netherlands	Green hydrogen produced at the Port of Rotterdam will be supplied to major industrial partners in Europe. The focus is on decarbonizing heavy industries.	BP, Shell, Uniper	[92–94]
HyNet Northwest	United Kingdom	A green hydrogen network focusing on decarbonizing industries in the Northwest of England. HyNet is expected to meet 80% of the region's hydrogen demand by 2030.	UK industries	[95,96]
Green Hydrogen offtake agreement by Iberdrola	Spain	Iberdrola's green hydrogen project in Puertollano will power fertilizers and ammonia production, with plans for further expansion into other industries.	Fertiberia	[97,98]
Asian Renewable Energy Hub (AREH)	Australia	This project aims to export green hydrogen to Southeast Asia, focusing on using abundant renewable resources in Australia to create a large green hydrogen export industry.	Japan, South Korea	[99]
Hydrogen Energy Supply Chain (HESC)	Australia—Japan	This pilot project exports liquid hydrogen from Australia to Japan, using coal gasification for hydrogen production, combined with carbon capture and storage (CCS).	Kawasaki Heavy Industries, J-Power	[100]
Hy2Gen Green Hydrogen Plant in Norway	Norway	Focused on providing green hydrogen to the maritime and logistics industries in Europe. Part of the European green hydrogen infrastructure expansion.	European maritime industries	[101]

3.6. Policy Recommendations for Building a Hydrogen Economy

The transition to an H_2 economy is an urgently essential step that must be taken in order to achieve global decarbonization goals in sectors that are difficult to electrify, such as heavy manufacturing, long-distance transportation, and aviation. An integrated policy regime is required in order to facilitate the expansion and deployment of hydrogen-based technology [21,102–104]. The ideas that are presented below are some of the most significant ways in which a thriving H_2 economy might be constructed:

1. Developing a Policy Framework That Is Both Consistent and Open to Change

A strong economy that is based on H_2 contains a comprehensive set of policies that are coordinated with national energy and decarbonization procedures. To guarantee that there is consistency and transparency throughout the value chain, the system must have clearly defined definitions, standards, and certification procedures for the processes that are used to generate H_2. Both innovation and investment will be driven in the H_2 economy by regulatory regimes that are able to keep up with the latest technical breakthroughs and trends in the market [105].

2. Promotions of Financial Gain

To promote investment and bring the price gap between renewable H_2 and its counterparts made from fossil fuels to a level that is more manageable, governments need to develop specific finance institutions. The grants that are intended to reduce the capital expenditures associated with H_2 projects, industrial subsidies, and tax advantages are all examples of these types of programs. The scientific advancement of hydrogen fuel cells has been considerably aided by tax advantages on production, such as Section 45V in the United States economy [106]. Research and development are also boosted by financing, which results in an increase in technological advances and a decrease in expenses.

3. Supply Chains and Civil Construction of Infrastructure

To ensure that H_2 technology is deployed in an efficient manner, the creation of H_2 infrastructure is essential. Construction of distribution networks, storage facilities, and manufacturing facilities is all part of this step of the process. In addition to enhancing energy resilience and security, investments in infrastructure make it easier to transport H_2. The ability to share risks and costs that have been incurred can be facilitated through public–private partnerships [107].

4. Enabling International Cooperation and Specifications for Standards

Standards, certifications, and laws that control H_2 must be harmonized through international collaboration in order to accommodate international energy markets. Market fragmentation can be avoided by international collaboration, which also helps to facilitate international trade and encourages the adoption of best practices. The credibility and legitimacy of national H_2 policies can be improved through the use of multilateral discourse and the efforts to harmonize international institutions [108,109].

5. Stimulating Demand and Giving Encouragement to The Creation of New Markets

In order for the H_2 economy to achieve significant expansion on a comprehensive scale, it is vital to stimulate demand for H_2; this is especially true in businesses that are difficult to control, such as the transportation and heavy industry sectors. The implementation of public procurement laws, mandates, and incentives for end-users is one way in which governments might boost demand for their products and services. A good example of this would be the provision of financial incentives for the use of vehicles driven by H_2 fuel cells in public transport fleets. This would serve as a catalyst for the acceptance of these vehicles by a wider market [110].

6. Fostering a Sustainable Social and Environmental Environment

When it comes to social justice and environmental sustainability, policies should ensure that the production and utilization of hydrogen (H_2) promote both. In order to accomplish this, it is necessary to examine the release of greenhouse gases over the whole life cycle of various H_2 production systems and to provide support to those that have the least impact on the environment. It is also possible to address social concerns through the participation of stakeholders and the community, which makes participatory development easier to achieve [111].

7. Foster creativity, innovation, and technological advancement.

It is necessary to provide continuous financing for research and development in order to advance hydrogen technology, reduce costs, and improve efficiency. Technology advancements can be sped up with the assistance of facilities that are on a demonstration scale, pilot scale, and joint research projects [112].

Developing an H_2 economy that is capable of sustaining itself requires an all-encompassing policy strategy that includes clearly articulated goals, financial incentives, regulatory policies, investments in infrastructure, research and development, the formation of markets, and the cultivation of human resources [33]. The implementation of such regulations enables governments to not only obtain the economic and environmental benefits of hydrogen technology but also to help the transition to a low-carbon energy system.

Refined Policy Recommendations Based on Differentiated National Contexts

To increase the validity and feasibility of policy suggestions, it is essential to note the heterogeneity among African countries when it comes to developing hydrogen strategies. For countries like South Africa, Morocco, Egypt, and Namibia that have started pilot projects or initial hydrogen plans, the next steps should focus on turning these pilot projects into larger commercial ones, building local supply chains (like making electrolysers and obtaining necessary parts), and creating incentives based on performance for local agreements [113]. These countries also have the potential to benefit from pilot zones for hydrogen export and regional certification schemes to conform to international trade standards. For countries in the Economic Community of West African States (ECOWAS) and other areas without clear policies, the first steps should be to create supportive laws, find key areas for renewable energy, and start discussions across different sectors to include hydrogen in national energy plans. Capacity building and technical assistance via the African Union and multilateral fora can supplement these anchor activities [72]. Additionally, proposals need to take into account each country's unique economic structure (e.g., resource-led versus service-based), energy access needs, institutional governance capacity, and infrastructure readiness to ensure that policy guidance is not only country-specific but also realistically feasible to implement.

3.7. Financing Mechanisms and International Support for the Hydrogen Development in Africa

The development of a hydrogen economy in Africa could boost socio-economic growth and enable clean energy exports to Europe [32]. The estimated cost for developing a global hydrogen infrastructure is in the trillions of dollars [114]. African Development Bank (AfDB) has been a key player in promoting hydrogen development across Africa, supporting projects through PPP, development loans, and blended finance mechanisms [115–117]. The Green Climate Fund (GCF) provides financial support for hydrogen projects in developing countries, particularly focusing on mitigation and adaptation strategies related to climate change [118,119]. Table 4 shows the financing mechanisms for hydrogen development projects. Undoubtedly, hydrogen energy development faces financial challenges, necessitating innovative risk mitigation strategies. Government guarantees, regulatory clarity, long-term offtake agreements, climate change targets, market design, and liability regimes can de-risk projects [51]. Standardized contracts and public–private partnerships can effectively allocate and transfer risks [51,120].

While much attention is given to foreign support structures, mobilizing capital domestically must also take priority. Innovative African financial instruments such as sovereign green bonds, regional investment funds, and national development banks (e.g., Afreximbank, Bank of Industry, Nigeria) provide an opportunity to finance hydrogen infrastructure through the local route. Creation of tiered financing arrangements that combine international concessional finance with domestic equity and micro-investment systems will be essential to long-term sustainability and ownership. Examples include AfDB's blended finance arrangements and Kenya's PPP infrastructure arrangements, which show how local financing systems can be utilized to fund green hydrogen development.

Table 5 shows risk mitigation measures to attract investments in hydrogen development projects. Green financing solutions, such as diversifying funding sources between bank loans and green bonds, can optimize capital structure and reduce financing risks [121]. Additionally, establishing green credit guarantee corporations can attract private investments [121]. Other strategies include developing innovative financing models, implementing risk assessment frameworks, and promoting sustainable finance instruments [121]. These measures can create an enabling environment for hydrogen energy development and accelerate the transition to a cleaner energy future.

Table 4. Financing mechanisms for hydrogen development projects.

Financing Mechanism	Descriptions	Initiatives	Reference
Public–Private Partnerships (PPP)	Combines government and private sector funding for infrastructure projects, sharing risks and costs. PPPs are vital in scaling hydrogen infrastructure and production.	African Development Bank's hydrogen projects through PPPs in Africa. HyNet Northwest (UK) receives government and private support.	[122–124]
International Funds	Dedicated funds to support hydrogen and clean energy development globally. Often target emerging economies to scale green hydrogen production and usage.	The Green Climate Fund (GCF) supports hydrogen projects in developing countries; the European Green Deal Fund for hydrogen development.	[119,125,126]
Green Bonds	Bonds are issued to fund projects that contribute to environmental sustainability, including renewable energy and hydrogen.	Iberdrola Green Bond for hydrogen development in Spain; European Investment Bank (EIB) issues green bonds for clean energy projects.	[127,128]
Carbon Markets	Allows the trading of carbon credits, offering a way to finance hydrogen projects through the reduction of carbon emissions. Hydrogen projects generate credits for trading.	The EU Emissions Trading System (EU ETS) supports hydrogen projects. California's Low Carbon Fuel Standard (LCFS) integrates hydrogen.	[129–131]
International Development Loans	Low-interest loans provided by international financial institutions for clean energy and hydrogen development, targeting infrastructure growth in developing regions.	African Development Bank financing hydrogen development in Africa; World Bank loans for hydrogen infrastructure in Asia.	[38,132,133]
Private Equity and Venture Capital	Investments from private equity and venture capital firms into hydrogen technology companies, helping to scale production and innovation in hydrogen technologies.	Breakthrough Energy Ventures funds green hydrogen startups. HydrogenOne Capital focuses on hydrogen infrastructure investments.	[134,135]
Blended Finance	Uses a mix of concessional public finance with private finance to de-risk investments in hydrogen projects in emerging markets, attracting further private sector investments.	Climate Investment Funds (CIF) blended finance for clean hydrogen projects in Africa. AfDB leveraging blended finance for hydrogen.	[116,119]
Sovereign Wealth Funds	Government-owned investment funds finance hydrogen projects to diversify economies and transition to green energy.	Saudi Arabia's Public Investment Fund (PIF) invests in NEOM's green hydrogen project.	[136]

Table 5. Risk mitigation measures to attract investments in hydrogen development projects.

Risk Mitigation Measure	Description	Examples and Initiatives	Reference
Government Guarantees	Governments offer guarantees to reduce risks for investors, particularly in emerging technologies like hydrogen, by ensuring returns on investment or covering losses.	South Korea provides government-backed guarantees for hydrogen projects. Japan offers guarantees for hydrogen infrastructure development.	[137–140]
Regulatory Clarity	Clear and stable regulatory frameworks reduce uncertainties for investors by ensuring compliance standards, safety protocols, and long-term industry guidelines.	The European Union Hydrogen Strategy provides clear regulations for hydrogen production and trade. California's regulatory framework for hydrogen vehicles.	[47,108,141,142]
Long-term Offtake Agreements	Contracts between hydrogen producers and buyers that secure long-term demand, providing predictable revenue streams and reducing market risks for investors.	NEOM Hydrogen Project has a 20-year offtake agreement with Air Products HyDeal Ambition focuses on long-term hydrogen supply contracts.	[143–145]
Price Support Mechanisms	Governments or organizations set minimum prices for hydrogen, ensuring producers a certain level of profitability and reducing the risk of price fluctuations.	Germany's Contracts for Difference (CfD) for green hydrogen pricing The UK Hydrogen Business Model includes price support for hydrogen producers.	[146–148]
Insurance and Hedging Products	Specialized insurance products and financial instruments that protect investors from risks such as project delays, cost overruns, or market volatility.	Marsh McLennan offers hydrogen-specific insurance products. Zurich Insurance Group provides risk coverage for renewable energy projects.	[149–151]
Public–Private Co-investment	Governments co-invest alongside private investors, sharing risks and rewards in hydrogen projects, particularly in early-stage ventures.	HyNet Northwest (UK) is supported through co-investment from the government and private sector. The European Clean Hydrogen Alliance promotes co-investment.	[152]
Tax Incentives and Credits	Governments provide tax breaks, deductions, or credits to incentivize investment in hydrogen projects, reducing capital costs and improving returns.	US Hydrogen Production Tax Credit (PTC) under the Inflation Reduction Act	[153]
Grants and Subsidies	Direct financial support from governments to hydrogen developers, often provided during the early stages of project development to reduce upfront costs.	The European Union Horizon 2020 provides grants for hydrogen research and innovation Japan's NEDO offers subsidies for hydrogen projects.	[154,155]
Blended Finance	Combining public and private financing in ways that reduce risk for private investors, especially for projects in emerging markets or new technologies like hydrogen.	The African Development Bank (AfDB) uses blended finance for hydrogen projects in Africa. The World Bank applies blended finance for clean energy projects.	[126,156,157]

3.8. The Regional Roles and International Cooperation

African Union's Role in Coordinating Hydrogen Policy—The African Union (AU) has been actively involved in harmonizing policies across various sectors in Africa, including biotechnology [158], digital policies [159], and higher education [160,161]. The AU's efforts aim to achieve greater unity, solidarity, and integration among African states [162].

However, these harmonization initiatives face challenges, such as differing stakeholder understandings of convergence and harmonization [158], methodological flaws in policy development [159] toward hydrogen deployment, and the need to balance harmonization with legal pluralism [162]. Despite these challenges, the AU continues to pursue harmonization strategies in various fields, including environmental protection, corruption prevention, and terrorism combating [162], but needs to intentionally pursue harmonization strategies for hydrogen energy development.

Bilateral and Multilateral Cooperation—Regional cooperation in cross-border hydrogen projects is crucial for achieving net-zero carbon emissions by 2050 [163]. The Northeast Asian region, home to major energy importers and exporters, shows potential for hydrogen energy cooperation, driven by energy security concerns and technological advancements in countries like Japan, Korea, and China [164]. However, challenges such as domestic opposition, weak international R&D cooperation, and regional inequality may hinder progress [163]. The development of hydrogen economies can significantly impact global energy trade, potentially creating new energy exporters and reshaping geopolitical relations [165]. To mitigate risks of market fragmentation and geo-economic rivalry, international governance and investments in hydrogen value chains are essential [165]. Priorities for regional cooperation include the development of international natural gas and power infrastructure, which can lead to synergies between fossil and renewable resources [164].

International Standards and Certifications for Green Hydrogen—The need for international standards and certifications for green hydrogen production and export markets is crucial to ensure sustainability and meet global requirements [11,166]. Additionally, concerns about freshwater availability, land-use, and potential conflicts between local power grid decarbonization and hydrogen export must be addressed [166]. Developing appropriate regulatory frameworks and policies, aligned with international standards, is essential for Africa's successful participation in the global green hydrogen market [11].

3.9. Environmental and Social Impacts of Hydrogen Market Development

Environmental Impact—Research indicates that transitioning from coal to natural gas can offer air quality, carbon, and water co-benefits, except when using coal-based synthetic natural gas [167]. Green infrastructure for urban stormwater management provides multiple environmental benefits, including improved air and water quality, reduced urban temperatures, and potential carbon footprint reduction [168]. Improved water and nitrogen management in irrigated sugar cane can lead to significant reductions in non-renewable energy consumption and greenhouse gas emissions while maintaining or increasing yields [169]. Expanded geothermal deployment scenarios could create new job opportunities and offer environmental benefits such as reduced water usage, air pollution, and GHG emissions [170]. These studies collectively demonstrate the potential for various strategies to simultaneously address multiple environmental challenges, including carbon emissions reduction, air quality improvement, and better water resource management.

To effectively assess the social and environmental impacts of hydrogen development in Africa, one needs to move away from qualitative assertions and to consider empirical measurement and regional dynamics. Green hydrogen production, particularly by electrolysis, typically requires 9–12 L of deionized water per kilogram of resulting hydrogen. In dry regions such as Northern and Southern Africa, where freshwater supply is already under tension, this can be a source of significant pressure on indigenous water systems unless wastewater recycling or desalination is pursued. For instance, seawater desalination has been suggested in the Hyphen Hydrogen Energy Project in Namibia, with concern over the discharge of marine brine and its effects on the environment [113].

Land-use for renewable-powered hydrogen systems is also considerable. Expressed estimates state that for solar-PV-based electrolysis, around 0.1–0.3 hectares of land would be used per installed megawatt. To boost hydrogen production in Africa to export levels (e.g., the AMAN project of Mauritania planning 10 million tonnes per annum), land allocations could run into thousands of square kilometers, with possible repercussions for biodiversity and small-scale farming if zoned inadequately [171].

Furthermore, spatial analysis suggests that on a global scale, only ~40–50% of the hydrogen demand that can be met sustainably by 2050 will lead to significant land and water stress. Where agricultural land is essential for food security in Sub-Saharan Africa, these conflicts warrant comprehensive environmental impact assessments.

Socially, hydrogen development in Africa must transcend opportunity and risk. Although it can enhance energy equity, too: mini-grids of hydrogen power, for instance, may benefit off-grid rural communities in Kenya and Nigeria [56]. But if there is no inclusive planning, green hydrogen projects can reproduce extractive models of development that have hurt the past. Therefore, ensuring that hydrogen infrastructure development includes community benefit-sharing agreements, local worker training opportunities, and access to hydrogen for industries such as transport and fertilizer production is essential for a just transition [32].

Social Impacts and Energy Equity—Rural communities in developing countries face significant challenges in accessing affordable and reliable clean water and energy, which are essential for economic development and well-being [172]. Over 1.3 billion people globally lack electricity access, with the majority living in low-income rural areas [173,174]. Rural electrification can positively impact economic growth, agricultural production, industrialization, and quality of life [37]. However, implementing renewable energy services in these areas requires effective knowledge management, policies, standards, capacity building, and access to finance [175]. Innovative strategies pioneered by socially oriented energy enterprises are needed to address these challenges [176]. Capacity-building efforts are important to bring RE to rural populations, as many still rely on traditional fuels and inefficient technologies [177]. Addressing the water-energy nexus is vital for a sustainable future and ameliorating daily resource deprivation in rural communities [172].

Managing Environmental Risks—The production of green hydrogen poses significant sustainability challenges, particularly regarding water usage and land availability [166]. A global analysis reveals that less than 50% of projected hydrogen demand in 2050 could be met through local production without causing land or water scarcity [48]. To mitigate biodiversity impacts, management practices such as reducing chemical inputs and increasing field heterogeneity are recommended [178]. Proper siting of hydrogen facilities is important, with production and storage typically classified as industrial activities requiring appropriate zoning [179]. Strategies for managing these risks include developing international standards for hydrogen project governance [166], identifying potential hydrogen importers and exporters based on resource availability [48], and consulting local authorities and fire departments on site suitability [179]. These measures aim to balance the growing demand for hydrogen with environmental and safety concerns.

4. Conclusions

The global shift toward sustainable energy sources presents an unprecedented opportunity for hydrogen to play a key role in addressing climate change, energy security, and economic growth. However, regulatory challenges, outdated policies, and fragmented markets hinder the development of a thriving hydrogen economy. Policymakers hold the key to unlocking this potential by enacting targeted reforms. By updating energy sector regulations, reforming land-use policies, incentivizing private investments, and harmonizing safety standards, governments can pave the way for a resilient hydrogen market. Streamlined permitting processes and international cooperation will further drive the market's expansion. Seizing this moment will not only accelerate the global energy transition but also create lasting benefits for economies, particularly in emerging markets. The development of hydrogen as a clean energy source is no longer a distant goal; it is an urgent necessity. With decisive action, hydrogen can become a cornerstone of a sustainable energy future. Equally important will be ensuring geographical balance in Africa's hydrogen approach. Intentional incorporation of local models in countries such as Kenya and Nigeria will be required to avoid excessive concentration of projects in specific regions. Green hydrogen ought to not only provide foreign offtake markets but also allow African countries to meet their own energy needs, decarbonize local industries, and build independent value chains.

To harness hydrogen's potential in the global energy transition, policymakers must strategically integrate it into national and regional energy policies. This includes defining roles and standards for hydrogen production, revising land-use and zoning laws to support hydrogen production sites, encouraging multi-use land policies, introducing financial mechanisms like tax credits and subsidies, prioritizing hydrogen infrastructure investments, promoting international collaboration, harmonizing safety and environmental standards, and standardizing environmental impact assessments. Additionally, simplifying permitting processes and promoting dialog on hydrogen regulations between regions, particularly in emerging markets like Africa, can help promote cross-border hydrogen trade and market integration. Future research should focus on advancing hydrogen production technologies, particularly green hydrogen, to lower costs and improve efficiency. Studies on the integration of hydrogen into existing energy systems, such as its role in balancing intermittent renewable energy sources, are essential. Further exploration of hydrogen storage, transportation, and safety standards will support global adoption. Additionally, research on policy frameworks for cross-border hydrogen trade and market development, especially in emerging economies, is needed. Addressing socio-economic impacts, including job creation and equity, will be key in ensuring a just and inclusive hydrogen transition.

Study Limitations and Future Research Directions

One major drawback of the current research is that it relies on global datasets to support many technical and economic ideas, especially the levelized cost of hydrogen (LCOH). While country-specific data were drawn upon where available from countries such as Egypt, South Africa, Morocco, and Namibia, many African nations still are not well represented by such analyses, and therefore, international benchmarks were employed. While offering rich comparative insights, this approach necessarily cannot capture Africa's full range of climatic conditions, infrastructural variations, economic environments, and levels of access to energy. Future research endeavors should seek to obtain high-resolution, country-level data and conduct sensitivity analyses with respect to key variables such as resource quality, estimated costs of capital, and incentives offered by policies. Such efforts will enable the localization of development pathways towards hydrogen and increase the relevance of plans in the African context.

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