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Review

Green Hydrogen Production and Its Land Tenure Consequences in Africa: An Interpretive Review

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Abstract: Globally, a green hydrogen economy rush is underway, and many companies, investors, governments, and environmentalists consider it as an energy source that could foster the global energy transition. The enormous potential for hydrogen production, for domestic use and export, places Africa in the spotlight in the green hydrogen economy discourse. This discourse remains unsettled regarding how natural resources, such as land and water, can be sustainably utilized for such a resource-intensive project, and what implications this would have. This review argues that green hydrogen production (GHP) in Africa has consequences where land resources (and their associated natural resources) are concerned. It discusses the current trends in GHP in Africa, and the possibilities for reducing any potential pressures it may put on land and other resource use on the continent. The approach of the review is interpretive, and hinges on answering three questions, concerning the *what*, *why*, and *how* of GHP and its land consequences in Africa. The review is based on 41 studies identified from Google Scholar, and sources identified via snowballed recommendations from experts. The GHP implications identified relate to land and water use, mining-related land stress, and environmental, ecological, and land-related socioeconomic consequences. The paper concludes that GHP may not foster the global energy transition, as is being opined by many renewable energy enthusiasts but, rather, could help foster this transition as part of a greener energy mix. It notes that African countries that have the potential for GHP require the institutionalization of, or a change in, their existing approaches to land-related energy governance systems, in order to achieve success.

Keywords: Africa; green hydrogen; green hydrogen production; land; land administration; land management; land policy; land use; renewables; renewable energy

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1. Introduction

Despite its abundant resources, Africa still faces daunting energy-related challenges. More than 640 million Africans have no access to electricity as a source of energy. This places the electricity access rate on the continent at just over 40 percent—the lowest in the world [1]. The per capita consumption of electricity in sub-Saharan Africa (excluding South Africa) stands at just 180 kWh, compared to 13,000 kWh per capita in the US and 6500 kWh in Europe [2]. Moreover, renewables remain at an early stage of development, accounting for only 20 percent of the African power mix (consisting of 15 percent hydropower, and 5 percent from other renewable energy sources) [3]. Climate-friendly solutions, particularly renewable energy development and green industrialization, are being promoted to solve these energy limitations on the continent [4].

Elsewhere around the world (especially in economically advanced countries), efficient energy is in high demand, to enable easier access, and reduce the impediments that hinder sustainability in the growth of natural resources [5]. However, one of the greatest motivators behind the search for more efficient energy resources is the issue of climate change [6]. This is because, with the increasing global population and rising industrialization, there is also an increasing hunger for energy. Climate change matters aside, the need for efficient energy in Europe has reached unprecedented levels, especially due to the diplomatic and physical war (in relation to Ukraine) crises that Europe is facing with Russia [7]. More than half of humanity's energy comes from fossil fuels extracted from the Earth's crust and, since commercial oil drilling began in the 1850s, the world has used "135 billion tons of crude oil to drive our cars, fuel our power stations and heat our homes" [8]. "The unceasing energy demand in the world market and the global warming problem coupled with the increase in energy price have subsequently drawn attention to the necessity of renewable energy (RE) resources" [9] (p. 3873). Based on the recommendations of the Paris Agreement, carbon emissions must be cut, to improve the climate change situation globally [10].

Hydrogen occurs on Earth naturally (referred to as natural hydrogen) through various natural processes, but this is rare. It has potential as a source of clean energy, because the only input needed to release this energy is oxygen, and the only output is water [9]. However, to use it as a source of clean energy, it must be in its gaseous state (H_2) and, as this is rare naturally, it must be extracted from other materials, such as natural gas (primarily methane or CH_4), fossil fuels, minerals, and water (H_2O) [11]. This means, as an energy source, hydrogen produces zero greenhouse gas (GHG) emissions. Its combustion does not produce any substances that are harmful to the environment or the climate [7]. However, be used as a source of clean energy, it must be in its natural state. Hence, it must be extracted from another material, such as methane and water. The molecular formula of hydrogen, H_2, indicates that it comprises two atoms, with each of the atoms consisting of a single proton and electron.

Although the gas is qualified with colors (such as blue and green in the scientific literature), it is not actually black, blue, brown, green, or any other color associated with it in the literature. It is the different processes of producing hydrogen that lead to its association with colors. For instance, there are mentions of grey, brown, black, yellow, purple, turquoise, white, and pink hydrogen in the contemporary literature [12,13]. To ensure that references to all these colors do not distract from the focus of this study, it is important to note that the two main colors associated with hydrogen are green and blue [13]. On one hand, hydrogen is associated with green (as in green hydrogen) when it is extracted using a method that does not produce GHG emissions [7,8]. When associated with green, it is because its production is sustainable and environmentally friendly. On the other hand, it is associated with blue (as in blue hydrogen) when produced through a steam-reforming process (that is, using steam to separate hydrogen from natural gas) [10]. This process is considered blue because it produces GHGs, but it is possible to use carbon capture and storage technologies to capture and store the emissions [11].

As part of a worldwide effort to reduce carbon emissions, to reduce global warming, which has negative impacts on the global climate, many countries have embraced green hydrogen production (GHP) as a potential source of more efficient energy production [10]. GHP does not emit polluting gases, either during combustion or during production, and its storage is easy, and allows for its use for other purposes, including its use at times later than immediately after its production [12,13]. The countries from the global North are keen to embrace it as a key part of their future energy mix, while those in the global South view it as part of their future energy exports. For instance, "Germany's 'Energiewende' (energy transition)—the planned transition to a nuclear-free and low-carbon energy economy" requires the country to search for alternative sources of more efficient energy [6] (p. 2). It is not surprising that countries such as Germany (and all countries of the so-called developed world) are in a radical search for more efficient energy sources. However, hydrogen is not a new energy vector. It has a long history of use in the metal, steel, glass, electronics, food, and medical industries [12]. Most of these hydrogen-dependent production processes rely on the extraction of hydrogen from fossil fuel sources, leading to high carbon emissions (grey hydrogen) [13]. However, as the global pursuit of carbon neutrality and energy transition intensifies, the production of green hydrogen is dominating the discourse as a reliable potential catalyst for the decarbonization of both easy- and hard-to-abate sectors of the economy. In the whole discourse, the potential impact and consequences of operationalizing green hydrogen on the environment, especially the land, are being ignored.

The objective of this review paper is to explore the land perspective of the GHP discourse, with a focus on Africa. We argue that the much-advocated switch to, or embracing of, GHP in Africa will have land tenure (including land use) consequences, because most African countries are land-resource-dependent. The following sections of the paper are based on the structure of our arguments. In the next section (i.e., Section 2), we present the method for our interpretative or interpretive review. In brief, this is then followed by the emerging outputs from the review, which are presented in Sections 3–5. In Section 3, we provide an understanding of what green hydrogen entails, and justifications as to why Africa is a potential hub for GHP. Next, we present scenarios of how African countries are readying themselves to embrace GHP (Section 4). This is followed by our analytical review of the potential GHP consequences in Africa, from a land perspective (Section 5). Finally (Section 6), we conclude by proffering the scenarios necessary for ensuring that the identified consequences are controlled. Our recommendations could be useful for policymaking and the implementation of GHP initiatives in Africa.

2. Methodology

An interpretative review has been employed for this study, "to uncover meaningful patterns that describe" the phenomenon of GHP and its consequence on land tenure [14] (p. 1). By adopting an interpretive literature review, this study puts the focus on interpreting "what other scholars have written" about GHP, "to put them into specific perspectives" in an African context [15] (p. 5). Of note regarding our use of this method is that it adopts typical steps used in systematic reviews, following a qualitative communicative inquiry. In adopting this approach, it was important to clearly delineate how the literature data were sourced, but we did not seek to draw conclusions from all the relevant sources, or to identify what they suggest, as in a critical traditional literature or synthesis [16,17]. This is why we refer to our general approach as interpretative or interpretive.

2.1. Approach to the Review

Our approach was to seek out the qualitative information relevant to interpreting GHP and its land tenure consequences in Africa. Hence, interpreting the literature information in the context of land tenure consequences of GHP was the objective, rather than critiquing the views on the subject. The study hinged on answering three main questions: (1) What is GHP, and why is Africa a hub of interest for the European search for green energy? (2) How are African countries getting ready for GHP? (3) What are the potential and consequences of GHP in the context of land tenure in Africa? To answer these questions, we identified relevant studies about GHP (in general, and in Africa), and conducted a selection from the identified studies. The general process adopted in the research is described in Figure 1.

The process comprised four steps, sequentially involving *identifying the literature search sources*, *setting the search terms*, *defining the criteria*, and *extracting and synthesising data*. The application of these steps in the study is explained in Figure 1, and in the text below.

Identifying the literature search sources: This involved identifying Google Scholar as a source, and considering expert recommendations of literature sources. It led to searching for academic literature in Google Scholar, and a mix of grey and academic literature which resulted from recommendations from experts involved in GHP and land tenure studies.

Setting the search terms: this involved the delimitation of the search terms. To source literature within this period, we conducted a semi-systematic search in *Google Scholar* from 11 to 29 May 2023. *Google Scholar* was preferred for this research because, being a web search engine, it indexes scholarly literature, such as peer-reviewed journals, academic books, and conference papers, from multiple online sources. It presents a broad way to find literature (especially peer-reviewed literature) across various other databases. To access the relevant literature, a combination of search terms (or keywords) related to *land*, *land* *use*, *green hydrogen*, *GHP*, *green hydrogen potential* (in the context of *Africa*) was used (refer to Table 1).

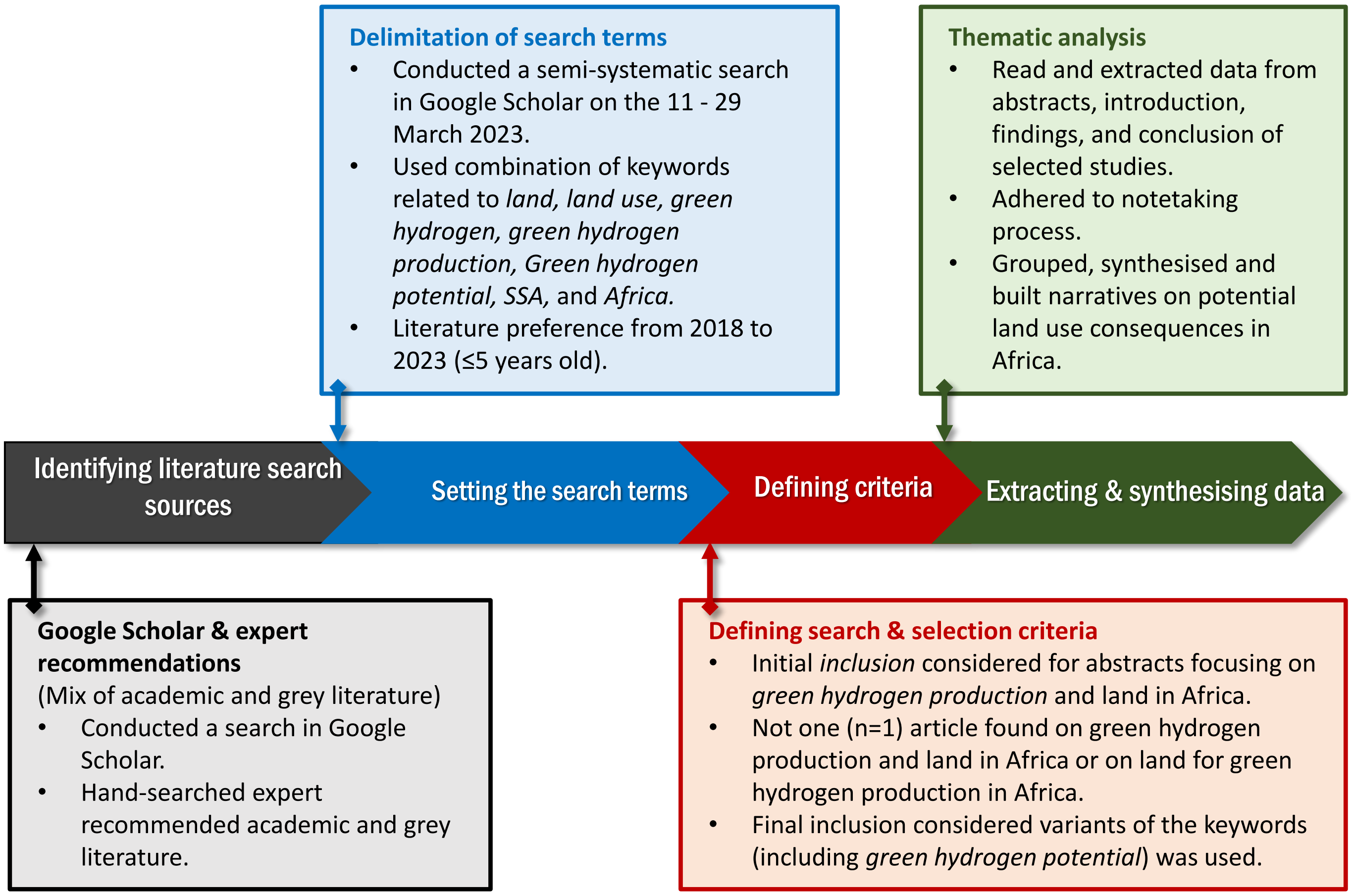

Figure 1. The specific steps adopted in the interpretative literature review.

Table 1. The combination of search terms or keywords used in the literature search.

Subject Focus of the Search *	Search Terms or Keywords
Green hydrogen production (GHP)	Hydrogen energy in Africa, green hydrogen production in Africa, green hydrogen production, GHP in Africa, green hydrogen production in Africa
Land tenure and energy demand in Africa	Status of energy in Africa, land for renewable energy in Africa, land tenure in African, land tenure consequences in Africa.
Land use and energy in Africa	Africa and land use, state of land use in Africa, energy use in Africa, GHP as new energy source in Africa.
Green hydrogen potential in Africa	Green hydrogen in Africa, energy demand in Africa, renewable potential in Africa

* The subject focus of the searches comprises terms, phrases, and expressions that probe the three main questions earlier identified for investigation in the study.

Defining the search and selection criteria: our initial *inclusion* considered abstracts focusing on *green hydrogen production and land in Africa*. In this regard, only one (n = 1) article was found specifically on *GHP and land in Africa* or *on land for GHP in Africa*. This is a general confirmation that, despite several speculative works on *GHP* in some African countries, there is still a big gap in research specifically focusing *on GHP and land in Africa*. Our final inclusion considered variants of the keywords, such as green *hydrogen infrastructure*, *GHP costs to Africa*, and *GHP potential*. Details on the literature search are presented in Figure 2.

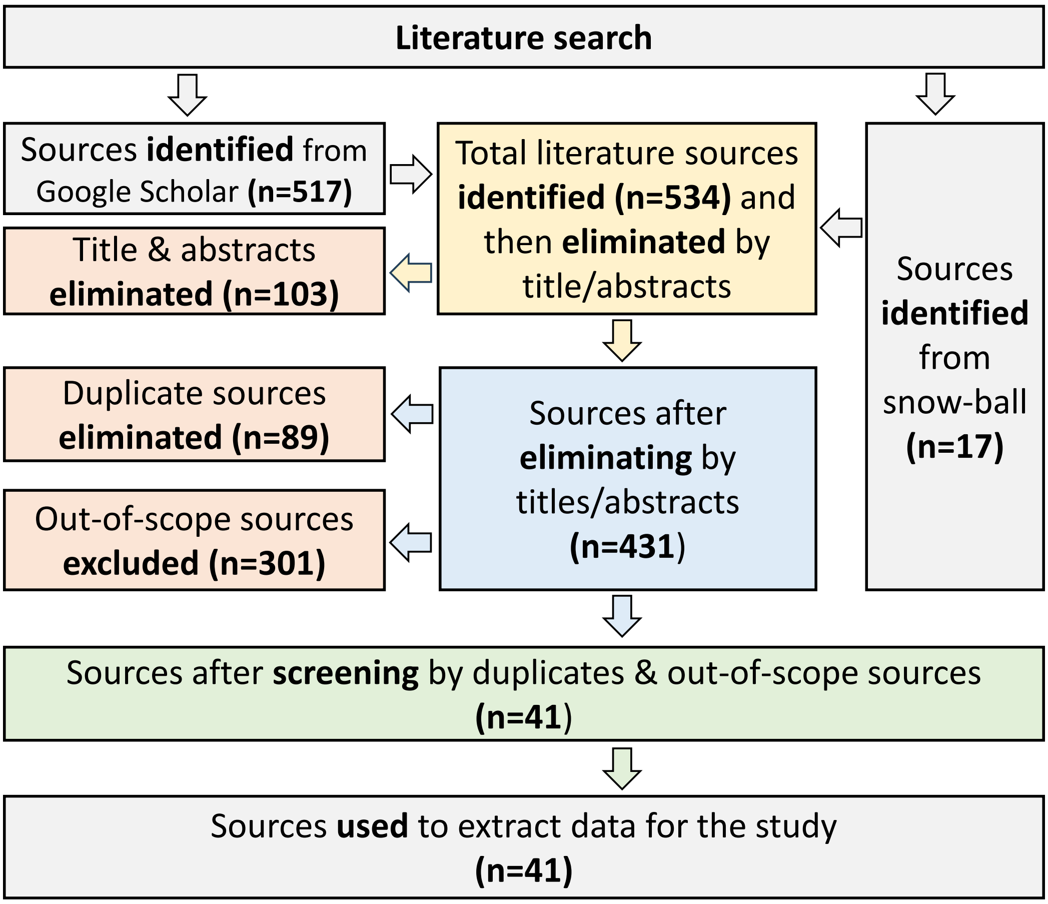

Figure 2. The flowchart of the literature search process.

The literature sources identified from Google Scholar numbered 517, and the sources identified via snowballed recommendations from experts numbered 17. This resulted in a total of n = 534 literature sources. These were screened based on unsuitable titles/abstracts, duplications, and out-of-scope sources. The screening process identified 103 unsuitable titles/contents, 89 duplications, and 301 out-of-scope contents. Screening by titles/abstract reduced the initial total of 534 identified documents to 431. However, further screening based on duplicate and out-of-scope contents reduced the total accepted literature resources to 41, which were then used for this study.

Extracting and synthesising data: the last step involved a thematic analysis of the selected literature. This involved reading and extracting data from the abstract, introduction, findings, and conclusion of each selected study. In this regard, we adhered to McMullin's [18] notetaking process, then we grouped, synthesised, and built narratives around the three key questions under investigation, particularly focusing on the consequences of GHP on land tenure in Africa. The following succeeding sections of this paper present an interpretation of the studies, within the context of the three questions explored.

2.2. The General Characteristics of the Reviewed Literature

The preferred literature period used for the study was from 2018 to March 2023 (≤5 years old). A six-year period was chosen because we found, during the scoping process, that most of the literature on GHP in Africa was published in the last 3 years (2020–2023); however, we chose to extend the review backwards by 2 years (i.e., 2018–2023), to capture the few publications that might have been published earlier. In doing this, we used publications within a period of 5–6 years. As this study adopts an interpretive approach, rather than a typical scoping study or systematic review [19], the names of the journals and their methods or emergent theories were not considered relevant, as they do not lend credence to the output produced. Furthermore, we focused on literature sources focusing on narratives around GHP (and, where available, projects) in Africa. This posed limitations to this study, as most of the conventional literature surveyed comprised accounts of official development assistance and foreign direct investment initiatives in countries for which information has been published in English. Our use of an interpretive review also meant that we focused on being descriptive and uncritical. However, it is necessary to identify the publications via the author identities, as well as the focal subjects (or the research gap addressed) that formed the subjects of the review (Table 2).

Table 2. Table of the publications from which the interpretations were derived.

Aspects of the Research Questions *	Authors and Year	Subject and Countries or Regions
What is GHP, and why is Africa a hub of interest for the European search for green energy?	AbouSeada & Hatem (2022) [9].	Prospects of green hydrogen in Africa.
	Bhagwat & Olczak (2020) [10].	Green hydrogen energy transition in Africa and Europe.
	Dawood et al. (2020) [20].	Overview of GHP (non-geographical).
	Sayed (2021) [21].	A critical review on the environmental impacts of renewable energy systems and mitigation strategies: wind, hydro, biomass, and geothermal (non-geographical).
	Nazir et al. (2019) [22].	A review of the environmental impact and pollution-related challenges of renewable wind energy paradigm (non-geographical).
	Van Wijk & Wouters (2021) [23].	Hydrogen as the emerging bridge between Africa and Europe.
	Mneimneh et al. (2023) [24].	A roadmap for achieving sustainable development via green hydrogen (non-geographical).
	Hosseini & Butler (2020) [25].	The development and challenges in hydrogen-powered vehicles (non-geographical).
	IEA (2019) [12].	The future of hydrogen-based energy production (non-geographical).
	Østergaard et al. (2020) [26].	Sustainable development using renewable energy technology (non-geographical).
	Midilli (2022) [27].	On hydrogen and hydrogen energy strategies (non-geographical).
	Sadik-Zada (2021) [28].	The political economy of green hydrogen rollout (non-geographical).
	Moritz et al. (2023) [29].	Estimation of global production and supply costs for green hydrogen and hydrogen-based green energy commodities.
	IRENA (2019) [13].	Hydrogen in the context of renewable energy sources.
How are African countries getting ready for GHP?	Abeygunawardane et al. (2022) [30].	Transnational land-based investing in Southern and Eastern Africa.
	Aliyu et al. (2018) [31].	A review of renewable energy development in Africa focusing on South Africa, Egypt, and Nigeria.
	Imasiku et al. (2021) [32].	A policy review of green hydrogen economy in Southern Africa.
	Mukelabai et al. (2022) [33].	Hydrogen in the context of South Africa's infrastructure.
	Li et al. (2023) [34].	Latest approaches on green hydrogen as a potential source of renewable energy toward sustainable energy (non-geographical).

Table 2. *Cont.*

Aspects of the Research Questions *	Authors and Year	Subject and Countries or Regions
	Ayodele et al. (2019) [35].	The economic viability of green hydrogen production via water electrolysis using wind energy resources in South Africa.
	Bhandari (2022) [36].	Green hydrogen production potential in West Africa: the case of Niger.
	Seada & Hatem (2022) [37].	The prospects of green hydrogen production potential in Africa.
	Müller et al. (2023) [38].	Green hydrogen production and use in low-and middle-income countries, focusing on Kenya.
	Creamer (2021) [39].	Experience of KfW in the EUR 200 million South Africa green hydrogen project.
	Terrapon-Pfaff et al. (2019) [40].	Assessment results for the NOORO I power plant in Morocco.
What are the potential and consequences of GHP in the context of land tenure in Africa?	Adow et al. (2022) [41].	Civil society perspectives on GHP (non-geographical).
	Akinyemi et al. (2022) [42].	Africa-wide assessment in gained and displaced agricultural lands.
	Vallejos-Romero et al. (2023) [43].	Energy transition for a more just and sustainable hydrogen transition in West Africa.
	Asiedu et al. (2022) [44].	Finance, poverty–income inequality, energy consumption, and the CO_2 emissions nexus in Africa.
	Dabar et al. (2022) [45].	Wind resource assessment and techno-economic analysis of wind energy and green hydrogen production in the Republic of Djibouti.
	Tonelli et al. (2023) [46].	The global land and water limits to electrolytic hydrogen production using wind and solar resources.
	Chigbu (2022) [47].	Green hydrogen production wand land implications in Namibia.
	Panchenko et al. (2023) [48].	Prospects to produce green hydrogen: review of countries with a high potential (non-geographical).
	Hassan et al. (2023) [11].	Green hydrogen resources routes, processes, and evaluation (non-geographical).
	Scita et al. (2020) [49].	Analysis of the technical and geopolitical implications of the future hydrogen economy (non-geographical).
	Chigbu et al. (2019) [14].	Land use planning and tenure security in Ethiopia.
	Kitegi et al. (2022) [50].	The potential for green hydrogen production from biomass, solar, and wind in Togo.
	Sarker et al. (2023) [51].	The potential and economic viability of green hydrogen production via water electrolysis using wind energy resources in South Africa.
	Bhandari (2022) [52].	Green hydrogen production potential in West Africa: the case of Niger.
	Ballo et al. (2022) [53].	A review of GHP in West African countries.
	Holmatov et al. (2019) [54].	The land, water, and carbon footprints of circular bioenergy production systems (non-geographical).

* The focal point of enquiry was directly on the research questions.

The list of publications (n = 41) interpreted to elucidate the consequences of GHP on land in Africa is diverse. Their subjects and geographical focus are also diverse. Rather than probe the subject based on the research gaps addressed by individual publications, we focused on the literature that either addresses a specific research question directly or indirectly. This way, it was possible to interpret the literature within the context of the subject of any study. In the course of narration and argumentation—which were the tools employed to interpret the issues found within the context of land tenure—various other literature has been cited, to provide evidence, and enable readers to learn more about the generic and specific scenarios embedded in this subject.

3. Toward Understanding GHP: Issues Emerging from the Literature

3.1. Green Hydrogen Production in a Nutshell

Green hydrogen is considered a critical enabler of the global transition to sustainable energy (as well as net zero emissions) economies [20]. "The technology for generating hydrogen from water is called hydrogen production and if this process is successfully done using electricity obtained from renewable resources, it will produce energy without emitting carbon dioxide". It is then called green hydrogen production [47] (p. 11). Green hydrogen is produced via the splitting of water molecules into their component parts using renewable electricity. This is why it is pursued as a potential replacement for fossil fuels in chemical and fuel production, and as a means of storing and transporting renewable electricity. Green hydrogen can be used for powering vehicles and non-electrified trains, and to allow the earning of extra revenue through their export.

Africa is considered a suitable place to produce green hydrogen, as it is rich with abundant energy sources, which have a high renewable energy potential, consisting of mainly wind and solar projects, and a miscellaneous wealth of natural resources [9]. This means that the continent would be capable of producing large amounts of extremely cost-efficient renewable energy, which could then be exported to Europe, due to surplus production [9]. Despite the many factors available in the literature [30,32], we consider two reasons why Africa has an advantage as a hub for GHP. Firstly, the continent has abundant natural resources with renewable potential. Secondly, it is still at an infancy stage of technological development. Hence, innovative technologies may be easily adoptable across its sectors.

3.2. Africa's Abundant Natural Resources Make It a Potential Hub for GHP

Although these factors are not exclusive to the continent, Africa has abundant resources in renewable energy, coupled with its low population density and large-scale availability of non-arable land. Several African countries, especially around the Northern and Southern Tropics, have excellent solar (average daily potential of 4.49 kWh/kWp) and wind resources (180,000 TWh per year) for GHP [55,56]. Africa has an installed hydropower capacity of over 37 gigawatts (GW), and the highest untapped potential across the world [56]. The continent has so far only utilized about 11% of its renewable energy resource capacity [57]. Ethiopia and the Democratic Republic of the Congo (DRC) have the largest hydropower potentials, with the continent's two largest rivers (the Nile and the Congo) flowing between their borders. Countries such as Nigeria (203.16 trillion cubic feet), Algeria (159 trillion cubic feet), and Angola (343 million cubic feet) have some of the largest gas reserves in the world for producing blue hydrogen [58]. When considering the availability of extensive non-arable land and the proximity to ports, it is hard to miss the North African countries, as well as Namibia, South Africa, Angola, and Botswana.

Furthermore, several other African countries, such as South Africa and the Democratic Republic of the Congo, have an abundance of mineral resources essential for producing solar panels, wind turbines, electric motors, batteries, electrolysers, and biological carbon (biomass) [59]. South Africa is endowed with around 95% of the worldwide supply of platinum group metals (PGMs) [60]. PGM catalysts are used to manufacture PEM electrolysers that produce hydrogen, and are used in fuel cells, forming an important flexible source of green hydrogen (although alkaline and SOE electrolysers are also making their way onto the market). Hence, with the current PEM electrolyser technologies, South Africa would have an advantage in the growing green hydrogen market.

3.3. GHP May Create Opportunities for New Technology Adoption across Sectors in Africa

Unlike Europe and other parts of the world, many African nations are not trapped in existing technology industries, and so large-scale devaluations and exit risks pose less of an issue to clean development in the continent. As a result, there are opportunities for new technology adoption for green hydrogen integration and developments in the energy, industrial, and transport sectors. Several countries on the continent are carrying out feasibility studies for such an adoption of new technology. Sasol (South Africa's chemical and energy giant) signed a memorandum of agreement (MOA) with the Northern Cape and Gauteng province governments, as well as with the country's Industrial Development Corporation (IDC), to conduct feasibility study for landmark green hydrogen projects in mobility and aviation. In Egypt, the Fertiglobe and the Egyptian Sovereign Fund are working together with the Norwegian Scatec to build a 50–100 MW green hydrogen plant in Ain Sokhna, to produce green ammonia. The plant will be Egypt's first attempt to establish itself as a regional green hydrogen hub.

In the electricity sector, green hydrogen has the potential to serve as a storage solution for mitigating the intermittence of renewable energy systems, overcoming the mismatch between the production and load, and providing more permanent energy access. Although green hydrogen is a promising method suitable for long-term storage, battery systems, however, remain the most widely used, due to their better self-sufficiency ratio and cost performance, mostly due to the prohibitive cost of electrolysers. Some scientists have, in this regard, suggested a hybrid battery and hydrogen storage system as a solution that can harness the advantages of both battery and hydrogen storage [29,44,51,61]. In Uganda, a solar-hydrogen-powered mini-grid has already been successfully deployed to power 3000 rural households and businesses in Kyenjojo, becoming the world's first project with such technology. The solar power plant (Sunfold) is backed up by an on-site hydrogen production and storage system (Storager), built in a standard 20 ft container. A Belgian renewable energy company, named Tiger Power, developed the project in cooperation with the Ugandan government. There are further opportunities for such hybrid solutions across the continent, with several new renewable energy projects, such as the 6450 MW Grand Ethiopian Renaissance Dam in Ethiopia, the 580 MW Noor Ouarzazate Solar Complex in Morocco, the 175 MW De Aar Solar Power in South Africa, the 50 MW Garissa PV Solar Power in Kenya, and the 1.8 GW Benban Solar PV power station in Egypt, which is currently in its final stages of construction. Furthermore, green ammonia can be directly used to power thermal power plants in African countries with existing plants, such as in Kenya.

4. How Are African Countries Readying for GHP?

4.1. New GHP National Initiatives, Strategies, and Plans

Several national initiatives, strategies, and plans are being put in place as a wholistic measure to drive hydrogen developments across the continent, particularly in South Africa, Morocco, Namibia, and Egypt, with upcoming plans in Nigeria and other countries. Another African country actively pursuing GHP ambitions is Mauritania [31,35,40]. Through strong strategies and planning, African countries stand to benefit economically, environmentally, and socially from the rapid development of new hydrogen technology. South Africa established the National Hydrogen Strategy (HySA), a hub that develops and guides innovation along the value chain of hydrogen and fuel cell technologies, with a vision of bringing about wealth, jobs, and IPR creation through the initiation of new high-technology industries based on minerals found on South African soil, especially platinum group metals (PGMs). The country's SASOL leads active green hydrogen supply feasibility studies. South Africa is also currently carrying out a feasibility study for its Hydrogen Valley, in partnership with Anglo American Platinum, the clean energy solutions provider Bambili Energy, and the energy and services company ENGIE. The hydrogen valley is expected to serve as an industrial cluster, bringing various hydrogen applications in the country together, to form an integrated hydrogen ecosystem, with nine green hydrogen and ammonia projects across the mobility, industrial, and construction sectors. It is planned that the Valley will start near Mokopane in Limpopo, where platinum group metals (PGMs) are mined, extending through the industrial and commercial corridor to Johannesburg, and leading finally to Durban.

In Morocco, plans also underway to develop green-hydrogen-powered ammonia projects, as the cornerstone of the country's hydrogen strategy, and to establish Morocco as a major exporter of ammonia to the EU and other international markets. Namibia, as one of the countries with the highest potentials for GHP on the continent, plans to release its National Hydrogen Plan in November 2021. The strategy includes the construction of desalination plants to provide the water for the giant electrolysers needed to produce enormous quantities of green H_2 for export. Nigeria has also expressed interest in developing hydrogen as an addition to its energy mix, and is exploring the potential of green and blue hydrogen exports. In May 2023, the Angolan government hosted the First Southern-African–European Green Hydrogen Forum, which provided a platform for stakeholders within the region to exchange perspectives on the best way to explore GHP opportunities.

4.2. GHP International Investments and Partnerships

Green hydrogen has increasingly garnered interest across the African continent, with several bilateral government-level talks, high-level conferences and forums, and the formation of new alliances. One of these alliances is the African Hydrogen Partnership Trade Association (AHP), which aims to foster clean hydrogen development on the continent by aligning actors in the government, industries, and communities in the pursuit and development of clean hydrogen and its related technologies, as well in the promotion of development in the clean energy and mobility sectors [62]. Several intra-continental hydrogen research hubs have also emerged within already-existing regional centres, including the West African Service Center on Climate Change and Adapted Land Use (WASCAL) in Ghana, and the Southern Africa Service Center for Climate Change and Adapted Land Management (SASSCAL) in Namibia. WASCAL recently launched regional training on Energy and Green Hydrogen, with funding from the German Federal Ministry of Education and Research (BMBF), and has awarded full scholarships in the International Master's Programme in Energy and Green Hydrogen to 60 students from all 15 West African countries.

With the significant green hydrogen potential of the continent, international players have placed a focus on African partnerships to fast-track green hydrogen development. With its National Hydrogen Strategy 2020 including plans to drive international partnerships with Africa, Germany is currently a front-runner in developing Africa's green hydrogen economy. Several intra- and inter-continental cooperation and partnerships, such as the H2Atlas and the H2-Diplo research project cooperation between Germany and Western and Southern African countries, have emerged as a result of these pursuits. The Hydrogen Potential Atlas (H2Atlas-Africa) project is a joint initiative of the German Federal Ministry of Education and Research and sub-Saharan African partners that aims to produce 165,000 TWh of green hydrogen annually in West Africa, across several projects [63]. The analysis of these states is intended to serve as a basis for future hydrogen partnerships, with 31 countries already analysed, including Nigeria, Niger, Mali, and Senegal. The project "Global Hydrogen Diplomacy (H2-Diplo)—Hydrogen Diplomacy with Russia, Saudi Arabia, Nigeria and Angola" seeks to support the Federal Foreign Office and the German embassies in the energy foreign policy dialogue with exporting countries of fossil fuels regarding CO_2-neutral hydrogen. The aim is to show these countries ways in which they can transform their energy and fuel economy in the long-term, using green hydrogen and its derivatives, and to promote international understanding on a coherent global governance and trade regime for CO_2-neutral hydrogen.

Furthermore, with its long value chain, an African hydrogen economy offers significant potential for international investment and job creation, particularly in renewable energy and fertilizer production sectors, in the region. For example, the German Development Bank (KfW) has initiated a program of up to EUR 200 million on behalf of the German government, to support the development of green hydrogen projects in South Africa, and has issued a formal request for information to identify project opportunities for the production, consumption, transportation, or storage of green hydrogen and its derivatives in South Africa [39]. These projects could involve the production, transportation, export, and/or storage of green hydrogen and green hydrogen products, as well as projects in existing materials and chemical value chains that support a transition from fossil-based processes to those based on green hydrogen [64]. The German Federal Ministry of Environment, Nature Conservation and Nuclear Safety (BMU) also launched the "PtX Pathway Project". This supports the development of sustainable hydrogen/PtX markets as a building block for the energy transition in South Africa.

In addition, Germany and Morocco have a binational research and development cooperation to develop and promote hydrogen technology, and the "Power-to-X" sector, especially to produce green ammonia. The Fraunhofer IGB has already carried out studies in this field, and is working with Moroccan research and industry partners in the "HEVO Green Ammonia" project. IRENA and Morocco's Ministry of Energy, Mines and Environment have also signed a strategic partnership for green hydrogen studies, and to jointly explore policy instruments to engage the private sector at a national level in the green hydrogen economy. Egypt, as one of the major economies of the continent, is also actively looking into hydrogen potential through their cooperation with the Norwegian Scatec to invest in GHP for making ammonia, and their partnership with ENI and Siemens to help explore their green and blue hydrogen production potential, and to develop their hydrogen export potential.

In Namibia, Germany recently committed USD 45.7 million to the National Green Hydrogen Development of Namibia in 2021 [65]. With this commitment, Germany plans to first carry out a feasibility study, followed up by German–Namibian pilot projects and the training of local specialists for hydrogen [65]. The Democratic Republic of the Congo (DRC) and Germany are also planning an energy partnership that would see the central African country provide a hydropower capacity at the Inga dam III, to produce green hydrogen for domestic use and export. The Inga dam III project, with a total potential capacity of 44 GW, was contracted to BHP Billiton in 2009, in a public–private partnership to develop the plant with a generating capacity of 2500 MW, with an estimated cost of USD 3.5 billion [59]. However, due to multiple challenges relating to economic viability and policy inconsistencies, BHP withdrew from the hydro project in 2012 [59].

5. The Land Issues and Potential GHP Consequences in Africa

5.1. On The Land Issues in Africa: The Tenure Security and Land Use Dimension

Given the increasing scarcity of arable land in Africa, the establishment of land tenure security has become one of the most essential needs of the people in these communities. Land tenure security (or, simply, tenure security) implies the "rights individuals and groups have to effective protection by the state against forced eviction. Under international law, this entails permanent or temporary removal against the will of persons, families and/or communities from the homes and/or land that they occupy, without the provision of, and access to, appropriate forms of legal or other protection" [66] (p. 4); [67]. In Africa, tenure security remains one of the big development challenges. It is dictating the economic and social power balance in favour of men [68,69]. It dictates the performance level of peoples' participation in the development process [70]. Tenure security can exist in the context of different types of ownership and rights (including restrictions, benefits and privileges, etc.) being protected by law or social norms against abuse, denial, and prohibition by others, whether these are governments, powerful individuals, or groups [71]. Tenure security is an essential driver of sustainable development [72]. Hence, it must be established, to achieve the efficient allocation of land among farm households, and to promote investment in land development [73]. The lack of reliable and secure land tenure in various parts of Africa is why there are incessant occurrences of land grabbing, land conflicts, and unequal growth and development within their various national economies [74,75]. It is also the reason why there is insecurity in property investment, as well as a low level of foreign direct investments on the continent [30,76]. Tenure security is a pre-condition for equitable and sustainable land use [14]. Land use embraces the economic, cultural, social, and environmental activities that happen on land. In Africa, land use occurs because of different activities on land. These include agricultural, recreational, transport, residential, commercial, and cultural (including religious) activities that depend on land. Tenure security dictates the state of land use because, when tenure is secure, it leads to better decisions regarding the choices of land use and associated land activities (that is, development). Furthermore, it is the influence of land uses on development outcomes (at the national, regional, and local levels) that necessitates the need for appropriate decisions and activities to guide the allocation and use of land for development purposes.

Land use has been considered a local development issue that has social, economic, and environmental dimensions. It is of continental (as well as global) importance regarding development activities in Africa. With Africa-wide changes to waterways, the need is driving airways, farmlands, and forestlands to provide food, fiber, water, and shelter to more than one billion people [77,78]. Over the past two decades, pasturelands, croplands, plantations, and urban areas have expanded in Africa [42,79,80]. This is further exacerbated by large increases in the demand for energy and water within, and from outside, the continent [44]. These changes in land use have enabled governments (both external and internal), groups (including local communities, corporate entities, and multinational companies), and individuals to appropriate land resources on the continent [81,82]. This rush for land resources could "potentially undermine the capacity of ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and ameliorate infectious diseases" [83] (p. 570).

5.2. The Potential Land-Related GHP Consequences in Africa

With Africa currently facing these land use and tenure security challenges, it is necessary to assess the potential consequences of GHP on the continent. The underlying questions are, what are the potential consequences of GHP, and how would they impact the already-challenging land situations on the continent? Not much is being said about this. Not much research is being conducted on it, either. Hence, our interest in presenting our position in this review paper. There is no way that the GHP, with its looming need for infrastructure (including the siting of GHP plants) would not require space (including land use and water use) [77]. African countries would require infrastructure for the storage, dispensing, transportation, and delivery of GHP products. This would mean an increase in land use and water use. As a water supply and electricity are essential for GHP, this means that GHP, as an essential demand on water use, could lead to new forms of water resource management in these countries. The engagement of communities in discussions over GHP in Africa does not appear to be happening. Without community participation regarding the sites of GHP, there would be a lack of appropriate environmental assessments to detect the environmental consequences of GHP. Then, there is the issue of the lack of adequate social impact evaluations to detect social consequences. Put simply, the potential consequences of GHP could create a challenging land-situation environment in Africa. We argue that GHP will have land use, water use, mineral mining, environmental, and ecological, as well as land-based socioeconomic consequences.

5.2.1. Potential Land Use Consequences

GHP generally requires large amounts of land resources both for the development of the electrolysis infrastructure, and for the construction of solar and wind energy infrastructure for powering the electrolysis process [84]. These lands are, however, in competition with other land uses for agriculture, bio-diversification, and housing, especially in developing countries, of which many are in Africa [85]. The construction of these large plants often leads to deforestation, the contamination of soils, and enhanced erosion and ecological imbalances [22,86]. Clearing existing vegetation to place solar or biofuel energy production infrastructure could substantially decrease and, in some cases, reverse the climate benefits that are being pursued [54,87]. In the same vein, the acquisition and degradation of fertile lands for GHP could lead to the exacerbation of the existing food insecurity, especially in countries with scarce food production and availability [85,88–90]. Natural habitats and biodiversity can also be adversely affected, particularly in regions with high biodiversity, such as Kenya and Tanzania [84,91].

Past experiences with the development of such renewable energy projects in Africa also show the non-active engagement or exclusion of important stakeholders in the construction process, especially project host communities, which has often led to conflicts, forced resettlement, and human rights abuse [92]. All of these processes could further be exacerbated in the pursuit and development of green hydrogen on the African continent.

5.2.2. Potential Water Use Consequences

Another valuable resource for GHP is freshwater, which is currently a scarce resource in many parts of Africa [93]. As GHP involves the splitting of freshwater into hydrogen and oxygen, ample freshwater resources are, therefore, a key input, not only in the electrolysis process, but also in the construction and maintenance of solar and wind energy plants. The freshwater consumption required to produce 1 kg of hydrogen is currently estimated to be 9.1 kg for electrolysis using solid oxide electrolyser cells (SOECs) [94,95], and from 18 to 25 kg for polymer electrolyte membrane (PEM) electrolysers [96–98]. In addition, the total volume of freshwater used in the upstream segment of PV module production, as well as for the cleaning and cooling of PV mirrors during operation, has been estimated as being from 3.7 to 5.2 tons for each KWp [61].

If not well planned and managed, the use of the scarce fresh water in electrolysis can further impoverish communities, and exacerbate insecurity and conflicts in the African continent's fragile states and regions. About 400 million people in sub-Saharan Africa already lack access to clean drinking water, with projections of further scarcity as global warming and climate change intensify [99]. For instance, those countries that have already been identified as climate change hotspots in Africa (such as Madagascar, South Africa, and Namibia, to mention a few) are already water stressed. The high water demand of GHP could exacerbate their current stressful water situations. The current water scarcity, especially in the arid parts of the African continent, impedes social and economic development, creates water competition and conflicts, and is linked to poverty, hunger, sickness, violence, and conflict-led migrations [100]. Cases of such destabilizing situations related to water scarcity include clashes between farmers and herders in the Horn of Africa, disputes over large dam projects in the Nile River Basin, and violence and unrest in the Lake Chad region. These cases show how the links between water and conflict become far more complex, diffused, and connected to other socio-economic threats, with far-reaching development consequences [93]. The desalination of non-freshwater bodies has been suggested as a means to address this challenge, but the dependence on freshwater availability of GHP will remain a sensitive issue in many parts of Africa, especially in arid areas [41]. The most-written-about process for GHP is desalination. However, desalination is a treatment process that can produce saline brine solutions that have the potential to be detrimental to the environment when not properly disposed of [46,50]. Even though desalination can serve as a solution to water scarcity in some places, it also has well-known impacts, including its high energy requirement, and the production of a toxic hypersaline effluent [37].

5.2.3. Potential Land Stress Due to Mining

GHP in Africa also entails a further increase in the demand for raw materials for the electrolysis technology, as well as for the renewable energy system technologies. This will put further stress on land use for the mining of rare minerals. Renewable energy technologies generally require more metals and minerals for their production, in comparison to fossil fuel technologies [101]. They require large amounts of steel, aluminium, and copper for their infrastructure, as well as many other metals, such as gallium, silver, cadmium, silicon, neodymium (or dysprosium), indium, and tellurium, for other components of the technologies, such as wind turbines, PV glasses and cells, and generators [101]. For the electrolysis technology, high amounts of minerals, such as platinum, iridium, palladium, zirconium, nickel, lanthanum, and yttrium, are required [12]. These metals are difficult to extract, purify, and handle, and the potential for leakage or emissions is significant. According to Tammaro et al. [102], the increase in PV development by 2050 might result in high volumes of harmful substances such as lead (30 tons annually) and cadmium (2.9 tons annually) being emitted into the environment.

As intensive mining for renewable energy technologies is expected to continue to rise in the coming decades, to meet the rising raw material demand, there are serious concerns about the consequences for the ongoing environmental protection and biodiversity conservation initiatives in the continent of Africa [21,103,104]. These can further be exacerbated by the current low levels of mineral recycling, with (for instance) only 1% of the current lithium demand recycled in Africa [105]. Excessive mining also increases the pressure and temperature of the Earth's surface, leading to an increase in incidences of earthquakes, especially in regions such as Southern Africa, where active mining is already ongoing [106].

5.2.4. Potential Environmental and Ecological Consequences

The development of renewable energy (RE) systems and electrolysis plants for GHP can also come with some environmental and ecological consequences in Africa. Ecological footprint indices, which monitor the environmental sustainability of projects, reveal that, despite reducing emissions, RE expansion presents several environmental risks, affecting biodiversity and polluting the atmosphere, particularly forest covers, water bodies, wildlife habitats, and bio-organisms [107,108]. Wind turbine blades affect the soaring range of birds, and their mortality due to collision, while machinery instruments (such as generators and cooling fans) cause noise pollution, and can generate electromagnetic interference [21,109,110]. Offshore wind plants could also interfere with benthic plants, and their high-power submarine cables and electromagnetic fields can negatively affect aquatic life [26]. Similarly, solar systems could also negatively impact vegetation and forest covers, and the potential release of fixed carbon into the atmosphere [111].

There are also consequences arising from hydropower, particularly the construction of large dams, the environmental consequences of which have been extensively documented in Africa and elsewhere over decades. For instance, the Grand Ethiopian Renaissance Dam in Ethiopia (despite its perceived opportunities) is a hugely controversial project, because of its environmental, agricultural, and geopolitical consequences. It poses a "serious risk for the downstream river basin, agricultural and historical sites, wildlife habitat and communities in the event of a catastrophic dam failure or breach" [112] (p. 341).

Other than the environmental impacts of RE systems, the electrolysis technology has been estimated to have a carbon footprint and global warming potential of 29,000 gCO_2eq./KgH2 [113]. Further, as green hydrogen is currently being considered for export from the African continent, carbon emissions and environmental depreciation can be caused in the process of storing and transporting hydrogen using ammonia, cargo ships, and pipelines [85,111]. Furthermore, scholars have raised concern over the safety of hydrogen as a highly inflammable and explosive gas, with the potential to result in major safety hazards if mismanaged [114,115].

5.2.5. Land-Based Socioeconomic Consequences

There are records of the potential socioeconomic benefits of renewable energy development, such as job creation, skill transfer, and the generation of tax income and foreign exchange, all of which have the potential to contribute to local value creation and socioeconomic development [10,49,115,116]. However, several renewable energy developments in the past have demonstrated that these associated advantages may not always accrue in local populations. Locally undesirable land uses; forced and unjust land acquisition and dispossession, relocations, and compensation processes; and interference with local landscapes, cultures, and social activities have all been linked to RE development in Africa and other parts of the world [40,92,117].

6. Conclusions

This review entails a qualitative interpretation of issues (in this case, GHP) presented in the various literature, not necessarily "to uncover meaningful patterns that describe a particular phenomenon" [118] (p. 1). It appears that most of the African countries identified as having the potential for GHP have shown interest in going ahead with investment. The question, as per our concern in this paper, is how they are going to do it. Considering that most of these countries are already behind in the use of other forms of renewable energy sources, GHP could help foster this transition as part of a greener energy mix. However, this will require their institutionalization of, or a change in, the existing approaches to energy governance in these countries, in ways that benefit citizens [119,120]. In this regard, a contemporary normative that comes to mind is "responsible"—a term that has gained attention in the land and natural resource management literature [121] (p. 190).

While GHP is being considered and pursued in the African continent, it is important to thoroughly consider its land resource sustainability dimension, and the above-discussed consequences. The energy–food–water nexus in GHP should be jointly studied by scientists, policy-makers, practitioners, and civil societies, to ensure that all economic, social, and environmental dimensions of GHP in the context are considered [41,122]. Formulating strategies and frameworks for GHP from holistic, socio-economic, and environmental assessments would ensure the deployment of green hydrogen technologies in a manner that reduces the pressure on the scarce land and water resources.

In addition, there should be proper planning, to ensure that the socio-economic and environmental consequences of GHP do not offset or outweigh its benefits. To ensure this, there must be a thorough cost–benefit analysis of several GHP pathways [104]. It should be ensured that the environmental pollution risks posed by the mining of critical minerals such as cobalt and nickel do not outweigh its benefits in GHP. It should also be ensured that the use of freshwater, and other land uses, for GHP do not exacerbate the current food and water scarcity on the continent. One way to ensure this is to apply the principle of additionality in GHP on the continent, whereby every pursuit or project in GHP should be an addition to socio-economic welfare and environmental benefits for the local communities and the country, and not a cost [41]. For instance, GHP could contribute to the desalination of water bodies, and the proliferation of its technologies could ensure the availability of fresh water for other sectors beyond GHP, such as agriculture.

Furthermore, the sustainability of GHP production, especially as regards land and natural resource use, depends on the extent of good governance and strong institutions on the continent. To ensure sustainability, security of supply, and attraction of investments, there must be political stability and respect for the rule of the law, to ensure that there are no widespread corruption, favoritism, or policy reversals [117]. The implementation of standards and certification systems through good governance will help to ensure that there is a uniform adherence to the sustainability of GHP [25,121]. Such standards will also help to ensure that certain hydrogen safety concerns are mitigated through clear operational rules of engagements [41,49]. Good governance and strong institutions will help to ensure social acceptance, monitoring, and distributional justice, through clear rules for distributing the risks and benefits, as well as frameworks for resolving the ensuing conflicts regarding land ownership and usage costs [123]. All relevant stakeholders, ranging from investors and policy-makers to the project host communities, should be actively involved in the planning, construction, monitoring, and evaluation stages of project development, to ensure complete and transparent information, fair and informed consents, and procedural and distributional justice in the pursuit of GHP on the continent [104,124].

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