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Is Africa ready for green hydrogen energy takeoff? – A multi-criteria analysis approach to the opportunities and barriers of hydrogen production on the continent

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HIGHLIGHTS

- This study identified the opportunities and barriers to hydrogen energy in Africa.
- The Best-Worst Method was used to prioritize the various identified factors.
- Availability of renewable energy resources on the continent was identified as the highest opportunity.
- Lack of the needed regulatory and legal framework was identified as the greatest barrier.

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ABSTRACT

Hydrogen is mostly seen as a potential universal fuel that can be used in place of fossil fuels. Africa has been identified as a potential key player in the production of green hydrogen not only for itself but also for other countries in Europe. There are however several factors that may either positively or negatively affect the development of green hydrogen on the continent. This study identified some opportunities and barriers to the production of green hydrogen in Africa and used the multi-criteria decision-making approach to prioritize them. The study identified the opportunity to export to EU market (20.90%), availability of RE resources (34.88%), youthful population (13.95%), Agenda 2063 (9.30%), and ammonia production (20.90%) as some of the opportunities available on the continent. The availability of RE resources was selected as the highest opportunity for the development of hydrogen energy in Africa. High cost of hydrogen (11.78%), dealing with the status-quo (8.82%), corruption in the energy sector (4.52%), land availability issues (7.06%), political instabilities and insecurity in certain parts of the continent (11.76%), lack of the needed skills and education (11.76%), limited supporting infrastructure and financing (15.38%), and lack of the needed regulatory and legal framework (28.95%) were identified as some of the barriers that could affect the development and use of hydrogen in Africa. The study recommends regional and country level policies and cooperation among the various blocs in Africa as an important tool to remove barriers that could hinder the deployment of hydrogen energy on the continent.

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1. Introduction

The world is currently finding more sustainable ways of meeting its energy needs, as such more countries are moving towards more environmentally friendly forms of energy generation. The linkages between energy consumption, economic growth, and carbon emissions is among the most researched topics in recent years due to the need to save the environment from destruction [1–3]. The consumption of energy by a country generally has a key impact on that country's economic development. This is because both developed and developing nations require energy for their industrial and socio-economic transformation. This results in an increase in the demand or consumption of energy globally leading to environmental challenges [4–6]. The need for more economic development in a sustainable way has become a topical issue of discussion among various stakeholders, international bodies, and governments around the world. Various governments across the world have instituted different policies, laws, and interventions to help promote the reduction of greenhouse gas emissions (GHG). However, GHG emissions may continue to see an upward trend since several developing economies are still striving towards becoming self-sufficient and may thus rely on traditional approaches adopted by the already developed economies in that regard [5,7].

Hydrogen energy is one of the several options available to the world in its quest for energy transition. It is one of the most promising fuel types in terms of sustainability. It can be used in the transport sector, industry and several other areas for the economic growth of a country [8]. Hydrogen can also serve as a seasonal bulk storage to counter the variability of solar and wind energies and has the potential to help decarbonize complex areas such as the chemical industry. Even though the production of hydrogen can be done in several ways, the production of hydrogen by the use of water in the form of water electrolysis using renewable sources of energy is the most preferred method due to its less carbon footprint [9–11]. Renewable energy resources at an area to a large extent determines the cost of energy produced and for that matter the cost of hydrogen production [12]. Since the levels of solar irradiation, wind speed and suitable locations for the development of large scale renewable energy varies across the world, stakeholders in the energy sector have been advocating for the trading of green hydrogen across borders [9]. A report by Ref. [13] indicate that if the world will meet its target of keeping global warming below the 1.5 °C as envisaged, then green hydrogen will be required to meet 7–24% of the world's energy needs by 2050.

Several researchers have assessed different aspects of hydrogen energy's environment, ranging from technical, economic, social and environment. Norouzi [14] analyzed and ranked the various technologies used for the production of hydrogen in the direction of social, economic, exergy, energy, and environmental. The study revealed that steam methane reformation has the most significant economic and technological advantages relative to that of wind and solar electrolysis, it however has the most significant negative impact on the environment. Electrolysis using wind energy was found to be the most environmentally friendly compared to photovoltaic (PV) based electrolysis. Bhandari [15] also forecasted the hydrogen potential demand across the transport and electricity sectors until 2040 in Niger. According to the results of their study, the total required hydrogen for electricity supply and the transport sector in Niger is estimated to be about 0.0117 Mt. This is expected to require about 5% of the country's total land area to produce the required energy from solar PV to hydrogen. A study by Ref. [16] analyzed barriers that confront the power to hydrogen (P2H) market in Italy and strategies to overcome them. The authors demonstrated how issues from the regulatory, economic, and technical front remain unresolved in the country which resulted in the lack of investment in the sector. Gordon et al. [17] created a socio-technical framework to overcome hurdles to the transition of domestic hydrogen in the United Kingdom. The paper suggested that strategies going into the future should take into consideration the interactions among the technical, political, market, techno-economics, as well as social dimensions of the transition to hydrogen. In another study by Ref. [18] the authors reviewed the green hydrogen environment from the social sciences perspective, the main areas of research were identified, the relevant difficulties as a result of the impacts and benefits that hydrogen has on climate change and energy transitions were also studied. Chantre et al. [19] explored the perceptions, experiences and the expectations of shareholders in the hydrogen economy of Brazil. The paper revealed that the interviewees in the long-term vision highlighted decarbonization as the main advantage for the development of the hydrogen economy in Brazil.

Furthermore, Khatiwada et al. [20] investigated the barriers, technical, economic, and frameworks/policies of European Union that could influence its decarbonization with a case study on Portugal. They assessed the levelized cost of hydrogen for grey, green, and blue hydrogen. Grey hydrogen was found to be the cheapest, recording 1.33 €/kg.H_2, blue hydrogen followed with a cost of 1.68 €/kg.H_2, whiles green hydrogen recorded the highest cost of 3.54 €/kg.H_2 for solar power. They identified cost, public perception, market creation, amendments in regulations/rules, and provisions of incentives as the main barriers. Palacios et al. [21] reviewed the global landscape for the production of hydrogen, applications, and the alternatives for the production of hydrogen in Mexico. Their study indicated that based on the several opportunities available in Mexico, the country could make significant incursion in the production of hydrogen. In the study of [22], the authors reviewed the opportunities and challenges of various hydrogen production technologies. The wind electrolysis technology was found to be the best in terms of its impact on global warming recording 1.29 kg CO_2 eq/kg H_2, the biogas reforming technology was however found to be the worst recording 3.61 kg CO_2 eq/kg H_2. Hassan et al. [23] explored the possibility of hydrogen energy integration in Saudi Arabia's energy industry in the future. The results suggests that the country's existing energy mix can support the production of green hydrogen. Morya et al. [24] also reviewed the use of rice straw as a source of clean hydrogen energy production, as well as the opportunities and challenges associated with its production. They discussed the global hydrogen production situation and policies; and assessed hydrogen as a potential sustainable energy for the future. Lee et al. [25] conducted a study that identified the barriers in

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hydrogen fuel cell development in South Korea. The study used a joint qualitative approach which includes both the Analytical Hierarchy Process and the expert Delphi surveys for the analysis. They identified political and institutional factors as the most serious factors that hinder the development of hydrogen fuel cells. In another study by Pal et al. [26] the authors assessed the environmental impact of non-renewable energy systems and explored hydrogen as an alternative to the conventional energy systems. The study was conducted on the QUAD nations in relation to the cost, governmental policies, carbon emissions, storage, application, transportation, and delivery of hydrogen in those countries. Finally, Tarkowski and Uliasz-Misiak [27] analyzed the barriers that prevent the development of commercial scale hydrogen storage underground. The authors studied the production, use, prospects for the development of the hydrogen economy in the years ahead. The following were identified as the barriers to the development of underground hydrogen storage systems: legal barriers, geological and reservoir constraints, conflicts of interest, technical and safety limitations, and social acceptance.

With an estimated population of about 1.34 billion people, the African continent is arguably the second most populous continent in the world. The continent is diversified in terms of economic activities which consist of its rich natural resources including human resources, agriculture, trade within and without the continent, as well as its industries [5]. The gross domestic product (GDP) of the African continent is estimated to be about 3.1 trillion U.S dollars, as of 2023. It is the highest amount since 2010 when it recorded around 2.1 trillion U. S dollars. It is projected to reach more than 4.7 trillion U. S dollars by 2027 [28]. The recent expansion of the continent's economy has been mainly due to the increase in the services sector, manufacturing, and commodities. Sub-Saharan Africa's GDP for instance is projected to reach about 29 trillion U.S dollars by 2050. The continent has huge potentials in terms of the various natural resources and also currently hosts the largest free-trade zone in the world [5].

Despite Africa's low carbon footprint which is about 3% of the world's GHG emissions, the continent largely depends on traditional biomass as its primary source of energy for its everyday energy demands [29]. An estimated 81% of total primary energy in Sub-Saharan Africa (excluding South Africa) is obtained from biomass. Furthermore, Sub-Saharan Africa has an estimated 75% of the world's population that are without access to electricity, the continent has a 45% average in terms of access to electricity [30]. This calls for serious measures from the various governments on the continent to tackle the problems in the energy sector through diversification of the energy mix with cheaper, cleaner, and more sustainable energy sources. Africa has enormous potential for the generation of renewable energy due to its geographical location, and it could also benefit from the trade of energy between the continent and other continents especially Europe if the right measures are put in place. Green hydrogen is seen as a potential universal fuel that can be used in place of fossil fuels and if the needed measures are put in place, it can be produced at a cheaper cost in Africa and either used within the continent or exported to Europe. However, the African continent is confronted with a number of challenges/barriers that can affect investments in the production, storage, transportation, and use of hydrogen. The objective of this study is to identify potential opportunities and barriers in Africa that may either positively or negatively affect the production of hydrogen energy in Africa. This study is crucial in the study area because the African continent wants to position itself as a major player in the green hydrogen production space. Some countries on the continent have begun entering into partnerships with some European countries for the production and export of the product [31]. The study for the first time combines both quantitative and qualitative methods to identify and rank the opportunities and barriers to the development of the hydrogen economy on the African market. The Best-Worst Method which is one of the several multi-criteria decision-making approaches is employed for the ranking of the various factors identified based on inputs from experts from the sector. Hence this study will serve as a major reference material to guide key decision making going into the future for the various stakeholders on the continent.

The study is presented in 4 sections, the method adopted for the study is presented in section 2, the results and discussion are presented in section 3. The conclusion is presented in section 4.

2. Materials and method

The current study seeks to address these research questions: (a) what are the opportunities in Africa for a smooth takeoff for the development of hydrogen energy? (b) What are the possible barriers that could affect the development and use of hydrogen energy at large-scale? (c) How can the identified opportunities and barriers be prioritized, especially that of the barriers to help various stakeholders find optimal solutions to them? (d) What are the recommendations to overcoming the challenges/barriers that have the potential to derail the development of hydrogen on the continent? In order to identify the various opportunities and barriers on the African continent that can affect the development of the hydrogen energy sector, and to prioritize them, a hybrid methodology involving two steps were used. The first step includes the identification of various opportunities and challenges to the development of the sector through reviewing of existing literature i.e., articles, government documents, online documents, books etc., and engagement with some experts on renewable energy and hydrogen energy production for their views. Other published documents from international organizations such as the World Bank and the International Renewable Energy Agency (IRENA) were also reviewed. The second step involves the prioritization of the various factors identified using the Best-Worst Method (BWM) multi-criteria decision-making (MCDM) approach to rank the factors using experts' judgements. The MCDM enables one to solve complex problems, it also integrates experts' judgements, and objective value evidence in solving complex decision-making problems [32]. The flowchart of the method used for the study is presented in Fig. 1.

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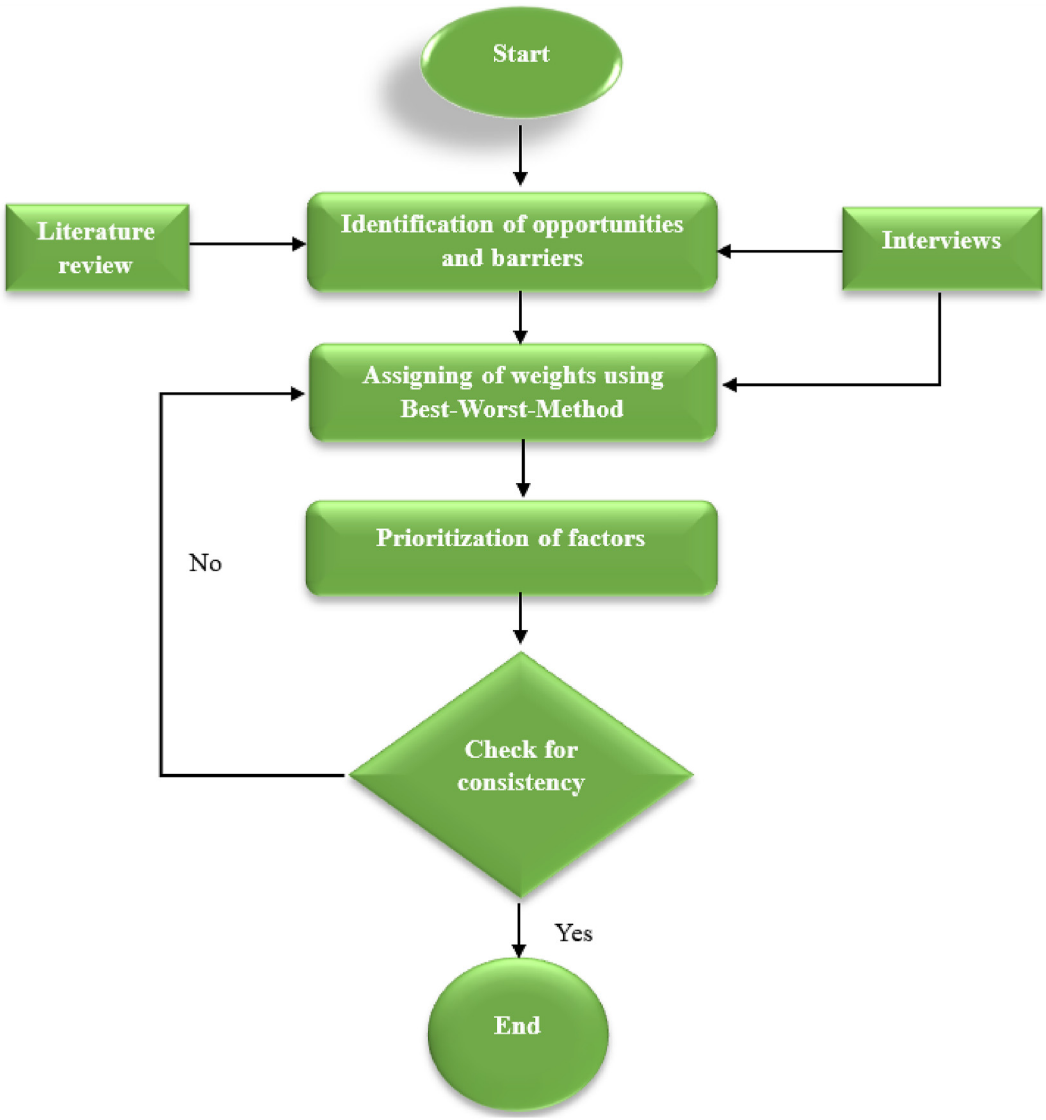

Fig. 1 – Flow diagram for the method used for the study.

2.1. *Best-worst multi-criteria decision-making method*

The MCDM tool is used by investigators to resolve difficult problems, particularly in situations that have multiple factors having an impact on an objective, it is a part of decision theory [33,34]. There are several of such tools that can employed for such studies, these include the ELimination Et Choix Traduisant la REalité (ELECTRE), Best-Worst Method (BWM), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Analytic Hierarchy Process (AHP), Analytic Network Process (ANP) etc. [35,36]. The BWM is another MCDM tool that is employed to evaluate composite problems due to its distinct characteristics such as [35]:

- Its ability to be either used independently for studies such as this or combined with the other MCDM methods to achieve same object,
- Its consistent comparison makes it highly reliable to use,
- This method employs integers that makes it easy to use,
- Compared to the AHP method, the BWM uses less pairwise comparison in its analysis.

Based on the various features enumerated supra, this study employed the BWM approach to assign weights to the various criteria identified as opportunities and barriers to the development of hydrogen energy in Africa. The BWM is computed by means of the following steps [34,35,37]:

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- Firstly, it requires the creation of the decision criteria set $\{C_1, C_2, C_3 \ldots C_n\}$.
- Secondly, the identification of the best (i.e., most desirable) and the worst criteria (least desirable) is done.
- Identification of the favorite of the best criterion over every other criterion through the giving of a figure from 1 to 9. Thus, the vector for the ensuing Best-to-Others can be presented as shown in Eq. (1).

$$A_B = (a_{B1}, a_{B2} \ldots, a_{Bn}) \quad (1)$$

Where, the preference of the best criterion B over the j criterion is denoted by a_{Bj}, and $a_{BB} = 1$.

- Next is to determine the preference of the various criteria over the worst criterion, also by assigning any number between 1 and 9. In this instance, the vector for the Others-to-Worst would be as indicated in Eq. (2).

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T \quad (2)$$

Where the preference of criterion j over the worst criterion w is denoted by a_{jW}, where $a_{WW} = 1$.

- The optimal weight calculation is performed at this step $(w_1^*, w_2^*, \ldots w_n^*)$. During the evaluation of the optimal weight for the criteria, each pair of w_B/w_j and w_j/w_w, we have $w_B/w_j = a_{Bj}$ and $w_j/w_w = a_{jw}$. To be able to find the conditions for the entire j, it is important to find a solution in which the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_w} - a_{jw}\right|$ for entire j is minimized.

This results in Eq. (3) when factoring the non-negativity and sum conditions for the weights.

$$\begin{gathered} \min \max_j \left\{ \left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_w} - a_{jw}\right| \right\} \\ \text{s.t.} \\ \sum_j w_j = 1 \\ w_j \geq 0, \text{for all } j \end{gathered} \quad (3)$$

The problem presented above can be formulated as presented Eq. (4) [38]:

$$\begin{aligned} &\min \varepsilon \\ &\text{St. } \varepsilon \geq \left|\frac{w_B}{w_j} - a_{Bj}\right| \forall j \\ &\varepsilon \geq \left|\frac{w_j}{w_w} - a_{jw}\right| \forall j \\ &\sum_{j=1}^{n} w_j = 1 \\ &w_j \geq 0, \forall j \end{aligned} \quad (4)$$

Solving the mathematical model presented supra results in the optimal value of ξ^*. However, it is important to note that in situations with more than three criteria, the solution may have multiple optimality for the above model. Hence, we can use models 4 and 5 to find upper and lower bounds for each of the weights (w_j) as follows:

$$\begin{aligned} &\min w_j \\ &\text{St. } \left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \varepsilon^* \forall j \\ &\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \varepsilon^* \forall j \\ &\left|\frac{w_j}{w_w} - a_{jw}\right| \leq \varepsilon^* \forall j \\ &\sum_{j=1}^{n} w_j = 1 \quad w_j \geq 0, \forall j \end{aligned} \quad (5)$$

$$\begin{aligned} &\max w_j \\ &\text{St. } \left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \varepsilon^* \forall j \\ &\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \varepsilon^* \forall j \\ &\left|\frac{w_j}{w_w} - a_{jw}\right| \leq \varepsilon^* \forall j \\ &\sum_{j=1}^{n} w_j = 1 \quad w_j \geq 0, \forall j \end{aligned} \quad (6)$$

The optimal weight of the criteria can be computed using Eq. (7) after solving Eq. (5) and Eq. (6).

$$w_j^* = \frac{\min w_j + \max w_j}{2} \forall j \quad (7)$$

where the decision makers in a BWM are two or more, the geometric means of the decisions are used. In the situation whereby there are a total of k decision makers $(k = 1, 2, \ldots, K)$, each having a weight of γ_k which are defined such that $\sum_{k=1}^{K} \gamma_k = 1$, as well as their views on the preference of the jth criterion relative to the best criteria i.e., a_{Bj}^k and the worst criteria i.e., a_{jw}^k, their views can thus be consolidated using the equations below [35,38].

$$a_{Bj} = \prod_{k=1}^{K} \left(a_{Bj}^k\right)^{\gamma_k} \quad (8)$$

$$a_{jw} = \prod_{k=1}^{K} \left(a_{jw}^k\right)^{\gamma_k} \quad (9)$$

In order to obtain consistency, a consistency ratio (CR) which is also called the K_{si} value is evaluated via ξ^*. It is apparent that, the higher the ξ^* value, the less reliable the CR, and the comparisons, it however, becomes more reliable when the ξ^* value is closer to zero.

A total of 12 emails were sent to the experts to share their views and rank the various factors (i.e., criteria) according to their experience in the area. A total of 10 emails were returned, however, 2 were not properly filled so they were disqualified and were not used for the analysis. The people contacted included lecturers and experts from the renewable energy industry who had worked in Africa and in the area of study for at least 5 years.

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3. Results and discussion

The opportunities and barriers in Africa that can either positively or negatively influence the development and use of hydrogen energy in Africa are presented and discussed in this section. The quantitative aspects of the study which uses the BWM approach to rank the various identified opportunities and barriers are also presented.

3.1. *General opportunities available for the development of hydrogen in Africa*

3.1.1. *Availability of renewable energy resources*

The African continent is generally endowed high renewable energy potential, these resources are still mostly untapped. The continent has an estimated hydroelectric potential of about 350 GW, 1000 GW of solar energy, 15 GW of geothermal, and 110 GW of wind energy [39]. Bioenergy potential on the continent is also great, with an estimated 520 GW h per year wood supply from surplus forest. Solar energy is the most promising due to the continent's geographical location: although the potential varies across the continent, it can be harnessed almost everywhere on the continent. Sunlight distribution in Africa is mainly uniform, over 80% of the continent's landscape receives about 2000 kW h/m^2 solar radiation annually. The solar radiation in West Africa ranges from 3 to 4 kW h/m^2/day in Benin, to 6.2 kW h/m^2/day in Niger. It also ranges between 5 and 6 kW h/m^2/day in Southern Africa and in Southern Algeria it can reach 6.1 kW h/m^2/day [40]. For wind energy, the highest potential can be found in Eastern Africa with about 170,000 TW h, North Africa follows with a potential of 130,000 TW h. Southern, Western and Central Africa follows with 110,000 TW h, 40,000 TW h, and 10,000 TW h, respectively. However, about 85% of the continent's wind energy potential have capacity factors that range from 20 to 30% according to IRENA [41]. These resources available on the continent are very strategic for the development of large-scale sustainable energy generation including the production of hydrogen and could be the real game changer for the development of Africa. Whereas the country has much experience in the use of hydropower, other RE such as solar and wind are now gaining prominence among the people of the continent. Solar and wind energies are now being developed on large scale bases for the generation of electricity across the continent which are now competing with the traditional fossil fuel in relation to cost [42–44]. All these resources can be tapped for the production of green hydrogen on the continent.

3.1.2. *Opportunity to export hydrogen to the European market*

Green hydrogen as stated earlier is enjoying both business and political momentum around the world in recent years. However, in order to take full advantage of it, it will require the deployment of the needed infrastructure, reducing costs, scaling of technologies, and the enactment of appropriate legislation and policies to support its market structure [45]. According to a [46] a mutual strategy between North Africa and Europe on green hydrogen can help in the development of the European energy system based on 50% green hydrogen and 50% renewable electricity by 2050. For the European energy system, green hydrogen will comprise of European produced hydrogen, which shall be supplemented with hydrogen imports particularly from Northern Africa. Producing hydrogen in the Northern part of Africa will not only benefit North Africa but will also positively affect energy production in Europe. Already about 10% of crude oil and 13% of natural gas that are used in Europe are imported from North Africa, this translates to some 80% of gas and 60% exports from North Africa [47]. Considering the resource proximity, potential and leveraging present trade relationships, countries in Northern Africa could be the first adopters in the African Union to export green hydrogen to the European Union. A hydrogen economy can be developed along the present infrastructure routes of seaports, railways, and roads for utilization across regions and within the region. According to a mapping performed by the African hydrogen Partnership, there are potentially six landing zones which have been found to be Nigeria-Ghana, Morocco, Tanzania-Rwanda-Kenya, Egypt, Ethiopia-Djibouti, and South Africa (see Fig. 2). This will come with lots of benefits to the region, for instance, it is estimated that for every 1 GWe of installed capacity of P2X, there could be about 300–700 jobs that can potentially be created [48]. A major resource in hydrogen production is water, and it is estimated that one cubic meter of hydrogen can be produced from a liter of water. Although Africa has a lot of water resources, not every area has abundant water resource hence it offers the opportunity to develop a synergy i.e., energy-water nexus, with initiatives in desalination, using renewable hydrogen plants as anchor off-takers for the desalination plants [48,49].

3.1.3. *Africa's agenda 2063 as an opportunity*

The agenda seeks to position the African continent as a global powerhouse in the years ahead. It is regarded as the master plan and the blueprint for Africa's transformation, and it is the framework within which the goals for an all-inclusive and sustainable development can be found [51]. The addition of green hydrogen to Africa's energy mix comes with lots of benefits to the region. It has the potential to use its enormous RE resources to meet its own energy demands, stimulate green industrialization and trade that takes advantage of the Africa Continental Free Trade Area, meet green objectives as defined in the Agenda 2063, Sustainable Development Goals (SDGs), Nationally determined contributions (NDCs), and also address climate change mitigation [52]. Governments on the continent are therefore designing strategies that will meet the targets set in the ‘Agenda 2063’ even though they come at a slower pace. This affords the investor community the opportunity to approach various governments on the continent on the way forward for their country's green hydrogen energy development strategy.

3.1.4. *Youthful population of Africa as an opportunity*

Studies such as [53–55] have found that older persons mostly resist the acceptance of hydrogen energy technology (HET). However, just as in the case of gender [56,57], the impact of age on the acceptance of HET does not appear to be weak compared to that of psychological factors. The reason for this

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Fig. 2 – Six potential identified landing areas [50].

link between HET acceptance and age is that the younger population have higher trust in new technologies and science, which therefore positively affect their willingness to accept new technologies [58,59]. If the said studies as reviewed are anything to go by, then the African continent has the highest youngest population globally according to the UN report. About 70% of Sub-Saharan African population are under the age of 30 [60]. These high numbers of young population come as an opportunity for the development of the continent. The development and use of hydrogen on the continent will require several professionals, most of whom will be youthful and as indicated supra people in the youth bracket will accept HET on the continent. This also means that if the potentials of these young individuals will be fully tapped, then it will require that they are fully empowered in the area of science and engineering especially in the area of hydrogen energy and renewable energy. This is the only way their full potential can be harnessed. Governments therefore have the responsibility to provide the right environment for their studies in the form of the right infrastructure and equipment for academic work. Science Technology, Engineering, and Mathematical courses have to be championed among the youth to entice them to choose such programs to study. Governments and other stakeholders will also have to deliberately train such individuals in specific areas of hydrogen production along the value chain, this will provide experts for the production, storage, and transport of the product. It also means that the young population have to be engaged and included in decision-making, they should be given the freedom to innovate and work to develop the sector. This is key to ensuring that the local workforce and expertise is built-up and passed on to other people within the various countries on the

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continent to prevent the situation whereby only foreigners control critical sectors of the production, storage, and maintenance processes.

3.1.5. *Opportunity to produce renewable ammonia for the African market and beyond*

The production of renewable ammonia from green hydrogen is one of the several opportunities available for the African countries, especially considering that most people on the continent are into farming. This could reduce the cost of synthetic fertilizer, given that the source of ammonia production is mainly from natural gas (NG) currently. About 183 Mt of ammonia is manufactured per annum worldwide, greater part of it representing some 72% is obtained from NG or coal which also contribute about 22% [61]. Kenya recently signed an agreement with a company in Australia i.e., Fortescue Future Industries (FFI), to construct green ammonia and hydrogen plant, this is a kickstart for the country's strategy to use renewable energy across the country [62]. A large-scale production of green ammonia and hydrogen will be key in the continent's quest to provide clean and cheap fertilizer for its people. The involvement of financial institutions is key in the construction of green ammonia plants, particularly when there is the need to install renewable power plants. Interest from several equity investors and lenders have been expressed at some locations, however, a major bottleneck in other countries is the availability of capital investment. Whereas the expenses for the operation of renewable ammonia plants are minor, its initial capital is intensive. Therefore, in order to reduce the risks associated with such investments, collaborations among countries should be encouraged, for instance stakeholders in the green fertilizer corridor could acquire international offtake [63].

3.2. *Barriers to the production and use of green hydrogen in Africa*

3.2.1. *High cost of hydrogen*

The cost of green hydrogen is still high and not yet competitive with the traditional sources of energy. This could be a major barrier to its acceptance in most developing countries. The cost of green hydrogen production is high since the cost of scaling-up cells is high [10]. The cost of green hydrogen production at a suitable location can be reduced if the market grows globally, it could move below 1 Euro/kg. For instance, in Morocco, a price of bidding of a wind farm was 850 MW in January 2019, and the cost of green hydrogen production with an 80% electrolyser efficiency and a CAPEX of 347 $/kW will be about 1.16 $/kg [48]. In general, green hydrogen production will require a combination of regulatory support and technological advancements to enable cost-competitiveness. Given that the cost of renewable energy is projected to drop in the future, with the advancement in the efficiency of electrolysers and lower CAPEX, the production cost of green hydrogen could fall below 1.16 $/kg come 2050. In terms of delivery, the current pipelines for gas delivery from Libya and Algeria through Spain and Italy can be a leverage. About 63.5 bcm is transported through them every year which translates to over 60 GW [64]. The current pipelines can be transformed into new pipelines or new ones can be built for transportation of the produced green hydrogen from Northern Africa to Europe as the market matures. According to Ref. [48], a 2500 km transportation dedicated corridor consisting of 2 pipelines with a diameter of 48 inches each will cost about 19.14 billion US dollars. Therefore, the cost of transporting hydrogen through those pipelines will be 0.0058 USD/kWh or 0.22 USD/kg, this is a practical proportion of the entire cost of transporting hydrogen to Europe.

3.2.2. *Dealing with the status-quo*

Currently fossil fuel forms the largest majority of Africa's sources of energy. Several governments on the continent have provided subsidies on fossil fuel products making them relatively cheaper to the consumer. Financial institutions are still providing financial support to certain sectors of the value chain for fossil fuel in Africa. Whereas majority of institutions are not in support of new coal capacity for the generation of power, generation of power using fossil gas is however still supported [65]. This includes the development of massive liquefied natural gas export as a result of the current difficulties in the energy sector globally. The drive for the development of new fossil gas in Africa is also another issue that could affect the development of green hydrogen and for that matter renewable energy as a whole. A combination of the heavy subsidization of fossil fuels using government budgets and the continuous reliance on fossil fuel need to be re-looked at by the various governments on the continent.

3.2.3. *Corruption in the energy sector*

Generally, corruption is seen as an abuse of public power by a person for his/her personal gain, it is globally seen as a threat to development [66]. It is also defined by others as the act by which an insider benefits at the expense of those outside. Corruption mostly flourish in overregulated and deregulated countries, in developed countries through money laundering or tax evasion, or in developing countries through nepotism or bribes [67]. There is an international dimension in corruption for RE markets. Firms, investors, and politically exposed individuals with business connections in the global north have the potential to drive corruption in the RE sector in emerging markets. For instance, former minister in the United Kingdom was charged of breaching the ministerial code after a multi-million-pound deal between the government of Uganda and her family was signed to supply solar power equipment [68,69]. Another investigation was commenced into an allegation against the largest electric utility company in Spain, who have been accused of paying some US$3.5 million to Chilean politicians in order to get the contract to build and run a hydro power plant [69]. The risk of corruption exists throughout the different levels of development of RE which asset operators and RE developers ought to manage. The requirements that have to be met differ from one country to another, however, investors or developers need to obtain planning permission, connectivity with transmission networks, licenses for the generation of energy or production of hydrogen, and environmental permits. These processes can be cumbersome, slow, and bureaucratic especially in developing economies where much of these works have to be done on paper and in person instead of online. The risk of corruption is even high because mostly governments give out limited

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numbers of licenses and permits for energy generation, and investors sometimes are made to pay certain monies and offers to some persons to obtain permissions [70].

3.2.4. *Political instabilities and insecurity in certain parts of the continent*

Financing of renewable energy projects has always been capital intensive, and developing countries usually lack the financial strength to embark on large scale development of such technologies. They mostly tend to depend on international donors and investors to embark on the development of renewable energy technologies. Political instability is a major hindrance to the development of renewable energy and electrification, as the development of such technologies gets halted in unstable political periods. For instance, Liberia's civil wars and during Idi Amin's presidency showed such trajectories [71]. Furthermore, political instability has major consequences on international energy trade. According to Ref. [72], cross-border trade needs a politically stable environment over many years to flourish. Several literatures on investment risk management have shown the need for political risk assessment before an investment decision is made. Studies have shown that nations with very low political risks tend to have more foreign direct investments [73–76], investors mostly cite political risks as the main risk in developing economies [77]. Political instability in some African countries could affect and delay the development of RE and hydrogen energy in those jurisdictions due to reasons stated earlier in this section.

3.2.5. *Land availability issues*

Although most African countries have large mostly unused lands available, getting access to them for large-scale development has been a major problem in most countries on the continent. In Nigeria it is listed as one of the barriers to the development of renewable energy in the country [78], it is not different from that of Ghana [79]. This is because access to lands in Africa can be extremely politicized [73,80]. Most of these lands also belong to different families and stools which makes their acquisition very cumbersome since several families and chiefs have to be consulted in order to purchase a large plot of land for RE development. According to Ref. [80], in sub-Saharan Africa, lands that can be marketed freely are less than 10%, majority of its lands are subject to complicated socio-cultural customary user rights. The usage of land is one of the major causes of conflicts and political struggles in several communities and countries on the continent. It can be a major barrier to the development of RE and green hydrogen production facilities since they usually require large land compared to that of fossil fuels [73]. According to IRENA, foreign companies who have interest in investing in RE in Africa are mostly faced with land acquisition issues due to complicated land tenure regimes [81].

3.2.6. *Lack of the needed skills and education*

The development of hydrogen energy in any country will require the needed skills from production, storage, use or transportation. With hydrogen being a relatively new energy source compared to the traditional fossil fuel, it is likely that Africa will lack the required expertise for its production. This is because the following studies [40,82] identified lack of awareness and knowledge as a potential barrier to the acceptance and use of RETs in Africa. The continent still has a large number of its people who fall within the illiteracy bracket, and studies have shown that people without enough education will most likely reject RE [40,58,83]. This is a contributing factor to the slow rate of RE penetration in Africa, and with green hydrogen being part of the RE group, it could suffer the same fate if deliberate measures are not put in place by the appropriate authorities to train and educate the populace about its production and use.

3.2.7. *Limited supporting infrastructure and financing*

A number of suggestions have been made by experts in the hydrogen energy sector about the shift to a hydrogen economy by 2050. The most crucial among those recommendations is the approach to adopt for the construction of the needed infrastructure for the production, delivery, storage, and utilization of hydrogen. A major difficulty in the commercialization of the hydrogen economy in the future is how to design the infrastructure and operate it, particularly due to the several technological options available in the sector, some of which are still been developed in the area of production, storage, and distribution [84]. Construction of the required infrastructure for hydrogen production demands quiet a huge investment, and in a developing continent like Africa this could serve as a barrier since most countries on the continent are battling with huge debt. Financing RE projects in general has been a major hurdle for developing economies since they come with high initial cost. The needed bilateral cooperations will have to be activated among government to governments or governments to multimillion international agencies or companies to design an appropriate financing mechanism for the development of hydrogen energy in Africa.

3.2.8. *Lack of the needed regulatory and policy framework in most countries*

The availability of regional and national strategies and road maps for the development of the hydrogen sector in clear terms is key to the uptake and development of the sector as an energy vector. However, the development of road maps for the sector in most African countries are still in the initial stages of adoption. South Africa, Namibia, and Morocco have made quiet significant progress in that direction. A pilot hydrogen framework has been developed by the Moroccan government dubbed the "Green Hydrogen Cluster" which aims at enhancing mutual participation by the global private sector for an intensified acceptance of green hydrogen use [85]. The Namibian government is also in the process of framing a national strategy for its hydrogen production sector. It additionally awarded a tender to Hyphen Hydrogen Energy recently to develop and operate a commercial scale green hydrogen project at the Tsau Khaeb National Park. The capacity of the production plant at the Tsau Khaeb National Park is anticipated to be 350,000 metric tons per year replacing 5–6 million tons/year of CO_2 emissions [86]. The South African government has also commenced its plans to make the country an exporter of green hydrogen and as a result allocated the Boegoebaai SEZ zone for production [85]. Although the few countries on the continent that have made efforts in getting the right legal and regulatory framework for

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the development of the hydrogen sector comes as positive, most countries on the continent are still lagging behind in that regard which may hinder the adoption and use of hydrogen on the continent.

3.3. Quantitative analysis of the various factors

The inputs of 8 out of the 12 experts consulted in renewable energy and hydrogen energy production using the BWM approach are discussed in this section. The various opportunities and barriers as presented in Table 1 are ranked to identify the factors that experts see as the greatest opportunity or barrier to the development of hydrogen energy in Africa. The consolidated preferences provided by the consulted experts on the opportunities and barriers are provided in Tables A1 and A2 in the Appendix section.

A Ksi* of 0.069 is obtained for the ranking of the opportunities and as indicated earlier in this study, in BWM the comparisons of the experts become more consistent when the Ksi* value is closer to zero. Therefore, the result from the analysis is an indication that the judgements obtained from the experts are consistent. The individual weights for the various factors (i.e., criteria) for the opportunities are shown in Fig. 3. The views of the experts on the opportunities explain the impact of the various factors on the development of hydrogen energy on the continent.

The outcome of the BWM analysis show that the highest potential associated with the African continent when it comes to the production of hydrogen is the availability of RE resources. They assigned a weight of 34.88% to the availability of RE resources. According to them, the availability of resources constitutes a primary requirement for the installation of hydrogen production facility, therefore with the numerous renewable energy resources as presented in earlier part of this paper is positive for the continent. The opportunity to export the hydrogen to other markets for instance Europe, and the opportunity to produce ammonia for use within and without the continent were given equal weights of 20.93%. The youthful population of the continent followed with 13.95%, according to them, the youth are expected to serve as the workforce for the development of the renewable energy industry. Hence their availability on the continent means that they can be given the necessary training and skills to work in the various sectors of hydrogen production without relying on workforce from foreign countries who will come at a higher cost. The African “Agenda 2063” followed with a weight of 9.30%. The agenda as presented supra seeks to provide sustainable energy to its citizens in an affordable and reliable

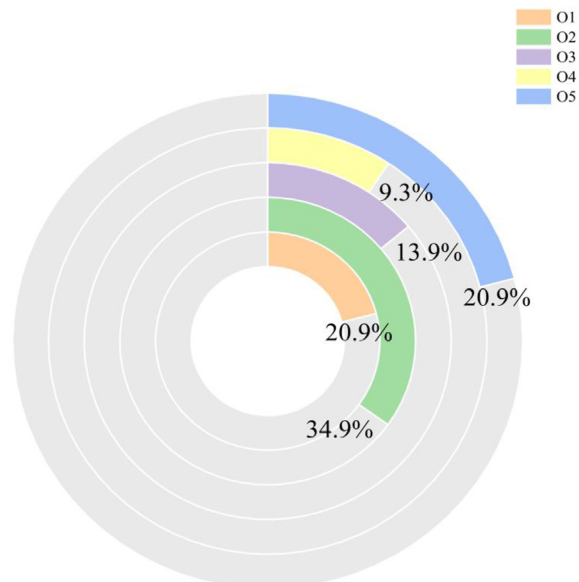

Fig. 3 – Weights for the opportunities considered in the study.

manner, hence most governments on the continent have set goals and targets for RE development [81] and have also started working on the integration of RE energy in their electricity generation mix. This according to the experts is a positive indication for green hydrogen production in the future.

The potential barriers to the production of large-scale green hydrogen in Africa as discussed earlier were also ranked by same experts. A Ksi* value of 0.063 is obtained for the barriers which is also close to zero hence the CR of the judgements from the experts is consistent. The weights for the barriers discussed in this study are presented in Fig. 4. Based on the results, the experts chose the lack of regulations and policies (28.95%) for the sector as the major barrier to the development of Africa's hydrogen economy. According to them although African countries seek to position themselves as leaders and initiators for the next industrial revolution in the production of green hydrogen, there exist a missing link for the realization of this vision. Even though most countries on the continent have policies and legal framework for renewable energy development as presented in Ref. [87] there seems to be very little information on the legal backing that permit the production and storage of hydrogen in most of the countries in commercial quantities. Comparing this to France for instance, in France there is the need for one to obtain a

Table 1 – Factors (criteria) used for the MCDM analysis.

Opportunities	Barriers
Opportunity to export to EU market (O1)	High cost of hydrogen (B1)
Availability of RE resources (O2)	Dealing with the status-quo (B2)
Youthful population (O3)	Corruption in the energy sector (B3)
Agenda 2063 (O4)	Land availability issues (B4)
Ammonia production (O5)	Political instabilities and insecurity in certain parts of the continent (B5)
	Lack of the needed skills and education (B6)
	Limited supporting infrastructure and financing (B7)
	Lack of the needed regulatory framework (B8)

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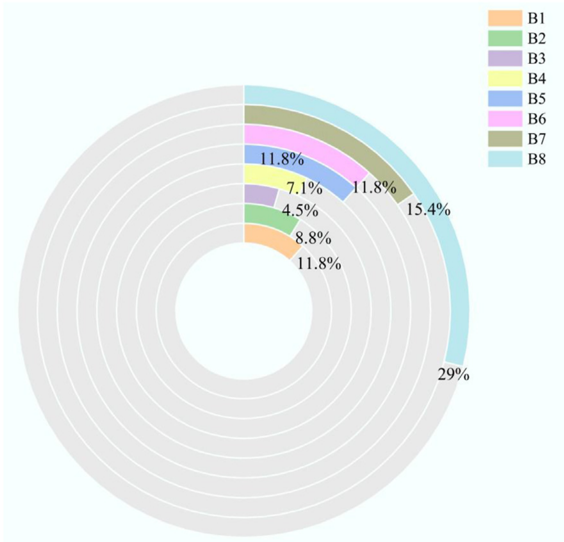

Fig. 4 – Weights for the barriers considered in this study.

special permit for the production and storage of hydrogen [88]. Authorization must be given by the Installation Classée pour la Protection de l'Environnement (ICPE) for sites used for the production of hydrogen in France. However, sites storing hydrogen less than 100 kg are not subjected to administrative constraints in France. The authorities in France are currently negotiating to provide a lesser restricting administrative regime for hydrogen produced from the electrolysis of water. An ICPE declaration is required for 100–1000 kg stored quantities, it is also compulsory to get ICPE permission to store quantities more than 1000 kg. In Spain, it is compulsory to obtain an integrated environmental authorization and environmental impact assessment, notwithstanding the quantity of the produced hydrogen. In Spain there is no legislation that differentiate the production sources, in effect, all hydrogen production must comply with environmental requirements [88]. Such regulations are missing in most African RE regulations which presents safety concerns going into the continents large-scale hydrogen production. It is this reason among others that the experts assigned the highest weight to the lack of adequate regulatory and policy framework for the sector.

The next factor or criteria that followed is the limited supporting infrastructure, it scored 15.37%, indicating the importance experts assign to building the required infrastructure for the production and storage of hydrogen. In Africa, the infrastructure for hydrogen has not yet developed to a stage where fuel cell (FC) systems can be utilized in decentralized approach. Thus, governments and other interested stakeholders ought to invest in its transportation and storage infrastructure to enable a quicker commercialization of FC technology across the continent. The high cost of hydrogen, land availability issues, and political instabilities and insecurity in certain parts of the continent were all ranked at par, all three scored a weight of 11.76% each. It is therefore important for the various governments to implement measures that can make lands easily accessible to interested parties to avoid the litigations that investors are sometimes confronted with. Political stability as already indicated earlier is key to drive into the continent foreign direct investment, it also reduces the risks, which will in tend reduce the high interest rates that comes with financing such projects. If checked, it will have a positive impact on the cost of hydrogen by reducing it. Dealing with the status-quo was assigned weight of 8.82%, it is the believe of the experts that since most African countries are now striking fossil fuels in commercial quantities, it could affect the continent's readiness to transition into cleaner sources of energy generation. It is the believe of the various governments that just as the developed countries relied on fossil fuels to develop their economies, the African continent will also use it for the development of its economy. This means governments on the continent will not rush into the development of RE aggressively once oil reserves are being discovered in Africa. Lastly, corruption in the energy sector followed with a weight of 4.52%, this is because as indicated earlier the energy sector is very lucrative and considering the high levels of poverty in developing countries, people could be compromised. This could lead to delays in project executions, poor supervision, and increased cost of projects that will ultimately affect the cost of energy or produced hydrogen.

3.4. *The way forward for green hydrogen development in emerging countries*

The creation of the required environment for the development of the hydrogen economy is crucial especially in developing countries that are perceived as places with high investment risk. The integration of hydrogen energy into Africa's energy mix will require building the right human capacity to man the various institutions and sectors of the production, storage, and transportation process. Governments and other stakeholders should assist the various academic institutions on the continent to design and implement teaching curriculums that emphasis on practical than the current theory-based approach that has not been helpful and effective on most occasions. Regional and country level policies and cooperation among the various regional blocs in Africa will be an important tool to break or remove some of the barriers that could hinder the acceptance and deployment of hydrogen energy on the continent. Since most of the experience with the use of green hydrogen production resides among the developed economies, such countries could engage in political power play. It is therefore important to design policies that promote the transfer of expertise and skills during the purchase of equipment for the installation of the production and storage facilities [89]. Viable financial models for growth in the renewable energy must be fashioned out in developing economies. The various suitable sites for the installation of renewable energy technologies including hydrogen power plants should be mapped out clearly across the continent. Doing this will reduce the stress an investor will have to go through in identifying optimum sites for the situation of the power plants, and it will also help to strengthen the bankability of the facility. Since most developing countries are saddled with huge debts, it increases the risks of investment, it is therefore recommended to encourage blended financial instruments to help de-risk the sector, especially private sector investments. The perception of people towards hydrogen energy differs, it is therefore important to educate people about the product and the potential job

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opportunities it could create for the youthful population on the continent. Education could help to increase the traction for technology both locally and internationally to help drive in the needed investments.

Conclusions

The use of green hydrogen would not only have a significant impact on the world's quest for decarbonization, but it can also create several job opportunities across its value chain. Africa has been identified as a potential place for large-scale production of hydrogen for itself and other markets across the globe. However, despite the various opportunities available on the continent, there are also several barriers that could affect investment drive onto the continent for hydrogen energy development. The aim of this study is to identify various opportunities and barriers to the development of green hydrogen energy on the African continent. The Best-Worst Method of multi-criteria decision making was used for the ranking of the various identified factors to help in decision making. The study identified the opportunity to export to EU market (20.90%), availability of RE resources (34.88%), youthful population (13.95%), Agenda 2063 (9.30%), and ammonia production (20.90%) as some of the opportunities available on the continent. The availability of RE resources was selected as the highest opportunity for the development of hydrogen energy on the African continent. High cost of hydrogen (11.78%), dealing with the status-quo (8.82%), corruption in the energy sector (4.52%), land availability issues (7.06%), political instabilities and insecurity in certain parts of the continent (11.76%), lack of the needed skills and education (11.76%), limited supporting infrastructure and financing (15.38%), and lack of the needed regulatory and legal framework (28.95%) were identified as some of the barriers that could affect the development and use of hydrogen in Africa. The highest threat to the development of hydrogen in Africa is the lack of the needed regulatory and legal framework to manage the production, storage, transportation, and use of the product. In order to ensure cooperation among the various countries on the continent and other continents, it is important to frame and agree on the rules for operation, and standardized safety guidelines for the sector.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.07.229.

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