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Hydrogen technology adoption analysis in Africa using a Doughnut-PESTLE hydrogen model (DPHM)

Mulako Dean Mukelabai [a,*], *K.G.U. Wijayantha* [b,c], *Richard E. Blanchard* [a]

[a] *Centre for Renewable Energy Systems Technology (CREST), Wolfson School of Mechanical, Electrical, and Manufacturing Engineering, Loughborough University, Epinal Way, Loughborough, Leicestershire, LE11 3TU, UK*

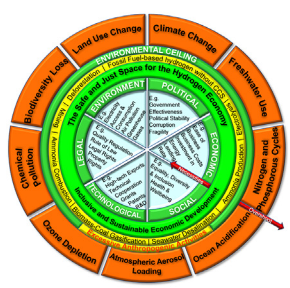
[b] *Centre for Renewable and Low-Carbon Energy, Cranfield University, College Road, Cranfield, MK43 0AL, UK*

[c] *Wolfson School of Mechanical, Electrical, and Manufacturing Engineering, Loughborough University, Epinal Way, Loughborough, Leicestershire, LE11 3TU, UK*

HIGHLIGHTS

- A safe and just hydrogen economy can enable sustainability and equity for all.
- Combination of doughnut economics and PESTLE analysis created a novel approach.
- The DPHM presents a safe and just space for a thriving hydrogen economy for all.
- Avoiding exacerbating planetary boundaries key when adopting hydrogen technologies.
- Hydrogen supply chain development in Africa requires the right PESTLE conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

The hydrogen economy requires the right conditions to produce hydrogen by sustainable routes and provide it to local and international markets for suitable applications. This study evaluated the political, economic, social, technological, legal, and environmental (PESTLE) conditions that can be instrumental in adopting hydrogen technologies most effectively by encapsulating aspects relevant to key stakeholders from hydrogen technology developers through to end-users. For instance, the analysis has shown that countries within a government effectiveness index of 0.5 and −0.5 are leading the planning of hydrogen economies through strategic cooperation with hydrogen technology developers.

Abbreviations: AHP, Analytical Hierarchical Process; IEA, International Energy Agency; IRENA, International Renewable Energy Agency; MCDA, Multicriteria Decision Analysis; DPHM, Doughnut-PESTLE Hydrogen Model; PESTLE, Political, Economic, Social, Technological, Legal, and Environmental Factors; R&D, Research and Development; SWOT, Strength, Weakness, Opportunities, and Threats; UN, United Nations.

* *Corresponding author.*
E-mail addresses: m.d.mukelabai@lboro.ac.uk (M.D. Mukelabai), upul.wijantha@cranfield.ac.uk (K.G.U. Wijayantha), r.e.blanchard@lboro.ac.uk (R.E. Blanchard).

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Furthermore, the combination of a Doughnut and PESTLE analysis created a novel approach to assessing the adoption of hydrogen technologies while evaluating the impact of the hydrogen economy. For instance, the estimated ammonia demand in 2050 and subsequent anthropogenic nitrogen extraction rate will be about two and a half times more than the 2009 extraction rate.

Introduction

The sustainable energy transition in developed and advanced economies is mainly centered on environmental impacts, energy security and fossil fuel costs, and exhaustion of finite fossil fuels [1]. It is for this reason that all the countries have greenhouse gas emission reduction targets through their Paris Agreement Nationally Determined Contributions [2]. The goal to curb greenhouse gas emissions and maintain global warming below 2 °C to prevent climate change after the Paris agreement [3] led to increased interest in sustainable energy sources such as renewable energy and carbon-negative technologies because they are perceived as critical solutions in avoiding catastrophic climate failure.

However, the benefits of adopting sustainable energy technologies should go beyond reducing greenhouse gas emissions because they have the potential to improve the socio-economic statuses of households and communities [4]. While the energy transition in developed countries is focused on the transition from fossil fuels to sustainable energy, the transition in developing countries is dynamic because of the complex energy landscape that encapsulates issues such as low access to electricity, low access to clean water, need of industrialization and economic growth [5]. Even so, advanced economies such as the United Kingdom are currently facing social injustices primarily energy poverty due to increasing gas prices, one of the core elements that is raising inflation [6,7]. Additionally, global oil prices have surged over 7% due to disruptions from Russia's invasion of Ukraine [8]. These issues are a reminder of the significance and urgency of a secure and global sustainable energy transition.

This debate is relevant to the production and utilization of hydrogen in advanced economies as part of the net zero solutions. Hydrogen is widely seen as a key energy carrier because it is readily available in water covering around 71% of the Earth's surface and produces only water when oxidized in fuel cells [9,10]. Furthermore, it expeditiously dilutes to low flammability limits in surrounding air due to being the lightest molecule on earth [11,12]. The versatility of hydrogen enables it to play a key role in decarbonizing the domestic, industrial, and transport sectors. It is also expected to curb the intermittency of solar and wind energy by offering grid flexibility [13] and reducing the volatility of oil and gas prices [1]. These issues are valid as well in developing countries towards a sustainable energy transition, but hydrogen adoption in these countries should go beyond this by emphasizing the opportunities offered by promoting access to clean energy (including clean cooking), gender equality and inclusion, job creation, socio-techno-economo-political development, industrialisation, and improving the resilience of developing countries.

As in developed countries, sustainable hydrogen production in developing countries to transition to a hydrogen economy requires the right conditions that will enable hydrogen produced sustainably to be utilized in different sectors locally and internationally. Long-distance transportation of renewable energy from developed and developing regions such as Australia, Canada and Africa with abundant resources will play a critical role in the global transition from fossil fuels [1,14–18]. Africa is considered a case study to build on the preceding study on the renewable hydrogen outlook in Africa [18]. There are commercialized ways in which sustainable hydrogen can be produced, for example, with renewable electricity using electrolysis, steam methane reforming with high-rate carbon capture, or biomass gasification [1,19–21]. These processes are understood; however, the processes do not only need the right technology, but they also need the availability and development of safe and just political, economic, social, technological, legal, and environmental (PESTLE) conditions to bring about the transformation of carbonized energy practices.

There are several studies on technology adoption and these are summarised in Table 1. From the studies reviewed, no study that comprehensively evaluated the complex and dynamic African landscape when assessing the adoption of hydrogen technologies on the continent. Furthermore, the studies on the adoption of hydrogen technologies [22–27] are mainly review studies and did not carry out comprehensive PESTLE analysis as shown in Table 1. The previous studies focused on qualitative PESTLE analyses while the quantitative studies relied on expert opinions and views, and techno-economic analyses to shape their discussion. However, this study has taken a novel approach and uses robust and globally accepted data from The World Bank [28] and The Global Economy [29] to evaluate and comparatively analyze the PESTLE aspects.

Unlike previous PESTLE studies, it also drew inspiration from Raworth's doughnut model [30] which combines the social foundation with the environmental ceiling creating a doughnut-shaped area between social and environmental boundaries that depicts a safe and just space for humanity. Furthermore, a combination of a PESTLE and doughnut economic model analysis creates a novel approach (Doughnut-PESTLE hydrogen model, DPHM) in assessing the adoption of hydrogen technologies while evaluating the impact of the hydrogen economy. The objectives of this paper were: (a) assess

Table 1 – Technology adoption analysis studies (PESTLE-political, economic, social, technological, legal, and environmental factors, AHP-analytical hierarchical process, SWOT-strength, weakness, opportunities, and threats, MCDA-multicriteria decision analysis).

Ref.	Technology/Application	Method	Location	Key Results
[31]	Biofuel	PESTLE	Europe	The technological developments in industry significantly affect the competitiveness between different production characteristics concerning economic sustainability.
[32]	Fossil Fuel	PESTLE	Indonesia	The importance of strategical alignment of stakeholders' policies to the needs of other relevant stakeholders.
[33]	Tidal	PESTLE	United Kingdom	Stakeholders present benefits to the tidal developers through funding, incentives, and knowledge sharing whilst presenting risks to the future of projects.
[34]	Parabolic dish and micro turbine engines	PESTL-Index of market potential	Selected countries in South and North America, Europe, Africa, Asia, and Australia	Several factors such as irradiance influence the adoption of solar power technologies.
[35]	Renewable energy	PESTLE-Expert views	Ghana	The consulted experts ranked economic factors as the most critical challenge. Renewable energy resources and geographical location were ranked highest in terms of opportunities.
[36]	Solar home systems	PESTLE-Surveys	Rwanda	The solar home projects should be informed by the needs and priorities of end-users whilst being aligned with national policies
[37]	Solar water heating	PESTLE	Africa	An entrepreneur can still make a profit if a solar heating product retails at 52% of the equivalent competition prices.
[38]	Renewable energy	SWOT- AHP	Morocco and Egypt	Indicated that Morocco may be more efficient than Egypt in promoting European energy cooperation as a host country
[39]	Renewable energy	PESTLE	Malawi	Suggested a paradigm shift that has the potential to provide long-term supportive mechanisms for Malawi's renewable energy development.
[22]	Hydrogen	PEST-Expert views	European countries	Stakeholders, experts, academics, and industrialists have a key role to explain to decision-makers, and local and national governments on hydrogen
[40]	Wave and tidal energy	PESTLE- Levelised Cost of Energy	United Kingdom, France, Canada, Spain, Chile	Two separate case studies are required to accurately assess the needs of the ocean energy sector. These are the suitability of different geographic locations and the progress of the technology in the research and development cycle.
[41]	Desalination	PESTLE-Life Cycle-MCDA	Saudi Arabia	Reverse Osmosis combined with renewable energy performed better in terms of human health, ecosystem quality, and resources, as well as greenhouse gas emission reduction.
[42]	Carbon capture and storage	PESTLE-Life cycle-MCDA	–	Applying process improvement and renewable energy sources such as biogas for absorbent regeneration result in reduced environmental and social impacts.
[25]	Hydrogen	Review	Mexico	Commercial, ecological, human, economic, and technological challenges may counter international agreements by discouraging the hydrogen market and curbing expected decarbonization.
[43]	Geothermal	PESTLE-Expert views	United States of America	Geothermal innovations that increase the footprint of the geothermal industry might provide an avenue for the oil and gas industry to enter the geothermal domain.
[24]	Hydrogen	Review	Asia-Pacific	Countries with active hydrogen policies and high research and development capacity could lead the strategy, whilst countries with high primary energy supply capacity and economic advantage can benefit the region in catering the energy and commercial resources.
[44]	Waste to Energy	PESTLE	China	For the private sector, policy changes, extensive application of public-private partnerships and the complex characteristics of municipal solid waste are the critical factors to be accounted for.
[45]	Electric vehicles	PESTLE-Facebook posts	United States of America	Political, economic, and legal posts had dense clusters around the technology policy of electric vehicles.
[46]	Renewable energy	PEST	Poland	Indicated that the renewable energy sector can continue to grow with economic and macro-environmental being the most favorable factors.

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Table 1 – (continued)

Ref.	Technology/Application	Method	Location	Key Results
[23]	Hydrogen	Review	Turkey	The barriers to the hydrogen economy are not technical but the mindset, regulatory, and political interferences.
[26]	Hydrogen-fuel cell vehicles	Online questionnaire	India	The government must involve stakeholders including automobile manufacturers, hydrogen producers, and research institutions coupled with funding to address the bottlenecks.
[27]	Hydrogen-fuel cell vehicles	Fuzzy-set quality comparative analysis	South Korea	Identified three auspicious pathways i.e., hydrogen station to fuel cell vehicles, government-led fuel cell vehicle adoption, and government subsidy-led fuel cell vehicle adoption.

the environmental impact of adopting hydrogen technologies, (b) assess the social impact of adopting hydrogen technologies, and (c) evaluate the political, economic, social, legal, and environmental conditions that can be instrumental in adopting hydrogen technologies in Africa in the most effective way by encapsulating aspects relevant to key stakeholders from hydrogen technology developers through to end-users.

The next sections of this paper are arranged as follows: section Materials and Methods presents the methodology used in assessing the complex and dynamic landscape. Section Doughnut-PESTLE Hydrogen Model (DPHM) discusses aspects of the DPHM, section DPHM Implications and Recommendations discusses the DPHM implications and recommendations before concluding in section Conclusions.

Materials and Methods

A PESTLE analysis employed in this study can be described as a mechanism for assessing the ramifications of current and future external factors on a system or technology while assessing the effect of the system or technology in the context of where it is implemented [47]. It is handy when evaluating qualitative factors and for assessing problems comprehensively [36]. The quantitative aspect of this study involved the selection, collection, and ArcGIS Pro mapping of publicly available political, economic, social, technological, legal, and environmental indicators from The World Bank [28] and The Global Economy [29] relevant in analyzing the complex African landscape towards the adoption of hydrogen technologies. The PESTLE criterion in this study is focused on indicators relevant to key stakeholders from hydrogen technology developers through to the end-users. These indicators comprise of:

(a) Political - fragile state index, political stability index, government effective index, and control of corruption index.
(b) Economic - the cost of starting a business, ease of doing business, investment in energy with private partnership, and lending interest rate.
(c) Social – human development index, unemployment rate, and literacy rate - total adult and female.
(d) Technological - R&D expenditure, patent applications, high technology exports, and technical cooperation grants.
(e) Legal - rule of law index, regulatory quality index, strength of legal rights index, and property rights index.
(f) Environmental - access to electricity, electricity power consumption, CO_2 emissions, and total greenhouse gas emissions.

Doughnut-PESTLE Hydrogen Model (DPHM)

Planetary and Social Boundaries of the Hydrogen Economy

The hydrogen economy has a consensually projected potential of playing a key role in contributing to the net zero energy transition. However, its unsustainable

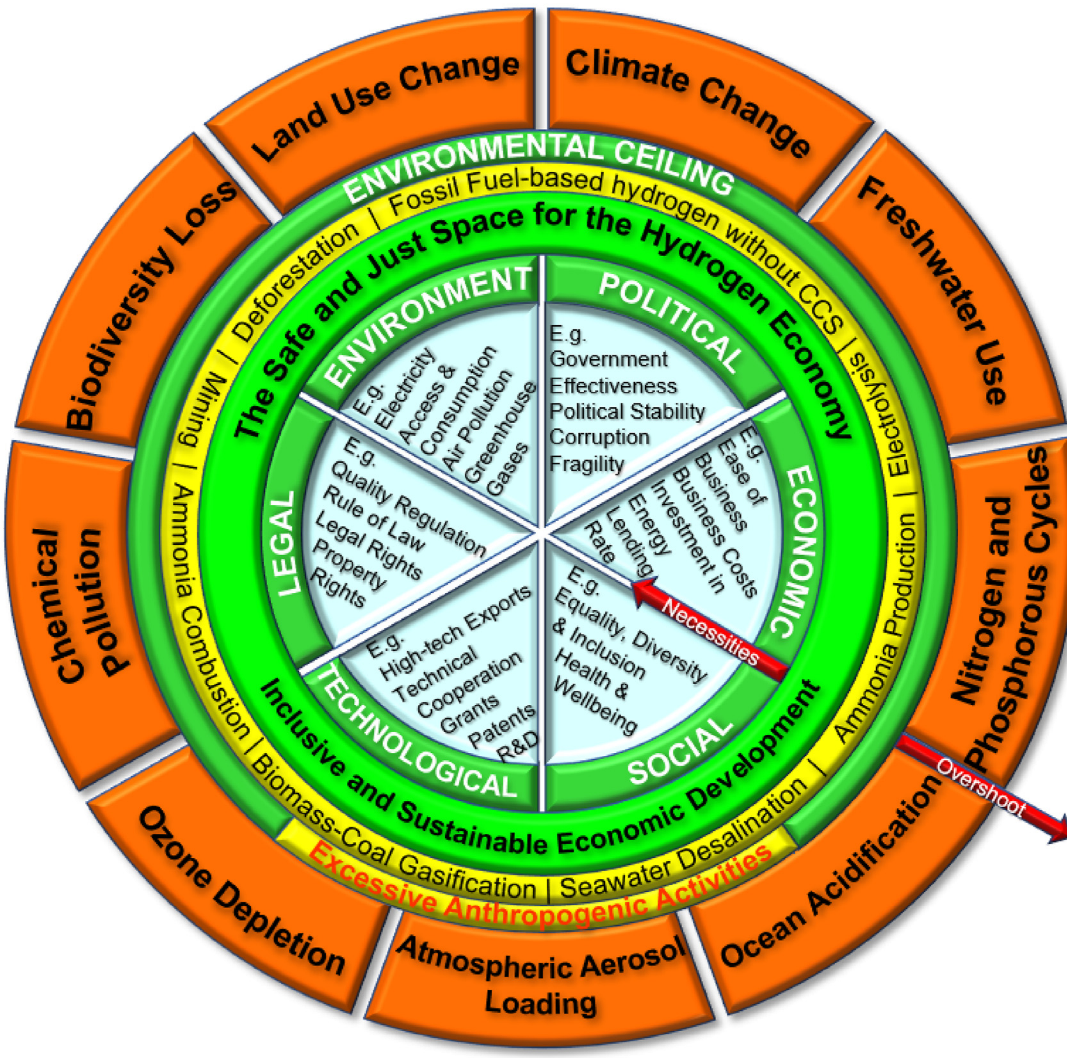

Fig. 1 – Doughnut-PESTLE Hydrogen Model (DPHM): A safe and just space for a thriving hydrogen economy.

production may come with unwanted consequences that may exacerbate planetary and social boundaries. The planetary boundary concept imparts a strong starting point aimed at understanding the natural resources and processes upon which humanity's sustainable development is dependent [30,48]. The nine planetary boundaries were developed in 2009 at the Stockholm Resilience Centre by 29 leading Earth-System scientists [48]. Planetary boundaries are defined as the safe and operating space for humans concerning the systems on Earth and are linked with Earth's diverse biophysical subsystems [48]. Surpassing either of the subsystem limits can lead to catastrophic effects such as extreme and disastrous weather events being experienced globally.

Human activities have been the primary cause of global environmental change since the industrial revolution and the hydrogen economy is no exception from worsening the current global environmental change if its implementation will not be sustainable. Fossil fuels which are the primary source of emissions enabled unprecedented economic growth since the beginning of the industrial revolution as society moved away from biomass as the primary source of energy. Hydrogen is no exception and could have disastrous effects too if not implemented sustainably. These interlinked Earth systems are discussed in the context of the hydrogen economy and how it may worsen these boundaries.

The Doughnut Economic Model is a tool that combines societal boundaries with planetary boundaries creating a doughnut-shaped area within which the human/earth systems can operate sustainably [30]. Exceeding the model boundaries will have negative consequences for the environment and economy. In this study, a Doughnut-PESTLE Hydrogen Model (DPHM) has been developed which is an adaptation of the Doughnut Economic Model. The DPHM places all the social boundaries within the social aspects of interlinked PESTLE analysis. A PESTLE analysis, combined with the planetary boundaries gives a broader perspective of hydrogen technology adoption and can be adapted for any system. Fig. 1 shows the DPHM highlighting the safe and just space for a thriving hydrogen economy. The main planetary boundaries and PESTLE conditions of the hydrogen economy are now discussed in the following sections.

Climate change

Hydrogen production processes such as fossil fuel-based hydrogen production without adequate carbon capture can increase the atmospheric carbon dioxide concentration leading to further global warming. For example, blue hydrogen (hydrogen produced from natural gas with carbon capture, utilization, and storage) is seen as a transition energy carrier while scaling green hydrogen production, however, utilization and subsequent release of this carbon dioxide into the atmosphere question the sustainability of such hydrogen. Knowing the carbon footprint and sustainability impact of hydrogen is necessary if the hydrogen economy were to play a key role in mitigating the impacts of climate change [1]. Hydrogen certification can foster reliability standards, transparency, and independent auditing and this can be attained through "guarantees of origin" because there are currently no global standards [1,49]. Furthermore, the currently proposed schemes differ significantly in the definition of sustainability and accountability of the emissions in the hydrogen supply chain [50]. International cooperation will be crucial in ensuring consistent terminologies and data to enable transparency and consistency in conversion between certification schemes [1].

Freshwater use

Excessive electrolysis can be described as the consumption of water for hydrogen production beyond the capacity of a country's renewable freshwater resources. Renewable freshwater is, without doubt, the most important element sustaining all the systems of the Earth thus its depletion, conversion, or uneven distribution across the Earth will have detrimental effects such as affecting the water cycle which sustains rainfed agriculture and life on earth in its entirety. Moreover, the sustainability and greenness of renewable hydrogen from regions with acute water shortages, and vast populations living without and below the UN daily limit of access to clean and safe drinking water [18,51] will be highly questionable.

The IRENA report [1] indicated that the forecasted green hydrogen production in 2050 (409 million tonnes) would require around 7–9 billion cubic meters of water which is less than 0.25% [52] of current freshwater. While this is true, it does not paint the true picture of acute water scarcity issues and millions of people who currently do not have access to clean and safe drinking water. For example, countries such as Namibia, South Africa, and North African countries are developing hydrogen strategies and planning implementation without first addressing the acute water issues in these countries. To put this into context, North African countries, Sudan, South Africa, Namibia, Zimbabwe, and Somalia have an overall forecasted water deficit of around 190 billion cubic meters in a sustainable 2050 water availability scenario [18].

An option for countries with fossil fuel reserves [53] can be to consider blue hydrogen while implementing long-term green hydrogen capacities. However, this pathway should be carefully assessed because the assets could suffer from premature write-downs due to green hydrogen cost reduction, tight global environmental policies [1], and lack of funding for new oil and gas projects [54]. Moreover, natural gas dominates blue hydrogen production costs, whilst the capital expenditure of carbon capture and storage additionally plays a key role [55]. Regions with high natural gas costs and not close to carbon storage sites would be characterized by high hydrogen production costs [55].

Nitrogen and phosphorous cycles

Large-scale nitrogen and phosphorous environmental impact have been primarily due to agricultural activities ranging from fertilizer production to utilization [56]. The incremental quantities of nitrogen and phosphorus activated anthropogenically are substantially large and massively disturb the global cycles of nitrogen and phosphorus [57,58]. The nitrogen and phosphorus cycles are expected to undergo more severe stress and perturbation because ammonia will now be produced for use as a hydrogen carrier in addition to fertilizer production for food production. Moreover, fertilizer production is poised to increase significantly to meet the needs of the fast-growing global population. Annual ammonia production is projected to reach 355 Mt in 2050 from the current 185 Mt [59]. This will be equivalent to extracting and converting about 292 Mt of nitrogen from the atmosphere annually into reactive forms. To put this into perspective, the anthropogenic annual proposed nitrogen cycle boundary is 35 Mt, and the nitrogen extraction rate was 121 Mt in 2009, which is about 2 and a half times less than the projected amount in 2050.

Biodiversity loss

Renewable energy technologies have been primarily responsible for large-scale land conversions resulting in biodiversity loss, and this is expected to worsen with renewable hydrogen production. For example, the Western Green Energy Hub in Australia for green hydrogen and ammonia production will cover an area of 15,000 km^2, approximately the size of Lesotho [1]. One of the highly commendable examples is how the Australian government rejected the world's biggest green-energy export project-Asian Renewable Energy Hub on environmental grounds [60]. Hydrogen production technologies such as nuclear hydrogen can prevent biodiversity loss due to the low land requirements [61]. But, nuclear hydrogen is currently improbable in developing countries due to low nuclear technology adoption levels and high capital requirements [62–66]. African countries should use their competitive vast land areas sustainably within the safe and just space of the hydrogen economy and human existence. A collaborative and collective approach by African countries to developing a sustainable hydrogen economy will further increase this competitive advantage.

Land use change

Mining activities and subsequent deforestation have the most effect and lasting impact on land and ecosystems, and the green hydrogen revolution will exacerbate the effects of mining activities. Exploration and expansion of mining activities linked minerals critical in the hydrogen economy utilized in electrolyzers and fuel cells such as nickel, zirconium, lanthanum, yttrium, including rare minerals such as platinum [67], and already key minerals in the net zero transition such as copper will increase land conversion activities. This is also challenging the conversion of protected areas for mining activities in some regions and countries. For example, the Lower Zambezi, in Zambia, home to some of the world's most exotic and diverse wildlife is currently under significant threat of being converted into a copper mine [68,69].

Chemical pollution and ocean acidification

The Stockholm Resilience Centre defined ocean acidification as the global mean saturation state of aragonite in surface seawater [48]. Aragonite provides essential materials for most sea life while maintaining ocean water pH around its natural levels [70]. The criticality of oceans towards global and marine life cannot be overemphasized because half of the world's oxygen is produced in oceans [71,72]. Technologies such as seawater desalination pose serious chemical and ocean acidification. The elevated salinity of seawater reverse osmosis brine is about twice that of seawater and the chemicals utilized in pretreatment and cleaning processes pose environmental risks to organisms when discharged into marine ecosystems [73,74]. Brine, a byproduct of seawater desalination [75] has the potential of altering the thermal balance thus affecting the growth rate of marine species [76].

Atmospheric aerosol loading and ozone depletion

Whereas hydrogen has the potential of transitioning households in low latitude developing countries from using traditional biomass for cooking and heating, it also has the potential of increasing atmospheric aerosol loading. Atmospheric aerosol loading is described as the overall particulate concentration in the atmosphere on a regional basis [48]. Hydrogen production technologies such as biomass and coal gasification have the potential of producing and releasing particulate matter into the atmosphere which poses substantial health threats and environmental issues [77–79].

With regards to ozone depletion (responsible for increased cancer risks, blindness, and poor sight in humans coupled with harmful effects on the global ecosystem), nitrogen oxide became the most significant ozone-depleting substance released through anthropogenic activities [10,80]. With the onset of high-temperature hydrogen oxidation, ammonia production, combustion, and fertilizer production, nitrogen oxide emissions are projected to increase proportionally thus posing a severe threat to the ozone layer. Nitrogen oxide remission or avoidance technologies such as solid oxide fuels [81–84] or nitrogen oxide reduction solutions [85–93] can be instrumental in shaping a sustainable hydrogen economy. Furthermore, ammonia production technologies such as nitric oxide reduction reaction (NORR) can facilitate the capture of nitrogen oxides from intensive sources in the form of nitrates and nitrites and subsequent conversion into ammonia [94–99]. NORR is seen as a feasible ammonia production due to the available and growing nitrogen oxide emissions, mature capture technologies such as wet scrubbing, and attractive ammonia production yields [96,99–110].

The next section discusses the role of the various highly interlinked PESTLE aspects in the context of a hydrogen economy, within the complex and dynamic African landscape.

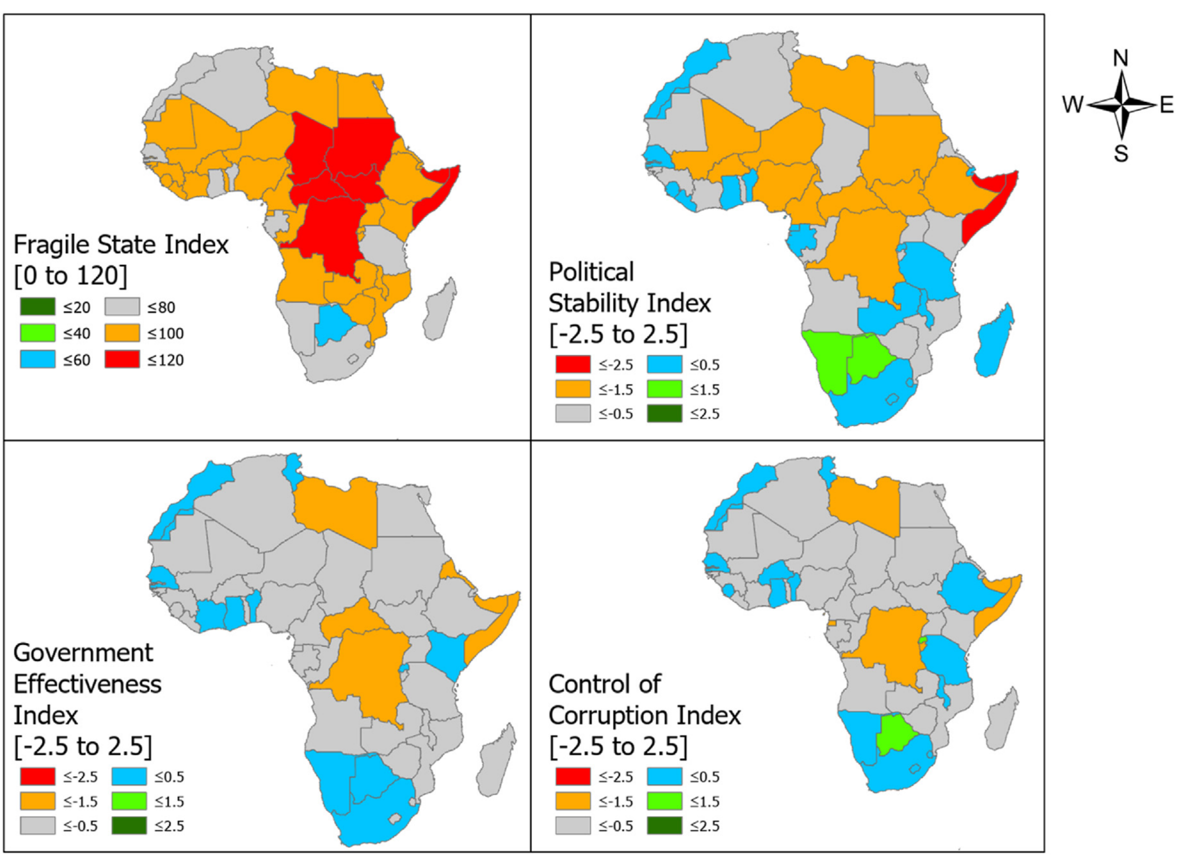

Fig. 2 – Political indicators (data mapped from Ref. [29]).

PESTLE Analysis

Political

Fig. 2 shows some of the political indicators that can exert an impact on hydrogen technology adoption in Africa. The government effectiveness index [29] represents perceptions of the quality of public services, quality of civil service, and the degree of independence from political interference. It also indicates the quality of policy formulation and implementation, and the credibility of a government in formulated policies. African countries with an index between 0.5 and −0.5 such as Namibia, South Africa, and Morocco are leading the planning of hydrogen economies through strategic cooperation and selection of hydrogen technology developers. While most countries fall below an index of −0.5, there are very few countries that are actively engaged with hydrogen technology developers such as Mauritius and Egypt. This index is also an important indicator especially due to the fragility of the hydrogen economy i.e., it has the potential to worsen the planetary and social boundaries as discussed in section Planetary and Social Boundaries of the Hydrogen Economy. The country-level environmental commitments in this regard can be accessed in Ref. [18].

The fragile state index [29] signifies the vulnerability of countries in pre-conflict, active conflict, and post-conflict environments. Implementation of hydrogen technologies bears significant risks due to the high capital intensity of hydrogen trade value chains, thus, reducing risks associated with technology development is cardinal for developers [1,111]. One of the ways of reducing these risks is by investing in countries with low fragile state indexes such as Botswana and Tunisia. However, investments still occur even in countries with high-risk profiles such as Mauritania and Nigeria. For example, an Australian developer signed a USD 40 billion memorandum of understanding with the government of Mauritania to construct one of the largest green hydrogen projects [1].

The political stability index [29] represents the perceptions of a likelihood that the government will be overthrown or destabilized by unconstitutional or violet means, including politically motivated violence and terrorism. However, the extent to which hydrogen developers can bear risks is limited by political stability to a great extent. For instance, some countries in central, west, north and east Africa may fail to unleash their hydrogen potential due to political instability and fragility [1] despite having huge renewable hydrogen potential [18].

The control of corruption index [29] represents the perceptions of the extent to which public power is utilized for personal gain, including both petty and grand forms of corruption, as well as capture of the state by elites and personal interests. Countries with low corruption indexes will attract developers due to the several benefits arising from corrupt free practices such as transparency, efficient procedures, and enabling a safe and just hydrogen economy for all.

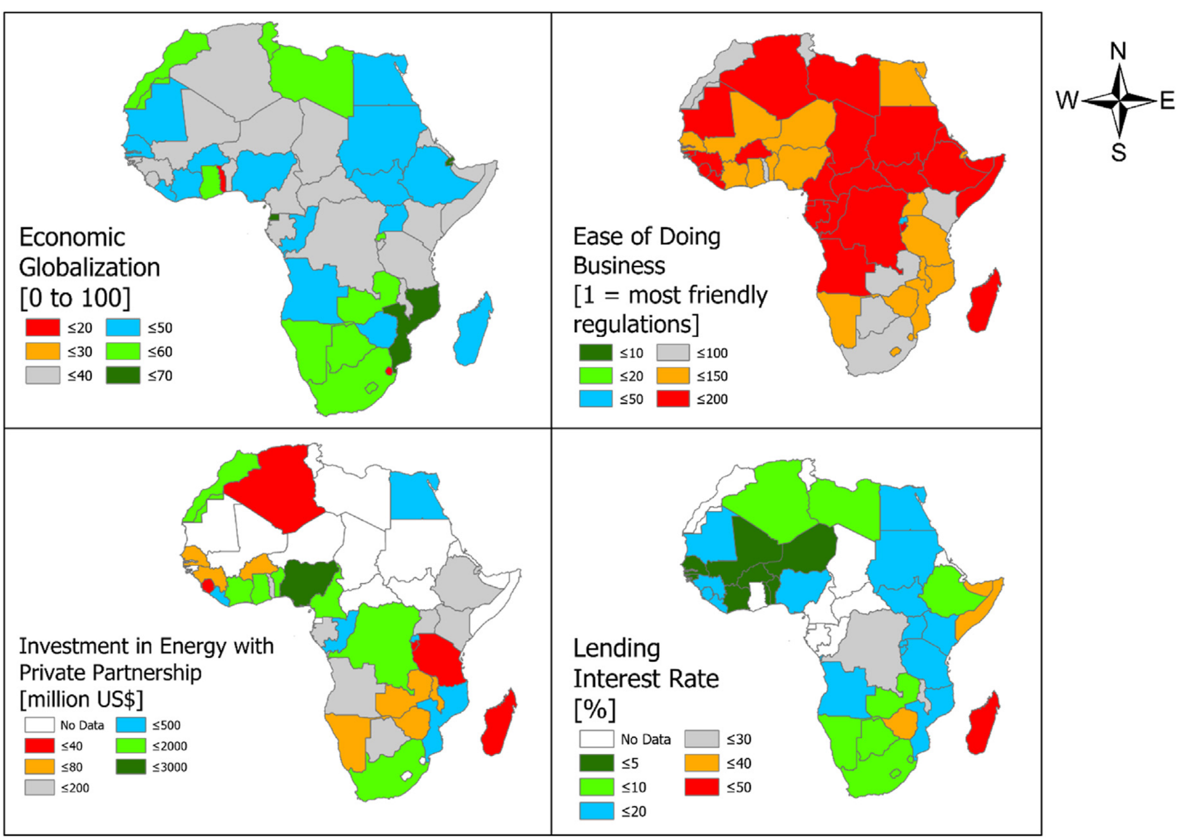

Fig. 3 – Economic indicators (data mapped from Refs. [28,29]).

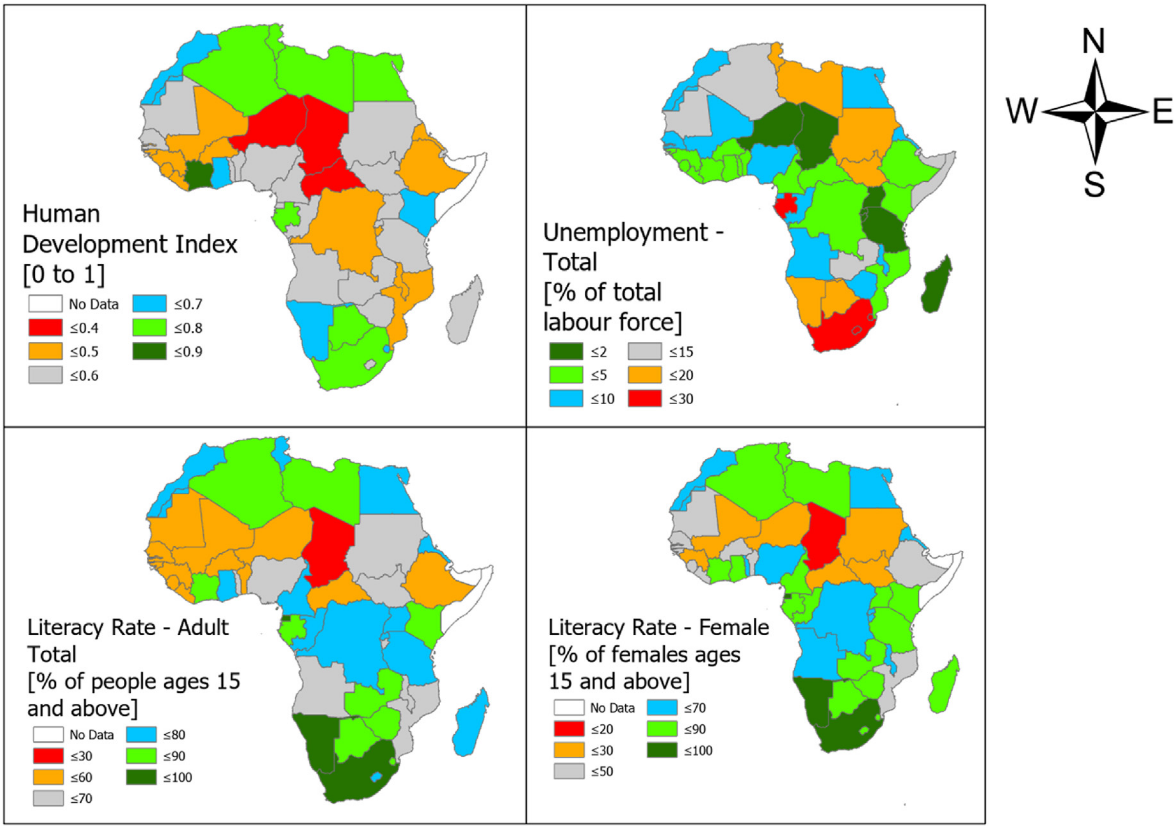

Fig. 4 – Social indicators (data mapped from Refs. [28,29]).

Economical

Fig. 3 shows some of the economic indicators that can be impactful on hydrogen technology adoption in Africa. The ease of doing business indicator [28] does not only measure the economic health of a country in macroeconomic terms but also by other factors that shape daily economic activities such as laws, regulations, and institutional arrangements. Business environment efficiency, accessibility, and implementation of rules and regulations will be key for hydrogen developers. For example, Morocco has the lowest indicator in Africa which can explain its development of renewable energy technologies in the past decade and its leading role in hydrogen development in Africa. Similarly, countries with a low cost of starting a business will be attractive to investors, though risks and revenues play a bigger role.

The economic globalization index accounts for the real economic flows and restrictions to trade and capital which include data on trade, foreign direct investment, portfolio investment, hidden import barriers, mean tariff rates, taxes on international trade, and an index of capital controls [29,112,113]. The importance of this indicator cannot be overemphasized due to Africa's potential of exporting renewable energy through hydrogen, and southern African countries are leaders in this aspect of trade attractiveness. A comprehensive analysis of hydrogen production potential and water availability, utilization, and distribution in Africa is available in our study [18].

Investment in energy in private partnership [28] represents the commitments to infrastructure projects in energy i.e., electricity and natural gas: generation, transmission and distribution, that reach financial closure and serve the public directly or indirectly. Investment in infrastructure projects with private participation is a crucial factor in reducing financial bottlenecks, efficiency improvement of infrastructure services, and the development of hydrogen technologies. Countries with a track record of successful investment in energy with private partnerships boost investor confidence consequentially tapping more of their hydrogen potential. For instance, countries such as Morocco, South Africa, Namibia, and Egypt are planning hydrogen projects with investors.

In the context of the hydrogen economy, developers will be keen on monitoring the strength of financial systems depending on the size and mobility of international capital flows because robust financial systems can spur economic activity, while unreliable systems can disrupt financial activities and lead to higher costs in a hydrogen economy [29]. Regional cost expectations of hydrogen production are also an important consideration, and this was mapped in the IEA report [114]. The mapping showed that the cost of hydrogen production in most southern, northern, and eastern African countries will be around 1.5 $/kg in 2030. However, the techno-economic assumptions in the report were not provided.

Social

Fig. 4 shows some of the social indicators that can be impactful on hydrogen technology adoption in Africa. The

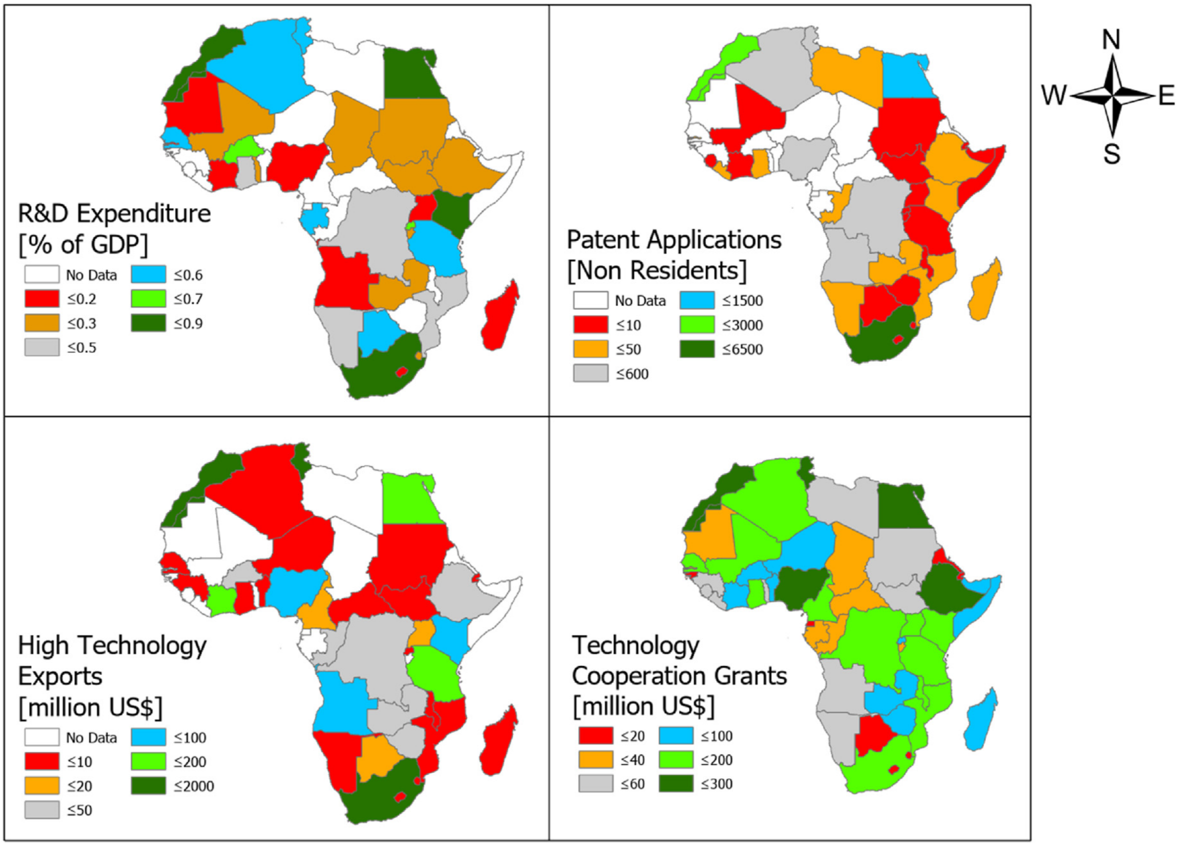

Fig. 5 – Technological indicators (data mapped from Ref. [28]).

human development index measures three basic dimensions of human development; long and healthy life, knowledge, and descent standard of living [29]. In the quest to develop a hydrogen economy that is safe and just for everyone, developers may use this index to see where the development of hydrogen technologies will have more impact while also benefiting from established dimensions such as the knowledgeability of a country.

While unemployment alone may not give a sufficient overview of a country's socio-economic status because low unemployment rates can signal considerably low socio-economic activity whereas high unemployment rates can signal high economic activity, interchangeably [28]. High unemployment rates are not desired because it translates into low progress in promoting sustainable and inclusive socio-economic growth. However, hydrogen technology developers can leverage high unemployment rates as a signal of a readily available labor force. But again, the availability of this labor force depends on other factors such as literacy levels and population distribution. And most importantly, the readily available workforce should not be exploited by developers due to a lack of opportunities elsewhere.

The literacy rates assist in predicting the quality of future labor [28] and can be used by hydrogen technology developers in predicting the labor force available for essential skill training. A high literacy rate in women implies a continued and sustained education system in the foreseeable future because literate women actively seek and utilize the information for the improvement of education, and the health and well-being of their households [28]. Hydrogen developers with gender equality objectives may benefit and want to penetrate markets with high rates of female literacy rates.

Technological

Fig. 5 shows some of the technical indicators that can have a substantial impact on adopting hydrogen technologies in Africa. The gross domestic expenditures on research and development (R&D) including both capital and current expenditures in business enterprise, government, higher education and private not-for-profit [28] will ultimately separate the big players from the passive and small players in the hydrogen economy. This R&D expenditure encapsulates basic research, applied research, and experimental development. Because expenditure on R&D is a critical indicator of government and private sector deliberate attempts to acquire competitive advantages in science and technology [28], hydrogen developers will be looking for countries that have an impressive record of investing heavily in R&D. One of the key areas R&D will play a key role is in technology performance due to Africa's current technological passive user status. Most of the current research on hydrogen technologies is based on European and Asian environmental and climatic conditions. Thus, it'll be essential to understand how these technologies will perform in different environments i.e., hotter, and dustier environments in comparison with conditions of technology origin.

Patent data is a substantial asset when studying the technical change in a country or region and provides a detailed

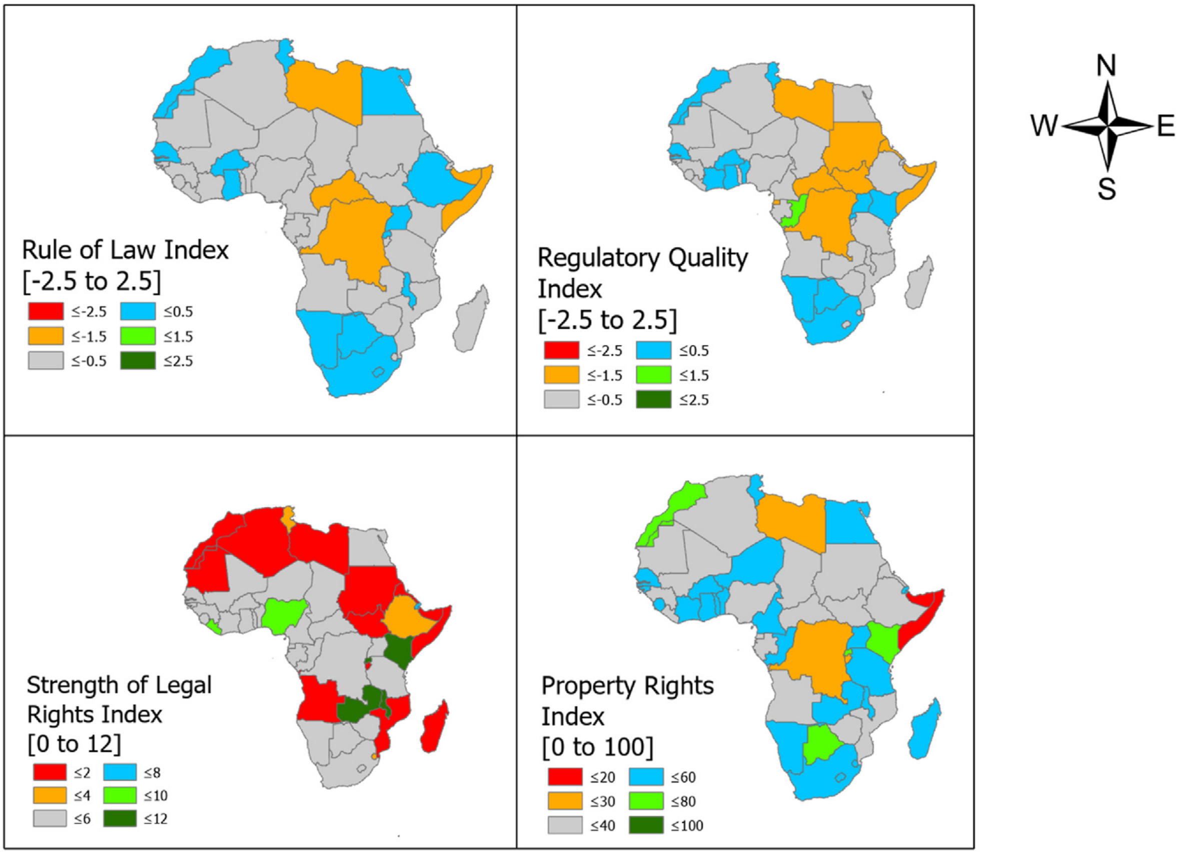

Fig. 6 – Legal indicators (data mapped from Refs. [28,29]).

source of information on inventions and several dimensions of the inventive process such as geographical location, technical and institutional origin, individuals, and networks [28], thus, it will be of uttermost importance to hydrogen technology developers. In the context of hydrogen technology adoption, patent data will create a consistent basis for comparative analysis between countries covering varying topics related to technical change and strategies by organizations, internationalization of research, and values of patents [1,28]. Patent-based statistics reflect the inventiveness of countries, regions and firms, including cooperation during innovation or technological paths [28], and this is seen in African leaders in hydrogen adoption such as South Africa which leads the entire continent by a huge margin, followed by Morocco and Egypt. Key players such as Germany and Japan will be looking to form strategic technological partnerships in Africa despite being net importers because it will be beneficial to establish technological partnerships with hydrogen exporting countries.

High technology exports [28] can be described as products with high R&D intensity such as aerospace, computers, pharmaceuticals, scientific instruments, and electrical machinery. While high technology exports signify the relevance of expenditures on R&D concerning the gross output and value addition of various types of industries that produce goods for export [28], they also signify the capabilities of countries to establish competitive trade markets in the hydrogen market due to developing regulatory standards in the hydrogen economy.

Technical cooperation grants are intended to finance and facilitate the transfer of technical and managerial skills or technological skills towards developing capacity without reference to any specific investment projects, and investment-related technical cooperation grants that strengthen capacity in executing specific investment projects [28]. Countries with high technical cooperation grants such as Egypt and Ethiopia will be attractive to hydrogen developers and importing countries due to their capability of developing capacity, in this case, hydrogen production capacity. The establishment of hydrogen trade relations can spur cooperation towards accessibility of technology, skilled workforce, information, and investment because different countries have different abilities in developing large-scale green hydrogen potentials. For instance, memorandums of understanding can be signed by governments and investors enabling the transfer of skilled workers between countries in the hydrogen service industry i.e., installation, commission, and maintenance of electrolyzers and fuel cells. This will not only be socially beneficial between countries due to the creation of employment and training of the local workforce, but it will also be highly beneficial to the investors due to reduction of initial workforce training thus facilitating quick hydrogen economy growth.

Legal

Fig. 6 shows some of the legal indicators that can have a considerable impact on hydrogen technology adoption in

Africa. The rule of law index [29], in the context of the hydrogen economy, can represent perceptions to which developers have confidence in and abide by the rules of society, particularly, the quality of contract enforcement, the police, and the courts. As previously, the rule of law index is one example of how the PESTLE factors are interlinked. For instance, countries with all-round favorable PESTLE conditions such as South Africa and Morocco are spearheading the hydrogen economy in Africa while struggling to achieve social equity.

The regulatory quality index [29] represents perceptions of a government's ability to develop and implement sound policies and regulations that permit and promote private sector development. The key role of the private sector involvement in developing hydrogen technologies cannot be overemphasized not only due to investments and knowledge transfer but also due to regulatory standards. Countries that have strong regulatory indexes such as the Republic of Congo will be in a better position to shape rules and standards that suit the international hydrogen trade market. Successful implementation of the hydrogen economy is bent on systematic and transparent rules and standards aimed at facilitating the implementation of hydrogen technologies within countries, regions, and continents [1]. Whereas the aim of hydrogen standards should be to enhance the quality, safety, and integration of technologies, varying standards have the potential of slowing the progression of the hydrogen economy thus leading to market disintegration, fierce regulation-based competition, and stimulation of trade obstacles [1].

The strength of legal rights [28] which measures the extent to which collateral and bankruptcy laws protect the rights of borrowers and lenders thus facilitating lending will also be critical for hydrogen technology developers. Robust laws enable expansion and accessibility to credit thus countries such as Kenya, Zambia, and Rwanda are attractive in this regard. However, countries such as Morocco and South Africa are leading technology development because the respective governments are effective, and have strong political stability and corruption indexes. The availability and accessibility to finance can increase opportunities for all with higher levels of access and use of banking services linked with lower financial obstacles for people and businesses [28] in the hydrogen space. Thriving local business environments and hydrogen trade markets will also be essential in the implementation of hydrogen technologies.

While the property rights index [29] which measures the extent to which private property rights are protected by a country's laws and the extent to which a government enforces such laws will influence developers, other factors such as a country's susceptibility to extreme climatic disasters will influence investors due to associated risks. Countries with high property indexes, among other factors, such as Namibia and South Africa have signed memorandums of understanding and are undertaking green hydrogen and ammonia export hub feasibility assessments [1,115].

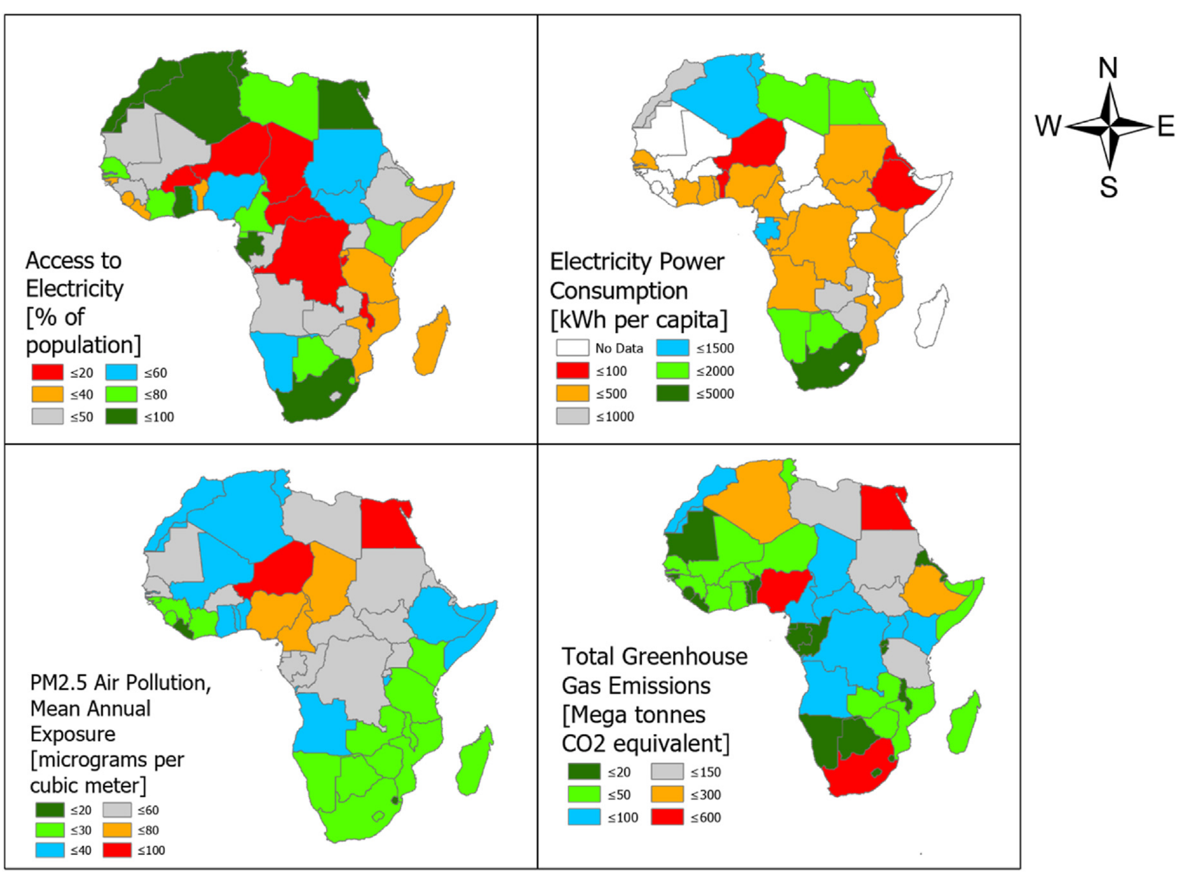

Fig. 7 – Environmental indicators (data mapped from Ref. [28]).

Environmental

Fig. 7 indicates some of the environmental indicators that can have a considerable impact on hydrogen technology adoption in Africa. For instance, electrification of the population without access to electricity in developing countries should be a priority before producing hydrogen using renewable energy sources for local consumption or export [18]. Hydrogen technology developers may choose countries such as South Africa, Ghana, Egypt, Tunisia, Morocco, and Algeria, that have substantial electricity access to maintain the sustainability and greenness of the hydrogen produced. Countries such as Namibia, South Africa, and Mauritania have hydrogen projects in the pipeline despite their low access to electricity. However, sustainable hydrogen technology developers have an opportunity not only to produce renewable hydrogen but also to tap into this potent market by providing clean electricity.

The energy security offered by hydrogen should extend beyond availability and affordability to enable sustainability and equity for all. Importing hydrogen from countries with low percentages of electricity access or a mainly carbonized electricity grid can hardly be seen as sustainable [1,18]. However, there is an interesting potential here for the hydrogen economy embedded in the lack of clean energy access because hydrogen developers have the unique opportunity to meet the energy needs of this available local market such as hydrogen for clean cooking, health services, industrial needs, or ammonia for fertilizer production. The hydrogen economy is usually perceived as an egg and chicken problem; thus, this existing market can be one way of initiating hydrogen demand. Countries with a lack of clean energy access may well be in a better position to attract hydrogen technology developers due to this synergy.

The electricity power consumption in Africa is yet another stern reminder and a grim picture of clean energy accessibility in Africa and the role hydrogen can play in this complex energy landscape. Besides South Africa, Botswana, Namibia, Egypt, and Libya, the other African countries are well below the ideal electricity power consumption necessary for economic growth. Contrastingly, countries such as Algeria, Tunisia, Morocco, and Ghana are well below ideal electricity power consumption despite having high access to electricity, and this shows that individual assessment of factors may not provide a comprehensive overview of a landscape. The electricity power consumption can also be an important indicator of clean energy poverty and subsequent harmful environmental activities such as deforestation due to a need of unclean woody fuels and charcoal.

Similarly, air pollution is a reminder of clean energy access in developing countries. Many households depend on charcoal, wood, dung, crop waste, or fossil fuels to meet daily energy requirements [28,116]. Though the air pollution in micrograms per cubic meter shows that African countries have different exposure levels, all the African countries have levels exceeding the World Health Organisation guidance levels [28]. It thus becomes imperative for hydrogen technology developers to seriously consider avoiding hydrogen technologies that have the potential of exacerbating the air pollution in developing countries.

The effect of greenhouse gas emissions and subsequent climate change is significant in low-latitude developing countries due to their extremely low resilience toward climatic disasters. Countries such as Malawi, Mozambique, and Madagascar continue to experience intense climatic disasters such as Storm Ana which leveled villages, killed dozens, and destroyed infrastructure [117]. In contrast, the total greenhouse gas emissions in these countries are very low compared to other countriesin Africa. The resilience [118] of developing countries needs to be improved especially if developers are going to install hydrogen technologies in these regions. Furthermore, hydrogen production may compete with food production in activities such as the conversion of hydrogen to ammonia for export purposes without meeting the local ammonia and fertilizer needs. However, high greenhouse gas emissions can also highlight an industrialized economy, and subsequently potential hydrogen demand opportunities. The next section discusses the implications of the DPHM.

DPHM Implications and Recommendations

The previous section and Fig. 1 have shown how hydrogen technology adoption may interfere with the interlinked Earth systems and worsen the planetary boundaries. The Doughnut-PESTLE hydrogen model (DPHM) approach to analyzing the hydrogen economy has raised more research questions than answers regarding the planetary boundaries especially because some planetary boundaries were already exceeded. Some of the questions are (a) how much more should hydrogen contribute to climate change since the boundary was already exceeded? (b) how much more biodiversity should be lost since the boundary was already exceeded? (c) how much nitrogen should be removed from the atmosphere for ammonia production? What will be the global or country-level sustainable nitrogen extraction rate since the boundary was already exceeded? (d) how much more seawater should be desalinated beyond unsustainable levels? (e) how much more land should be converted for hydrogen economy activities? and (f) what will be the accepted environmental pollution from the hydrogen economy? Further research and the lessons learned from the utilization of fossil fuels will be key in answering these questions to ensure that we do not repeat the same mistakes.

Furthermore, what will be the country-level planetary boundaries? Answering this question will enable a just and safe hydrogen economy for everyone due to maximum country-level accountability. Open-ended and global boundaries such as the Paris Agreement 1.5 °C goal are prone to individualistic efforts. For instance, a case could be made for developing countries with fossil fuel reserves to produce hydrogen unsustainably since the greenhouse gas emissions of most developing countries are well below those of developed countries. However, continuing a path of destruction in the name of playing ‘economical catch up’ will only lead to more catastrophic effects of surpassing planetary boundaries. Moreover, green hydrogen production offers developing countries a unique opportunity to catch up economically and industrially.

However, seizing the opportunities ingrained in the hydrogen economy is an individual country's responsibility as much as it is a global responsibility. Effective countries will be equal to the task of implementing a safe and just hydrogen economy while also attracting hydrogen technology developers. Fig. 8 and Fig. 9 show the overlayed PESTLE indicators and country ranking used in this study to give a better country overall picture of each country's position in developing a hydrogen economy. The characterization was applied without weighting but based on all parameters analyzed. Weighting could be an extension of this research with perhaps expert input to identify if certain factors are more important than others. However, The World Bank and The Global Economy data used in this study are robust and globally accepted.

Moreover, the PESTLE analysis was validated by comparing the results with south Asia, east Asia, and the Pacific region in the supplementary material. This region was selected because it has a perfect mix of advanced and developing countries, coupled with global leaders in the hydrogen economy. Fig. 8 clearly demonstrates that political, economic, social, technological, legal, and environmental conditions give a better overall picture when analyzed wholly unlike individually. For instance, some countries such as Kenya and Malawi have strong political and legal conditions but perform poorly in other aspects. Interestingly, the top 5 countries which include South Africa, Morocco, Nigeria, Egypt, and Ghana have all-round stronger conditions in comparison with other countries, while countries in the bottom 10 have all-round poorer conditions. The analysis agreed very well with the results in south and east Asia, and the Pacific where the top 5 countries are presently world leaders in hydrogen and include Japan, China, South Korea, and Australia. Therefore, this analysis provides the much-needed crucial landing platform for hydrogen investors interested in Africa. It also signifies the importance of improving the attractiveness of poorly performing countries to hydrogen technology developers and spearheading the hydrogen economy.

Africa presents a unique opportunity for investors to leverage the propitious conditions such as low access to electricity and low unemployment rates. Even though low access to electricity may entail higher investment capital, it is a win-win situation for all due to the readily available market. Therefore, the onus is on the respective country, regional and African association(s) leaders to be unequivocally intentional about spearheading favorable hydrogen-based policies for the hydrogen economy to have a meaningful impact on the continent and the global energy landscape as a whole. These include:

(i) Enabling transparent, independent and effective governments,
(ii) Creating robust democratic systems,
(iii) Creating business-friendly environments,
(iv) Establishing upskilling programs especially targeted at women because where women lead, economies thrive,

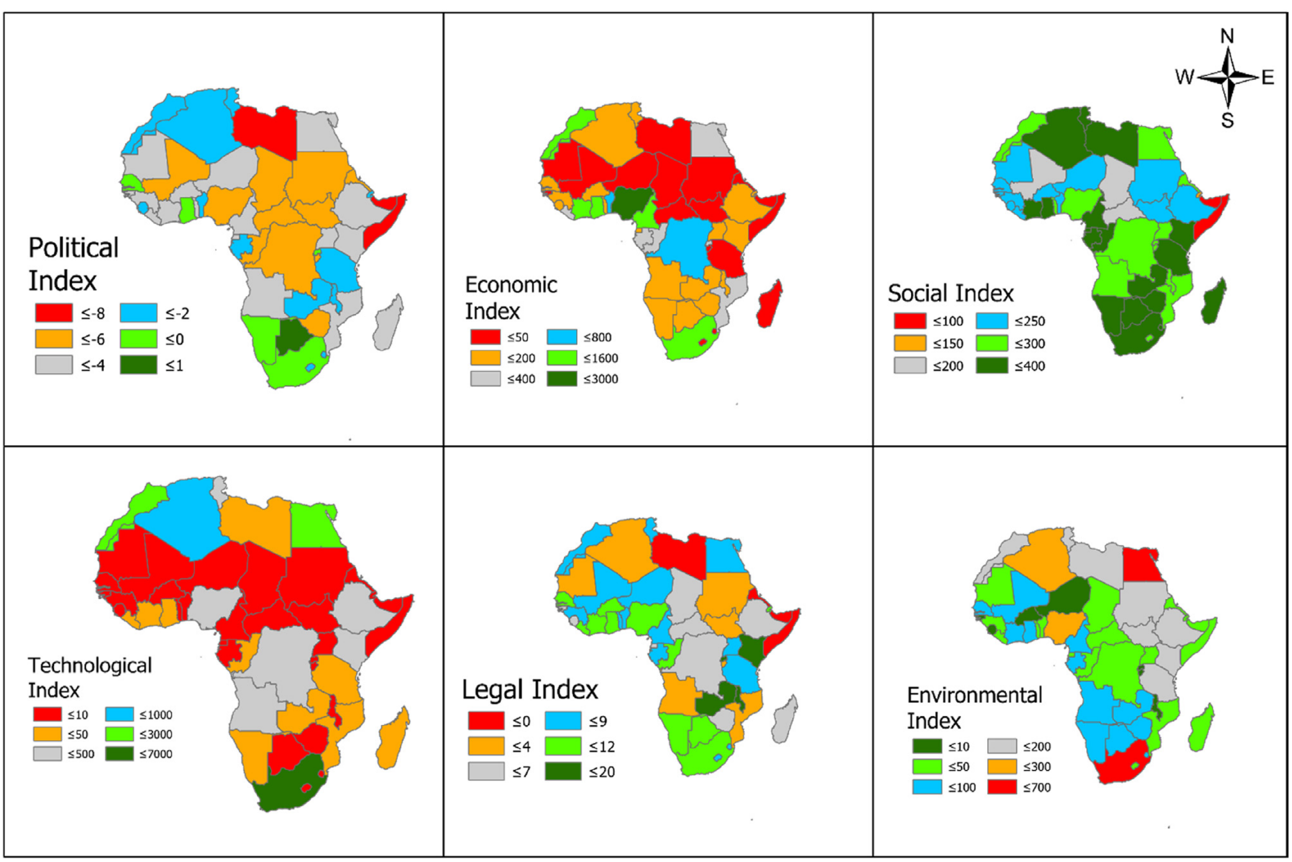

Fig. 8 – Overlayed PESTLE indicators.

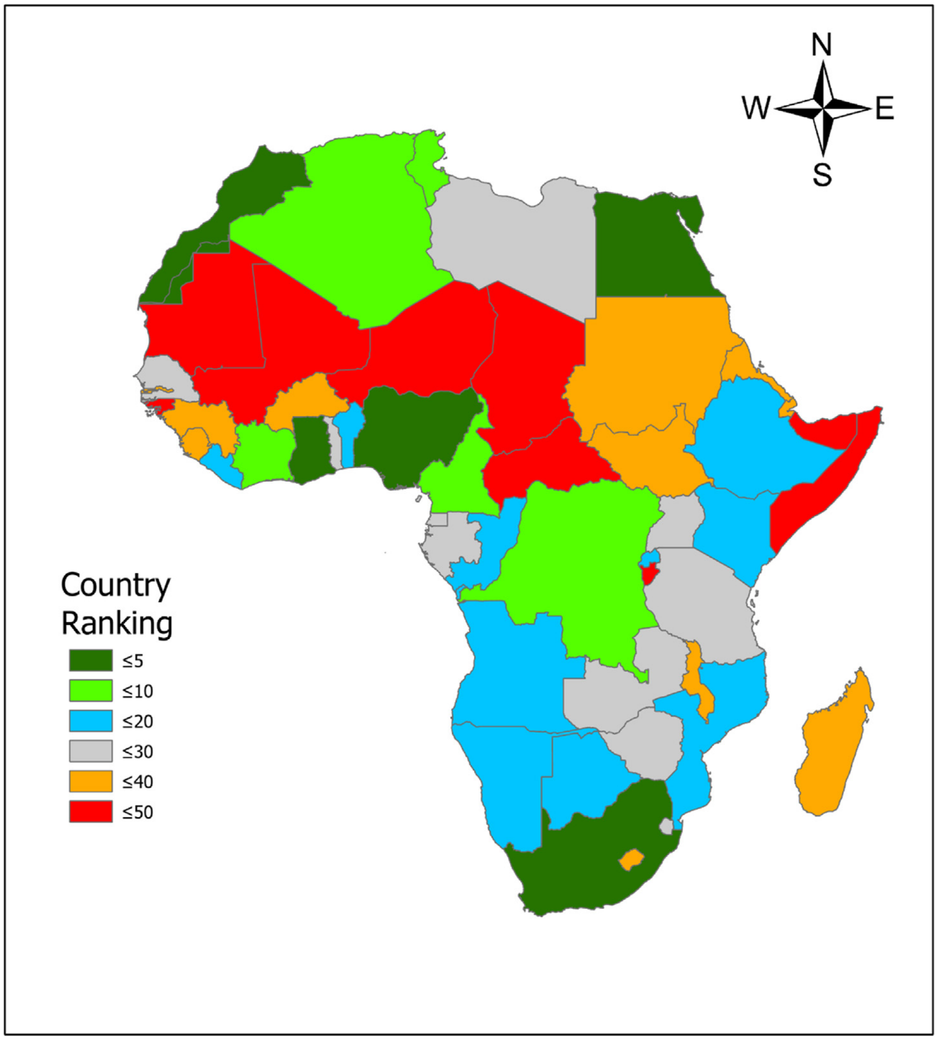

Fig. 9 – Country ranking.

(v) Spearheading research and development programs targeted at the entire hydrogen supply chain which will ultimately increase the technological attractiveness,
(vi) Developing transparent regulatory, legal, and property frameworks in line with international standards, and
(vii) Implement measurable policies aimed at improving access to electricity, and water, protecting the environment, and public awareness campaigns.

Conclusions

This study assessed the social and environmental impact of adopting hydrogen technologies. It also evaluated the political, economic, social, legal, and environmental (PESTLE) conditions that can be instrumental in adopting hydrogen technologies in Africa in the most effective way by encapsulating aspects relevant to key stakeholders from hydrogen technology developers through to end-users.

The hydrogen economy will play a key role in transitioning to a net zero energy economy. However, its unsustainable production may come with unwanted consequences that may exacerbate planetary and social boundaries. The excessive anthropogenic activities in the context of hydrogen technology adoption include activities such as fossil fuel-based hydrogen production without carbon capture and storage, excessive electrolysis, unsustainable ammonia production, excessive seawater desalination, and unsustainable biomass/coal gasification, unclean ammonia combustion, and unsustainable mining and deforestation.

The PESTLE analysis has shown that African countries with a government effectiveness index between 0.5 and −0.5 such as Namibia, South Africa, and Morocco are leading the planning of hydrogen economies through strategic cooperation with hydrogen technology developers. Meanwhile, there are very few countries that are actively engaged with hydrogen technology developers such as Mauritius and Egypt below an index of −0.5 where most countries fall. Furthermore, hydrogen technology development has significant risks and one of the ways of reducing these risks is by investing in countries with low fragile state indexes such as Botswana and Tunisia. Even so, investments still occur even in countries with high-risk profiles such as Mauritania. However, the extent to which hydrogen developers can bear risks is limited by political stability to a great extent.

The business environment efficiency, accessibility, and implementation of rules and regulations will be key for hydrogen developers. For instance, Morocco has the lowest indicator in Africa which can explain its development of renewable energy technologies in the past decade and its leading role in hydrogen development in Africa. In addition, countries with a track record of successful investment in energy with private partnerships boost investor confidence consequentially tapping more of their hydrogen potential as observed in Morocco and South Africa.

While hydrogen technology developers can leverage high unemployment rates as a signal of a readily available labor force, the availability of this labor force depends on other factors such as literacy levels. Hydrogen developers with gender equality objectives may benefit and want to penetrate markets with high rates of female literacy rates because high literacy rates in women imply a continued and sustained education system in the foreseeable future.

Because expenditure on R&D is a critical indicator of government and private sector deliberate attempts to acquire competitive advantages in science and technology, hydrogen developers will be keen on partnering with countries that have an impressive record of investing heavily in R&D. One of the key areas R&D will play a key role is in technology performance due to Africa's current technological passive user status. Thus, it'll be essential to understand how these technologies will perform in different environments i.e., hotter, and dustier environments in comparison with conditions of technology origin. Key players such as Germany and Japan will be looking to form strategic technological partnerships in Africa despite being net importers because it will be beneficial to establish technological partnerships with hydrogen exporting countries.

Furthermore, the key role of the private sector involvement in developing hydrogen technologies cannot be overemphasized not only due to investments and knowledge transfer but also due to regulatory standards. Countries that have strong regulatory indexes will be in a better position to shape rules and standards that suit the international hydrogen trade market. Additionally, countries with high property indexes such as Namibia and South Africa are attractive to hydrogen developers and have signed memorandums of understanding and undertaking feasibility assessments.

Lastly, but equally important, the energy security offered by hydrogen should extend beyond availability and affordability to enable sustainability and equity for all. Importing hydrogen from countries with high percentages of electricity access or a mainly carbonized electricity grid can hardly be seen as sustainable. However, there is an interesting potential here for the hydrogen economy embedded in the lack of clean energy access because hydrogen developers have the unique opportunity to meet the energy needs of this available local market such as hydrogen for clean cooking, health services, industrial needs, or ammonia for fertilizer production.

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Credit author statement

Mulako Dean Mukelabai: Conceptualisation, Methodology, Formal analysis, Writing – Original draft preparation. Writing – Reviewing and Editing, Visualisation, Preparation.: Upul Wijayantha: Conceptualisation, Supervision, Writing-Reviewing and Editing.: Richard Blanchard: Conceptualisation, Supervision, Writing-Reviewing and Editing.

Attribution

Fig. 1 is adapted from Professor Kate Raworth's Doughnut Economic model [119] which is under a Creative Commons License and subject to copyright https://creativecommons.org/licenses/by-sa/4.0/.

Disclaimer

The adopted model (DPHM) does not necessarily represent the views of Professor Kate Raworth.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.07.076.

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