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Review

A Policy Review of Green Hydrogen Economy in Southern Africa

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Abstract: Renewable energy and clean energy have been on the global agenda for energy transition for quite a long time but recently gained strong momentum, especially with the anticipated depletion of fossil fuels alongside increasing environmental degradation from their exploitation and the changing climate caused by their excessive carbon emissions. Despite this, Africa's pursuit to transition to a green economy using renewable energy resources still faces constraints that hamper further development and commercialization. These may include socio-economic, technical, political, financial, and institutional policy framework barriers. Although hydrogen demand is still low in Southern Africa, the region can meet the global demands for green hydrogen as a major supplier because of its enormous renewable energy resource-base. This article reviews existing renewable energy resources and hydrogen energy policies in the Southern African Development Community (SADC). The significance of this review is that it explores how clean energy technologies that utilize renewable energy resources address the United Nations sustainable development goals (UN SDGs) and identifies the hydrogen energy policy gaps. This review further presents policy options and recommends approaches to enhance hydrogen energy production and ramp the energy transition from a fossil fuel-based economy to a hydrogen energy-based economy in Southern Africa. Concisely, the transition can be achieved if the existing hydrogen energy policy framework gap is narrowed by formulating policies that are specific to hydrogen development in each country with the associated economic benefits of hydrogen energy clearly outlined.

Keywords: policies; green hydrogen; renewable energy; climate change; sustainable development; Southern Africa

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1. Introduction

The political momentum for hydrogen energy advancements and market use has continued to grow over the years. Since 2019, against the specter of climate change and diminishing fossil fuels, the world has developed significant interest in investing in low-carbon hydrogen. During this year, 2021, and subsequent years, many countries have announced hydrogen strategies and roadmaps globally to set investment targets to deploy hydrogen energy technologies. However, at the rate of carbon emissions globally and without increasing the low-carbon production capacity, further environmental degradation and poor health systems are eminent. This points to a need to transition to a green economy [1–3]. Transforming toward a green economy demands a profound overhaul of social and economic structures, updating the current infrastructure and technologies that were fossil fuel-based, and institutions concerning the green energy policy. Pegels et al. defined green energy policy "as encompassing any policy measure aimed at aligning the structure of a country's energy sector with the needs of sustainable development within established planetary boundaries, is critical to this end" [4]. Beyond merely focusing on countries in Southern Africa, this study focuses on the fourteen SADC countries, and these include Angola, Botswana, Democratic Republic of Congo (DRC), Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, South Africa, Tanzania, Zambia, and Zimbabwe.

Most nations in Southern Africa are characterized by several policy framework conditions that discriminate against the exploitation of renewable energy resources and other secondary clean energy options such as green hydrogen energy in Southern Africa [1]. As the green hydrogen energy market in Southern Africa and globally has progressed with the intention to achieve a green economy and their emission targets under the Paris Climate Agreement, many developed nations are looking into creating possible bilateral business partnerships with African nations to share their hydrogen energy technology advancements and expertise [3,5]. The reason for this renewed interest in Africa is because of its immense renewable energy resources. However, Africa still lags when it comes to renewable energy and green hydrogen policies that would serve as enablers to the decarbonization and energy transition plans of the region to reduce climate change impacts [1,5].

Furthermore, in most countries in Southern Africa, renewable energy resources are not clearly defined statutorily, but are rather inserted in frameworks of competition and regulations within the energy sector, and this general approach has already affected the implementation and investment possibilities of renewable energy projects [3,6]. This already puts secondary renewable energy solutions such as green hydrogen energy at a disadvantage concerning exploitation and investments.

Investing in green hydrogen energy and renewable energy is important because it reduces environmental degradation and boosts sustainable energy production and sustainable consumption in Southern Africa. Currently, out of the total energy consumption rationale in Southern Africa, modern renewable energy is still very low, standing at 8% as of 2013, but is expected to ramp up to 23% by 2030 [7]. This situation is further exacerbated by the fact that the existing policies in Southern Africa do not promote renewable energy development and hydrogen energy [1]. This works against the global goal to achieve a green energy transition in sub-Saharan Africa. Green hydrogen demonstrates a capability to provide fuel for power plants that are currently fossil-fuel based, especially in South Africa, making it a critical resource to transform grids to achieve 100% zero-carbon energy [8]. Furthermore, this will also help decarbonize the economy and help achieve a greater green energy transition that emphasizes clean energy technology such as green hydrogen. Since clean energy technologies such as green hydrogen can only take-off successfully with support from the public sector and governments, there is a need to review the public policy framework in Southern Africa for green hydrogen energy development. Politics play a major role in resource exploitation.

However, one major setback in the advancement of renewable energy resources is politics. The over underlined politics of energy transition to a green economy in the region favors conventional energy development more than renewable energy within the public sector regulatory and policy framework, which reduces the renewable energy development due to insecure legislation in the energy sector [4,9]. This puts the development of green hydrogen at a disadvantage because renewable energy resources are used to produce green hydrogen energy.

This review article analyzes the existing renewable resources and hydrogen energy policies in Southern Africa and recommendations for policy formulation at the regional and national level concerning green hydrogen as well as the development of a national and regional green hydrogen energy policy framework, strategy, and action plans.

The significance of this green hydrogen economy review article is that the green hydrogen economy policy review will make recommendations that will guide nations in Southern Africa (particularly SADC nations) on policy formulation concerning the energy transition for the development of a green economy at the regional and national level [1]. The United Nations Environmental program (UNEP), clearly states and clarifies that "enabling conditions consist of national regulations, policies, subsidies and incentives, as well as international market and legal infrastructure, trade and technical assistance" [10].

2. Methods

A six-step methodology of first reviewing the existing renewable energy and hydrogen energy policies in SADC states, and second, reviewing the hydrogen energy footprints, and highlighting the significance of having a strong policy framework that governs the hydrogen energy development in SADC was adopted. Furthermore, a detailed policy status in all the SADC countries was established, after which, the significance of having hydrogen energy policies in place that support its development is described. The last step of the review presents all the possible policy options that can be expected out of the hydrogen supply chain network. Figure 1 gives a visual display of the adopted methodology.

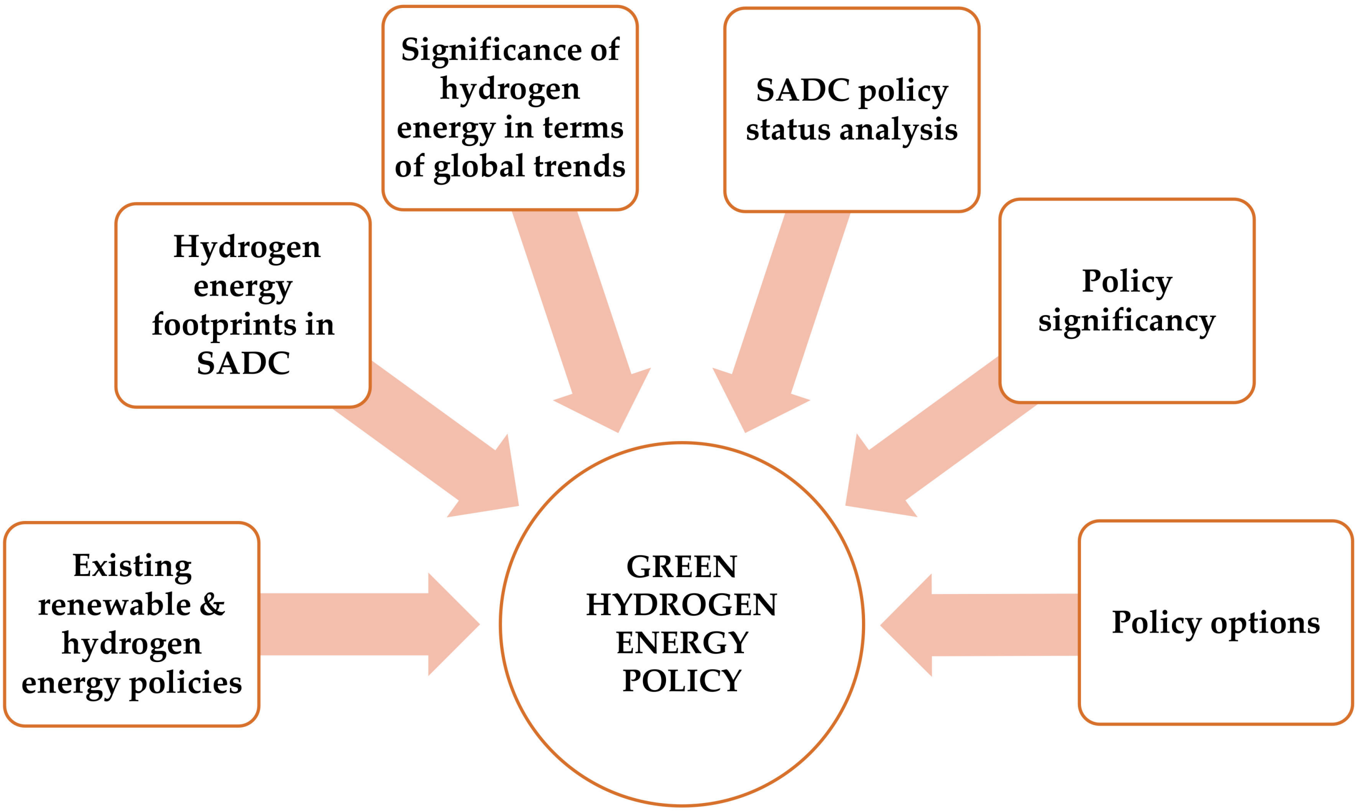

Figure 1. Green hydrogen energy policy review methodology in SADC.

In more detail, the different steps undertaken for this review are explained below:

Step 1. Reviews the different renewable energy and hydrogen energy policies in all the SADC states and then analyzes them to establish if the current standing allows or promotes the development of hydrogen energy in SADC countries.

Step 2. Reviews history of any footprints in SADC that would help make recommendations of how to approach the establishment of a sound policy framework.

Step 3. Reviews the significance of hydrogen energy development. Furthermore, the global trends are also taken into consideration and used to benchmark the development of hydrogen in the SADC region. The review also develops policy options by considering the entire hydrogen supply chain network from electrolysis through the infrastructure, industry, aviation, and shipping industrial sectors.

Step 4. The existing policies are then evaluated and analyzed using a matrix to establish the entire regional policy status. This would help investors know whether the SADC region is policy-ready for hydrogen development or whether they would need to include the formulation of policies in their initial phasing out of hydrogen energy projects. This may even be included in the financing proposal.

Step 5. An explanation of the significance of hydrogen energy in terms of social and environmental well-being is conducted by explaining the different ways in which SDG 7, which focuses on cleaner technologies such as hydrogen energy, interacts with the other sixteen (16) SDGs to achieve a better and sustainable future for all by the year 2030.

Step 6. Finally, at this stage, policy options are recommended for sub-Saharan Africa concerning hydrogen energy development in sub-Saharan Africa.

3. Hydrogen Energy Background

The energy sector in Southern Africa is faced with challenges and barriers to fully develop renewable energy and green hydrogen within the institutionalization, financial, and legal frameworks, which may lead to poor energy policies and renewable energy financing mechanisms that consequently lead to poor investor confidence and poor partnerships for take-off contracts and feed-in laws. Furthermore, such poor energy policies compromise the business climate for the development and competitiveness of renewable energy resources and other secondary projects such as hydrogen energy development [6].

While the renewable energy sector has also not enjoyed dedicated policies in the SADC region, the green hydrogen energy sector has enjoyed some fair share of these policies globally, especially in leading countries for green hydrogen development such as Germany, Japan, and South Korea. However, there is a need for enhanced policy support in all regions including SADC and at each stage of the three stages of green hydrogen policy support: technology readiness, market penetration, and market growth [11,12].

On a bright note, efforts have been made at a regional level to benchmark the SADC Protocol on the management of the environment to achieve sustainable development and Rio + 20 outcomes [13], the SADC region needs to develop a green economy strategy and action plan that will enhance sustainable development. This strategy aims at building a green economy that catalyzes the social, economic, and environmental challenges faced in the region to achieve resource efficiency and environmentally sustainable economies with low-carbon technology deployment, thereby creating a climate-change resilient region [1]. This can be achieved by pursuing sustainable practices during the production and distribution of goods and consumption [14]. The result of these efforts is an ecologically sustainable region that improves socio-economic development and human well-being over time while reducing environmental risks for future generations, thereby committing to the achievement of the UN sustainable development goals [15].

The establishment of a green hydrogen economy in SADC would help the region to reach sustainable development, to decarbonize the region, and reduce the effects of climate change. Furthermore, the decarbonization process would conjointly create many opportunities in the process of transitioning to a green hydrogen economy [2,12].

While this article focuses on green hydrogen, which uses electrolysis to break water into hydrogen and oxygen, the most predominant hydrogen type in Southern Africa is grey hydrogen. The grey hydrogen technologies deployed include a steam methane reforming (SMR) plant and coal gasification plant with coal and natural gas as the main feedstock. This hydrogen production method produces hydrogen and carbon dioxide (CO_2) as a by-product. Blue hydrogen and turquoise hydrogen are not popular in Southern Africa because of the cost that comes with the technologies for carbon capture and storage (CCS) and carbon capture and utilization (CCU), respectively [16]. Although the decarbonization process would conjointly create many opportunities in the process of transitioning to a green hydrogen economy, an enabling environment with clearly defined hydrogen energy policies is necessary. The enabling conditions for the development of a green economy through carbon emission-free energy carriers such as green hydrogen require national regulations and policies that are well outlined, with all incentives and subsidies also well-articulated. Unfortunately, in Southern Africa, a general approach is adopted to the energy sector where renewable energy resources are not well emphasized, and this puts secondary energy carriers such as green hydrogen development at a disadvantage. The complexity surrounding the hydrogen energy supply chain network presents a need to review the status of hydrogen energy policies in SADC nations.

3.1. Hydrogen Policy Review in SADC

The SADC nations renewable energy and green hydrogen policies for the different nations are reviewed as follows:

South Africa. The White Paper of 1988, on energy policy, guides the energy policy in South Africa. It outlines that the existing legal and regulatory framework guiding South Africa is the Electricity Regulation Act (ERA) 4 of 2006. The ERA further describes new generation capacity regulations that demand an integrated resource plan (IRP) for planning the electricity sector on a long-term basis. The idea behind this IRP is to help conduct scenario analyses to establish the electricity demand requirements while allowing the government to review the objectives to achieve a generation-mix economy. Updated in 2019, the latest IRP revision further gives greater allocation to the development of cleaner energy and renewable energy, but gives no explicit allocation for green hydrogen technology [5,17].

Another research innovation under the National Hydrogen Fuel Cell Technology (HFCT) that was approved by the South African cabinet in 2007 to achieve a 25% share of the global hydrogen energy products by 2020 is the Hydrogen South Africa (HySA) strategy. Lack of explicit allocations or policy framework on hydrogen energy that the HySA strategy has failed to meet HYSA's objectives, despite being non-existent for 13 years [5].

Namibia**:** In Namibia, the government has established a Renewable Energy Division in 2009 following the realization that renewable energy development plays an important role to achieve UN SDG 7, which emphasizes cleaner and affordable energy for all. The 1998 White Paper of energy policy guides the implementation of renewable energy and energy efficiency projects in Namibia [18]. The specific key roles in this paper include:

- Enhanced research and development (R&D) of renewable energy resources in Namibia.
- Renewable energy and energy efficiency public awareness.
- Implementing the Namibia Off-Grid Master Plan and
- Provide incentivized loans on solar energy technologies products.

Concerning green hydrogen and green ammonia, the Namibian government only announced the inclusion of the Harambe prosperity plan II action plan as one of the priority areas that is targeted to bring about economic growth and prosperity to the Namibians. The plan is expected to attract a capital expense of N$27 billion over five years beginning in 2021 [19].

Botswana: Botswana has several strategies, policies, acts, and regulations governing renewable energy [20]. These include:

- Botswana's vision 2036—Initially established in 1986 and revised in 2016. The vision enhances energy development by focusing on the following four thematic areas: sustainable environment and good governance, sustainable economic development, peace and security, and human and social development.
- The National Development Plan (NDP) II—This was established in 2017 and is expected to run until 2023. This plan recognizes that renewable energy can improve Botswana's energy security, off-grid solution, and climate change. It further indicates that solar power offers an off-grid solution to rural areas, low-income urban, and peri-urban, especially if subsidized.
- The Electricity Supply Act was established in 1973 and amended in 2007. The Act mandates the Ministry of Minerals, Energy, and Water Resource to issue licenses to the Independent Power Producers (IPPs) to produce and distribute power.
- National Energy Policy—This was adopted in 2015, and highlights the importance of developing renewable energy sources and energy efficiency for energy security.
- Botswana Energy Master Plan—Established in 1996 and reviewed in 2003, the plan emphasizes rural electrification, energy efficiency, and renewable energy.
- Biomass Energy Strategy—Established in 2009, this strategy aims at promoting the utilization of biomass energy resources alongside some interventions.

Zimbabwe. In 2012, Zimbabwe's National Energy Policy (NEP) was promulgated to incorporate modern energy supply as the National Renewable Energy Policy (NREP) of 2019, which focuses on the utilization of renewable energy resources. Alongside Zimbabwe's Vision 2030, this initiative is aimed at ensuring energy security and sustainability is achieved. Vision 2030 also aims at creating employment opportunities and poverty reduction to attain upper-middle-income status [21].

Zambia. The Rural Electrification Authority (REA) and the fund agencies that operate under the Rural Electrification Act (No. 20 of 2003) of the Republic of Zambia is what is guiding the renewable energy policy framework for renewable energy. The REA aims at boosting electrification for all rural areas according to the set targets by 2030. Furthermore, by 2013, the government drafted a renewable energy strategy that strengthened Zambia's renewable energy policies, institutional, and legal framework [22].

Mozambique. The energy sector in Mozambique is governed by the Electricity Law/Act of 1987, which is implemented by the Ministry of Mineral Resources and Energy also inter alia in the electricity tariff setting. Furthermore, the ministry has also developed an energy strategy that diversifies the 1987 Act to accommodate the energy mix for increased energy access and security. With this strategy, it is hoped that by 2023, a 50% grid connection will be achieved from the current 25.2%. Although Mozambique lacks a clear act on renewable energy, it supports renewable energy independent power producers (IPPs) in the sector and has even approved a regulation of feed-in tariffs [23].

Mauritius. In 2015, the Mauritius government enacted a renewable energy Act No. 11 and established the Mauritius Renewable Energy Agency (MARENA) to operate as an agency of the Ministry of Energy and Public Utilities (MEPU), which is regulated to overlook and enhance the development of renewable energy in Mauritius. Furthermore, MARENA also aims at achieving a 35% renewable energy share of the energy mix by 2025 through 2030 [24].

Tanzania. Preceded by the 1992 policy reports, the National Energy Policy (NEP) 2015 aims at addressing the challenges faced by the energy sector and improving the energy sector by utilizing all energy resources. Before the National Energy Policy of 2015, the 2003 national energy policy guided all activities of the energy sector, although the former was more focused on introducing a balance marketing mechanism between the public and private sectors of the energy [25].

Malawi. The Malawian national energy policy of 2018 is under the sole mandate of the Ministry of Natural Resources, Energy and Mining (MoNREM), but MoNREM operates through the Malawi Energy Regulatory Authority (MERA) and the Department of Energy Affairs (DoEA) to ensure that all regulations, policies, and the entire energy policy framework increases energy financing and economic growth. Furthermore, in 2017, the Malawian Government enacted the Malawi Renewable Energy Strategy to give policy direction alongside the integrated resource plan [26].

Democratic Republic of Congo (DRC). In the DRC, Law No. 14-2003 of 10 April 2003 on the Electricity Code mainly governs the energy sector with several other supplementary statutes:

- Law No. 17-2003 of 10 April 2003 focuses on development funds;
- Law No. 16-2003 of 10 April 2003 focuses on regulatory agency issues;
- Law No. 15-2003 of 10 April 2003 focuses on rural electrification issues;
- Law No. 10-2003 of 6 February 2003 which focuses on empowering the local communities; and
- Law No. 067-84 of 11 September 1984 focuses on the name changing of the name of the national electrical utility firm.

Furthermore, these laws have been supplemented with several regulations/decrees such as: Decree No. 2013-416 of 9 August 2013 focusing on the establishment of the national company of electricity in DRC (Société Nationale d'Electricité, SNE); Decree No. 2010-822 of 31 December 2010 focusing on the development of water and sanitation and electric power strategies; Decree No. 2010-808 of 31 December 2010 focusing on the working conditions of the electric power sector; Decree No. 2010-241 of 16 March 2010 and

Decree No. 2010-123 of 19 February 2010, which focus on improving the operations and responsibilities of the Ministry of Energy and Hydraulics, respectively; Decree No. 2008-560 of 28 November 2008 focusing on electric power sector for development funds; Decree No. 2007-291 of 31 May 2007 focusing on rural electrification; Decree No. 2007-290 of 31 May 2007 focusing on regulatory agency establishment in the energy sector; and Decree No. 2003-156 of 04 August 2003 focusing on improved operations of the directorate of energy [27].

Madagascar. The Electricity Law was enacted in 2015–2030, to legally allow the private sector to invest in the energy sector to increase electricity access. However, no feed-in tariffs that support the development of renewable energy exist. The Water and Electricity Company (*Jiro sy Rano Malagasy*—JIRAMA) is, however, unable to buy power from the independently produced power (IPPs) at good tariffs because the rates are dependent on contract negotiations. Furthermore, the rates are also supervised by the Board of Electricity Regulation (*Office de Regulation de l'Electricité*—ORE. [28].

Eswatini. The energy policy and regulations in Eswatini are guided by the Ministry of Natural Resources and Energy (MNRE). Like many other nations in Southern Africa, MNRE promulgated the National Energy Policy in 2018 to incorporate or allow: (i) access to modern energy services for all; (ii) enhance the labor market; (iii) ensure energy supply and security; (iv) stimulate economic growth and development; and (v) ensure environmental sustainability [29].

Apart from reviewing the renewable energy and hydrogen policies in SADC, a further hydrogen energy footprint was conducted to establish the level of commitment and engagement by the public sectors and governments in SADC in the areas of renewable energy and hydrogen energy development.

3.2. Hydrogen Energy Footprints in SADC

To further review the footprints of hydrogen energy in Southern Africa, it was inferred that green hydrogen is relatively new in Southern Africa. Currently, the Southern African Science Service Center for Climate Change and Adaptive Land Management (SASSCAL) implements the Atlas of Green Hydrogen Generation Potential (H2Atlas) in 12 SADC states. The project has three (3) phases: H2Atlas development, hydrogen production piloting, and hydrogen production commercialization. The H2Atlas–Africa project is funded by Bundesministerium für Bildung und Forschung, BMBF's Energy and Hydrogen Technologies Department in Germany [30]. In Southern Africa, grey hydrogen is predominantly deployed. Other footprints include:

3.2.1. Sable Chemical Industries Green Hydrogen in Zimbabwe

Sable Chemical Industries, also known as Sable electricity, is a chemical company located in the midlands region of Zimbabwe.

Since 1972, Sable has produced ammonium nitrate (NH_4NO_3) fertilizer as the main product. The design capacity of the plant is 240,000 mt/ annum (Sable Chemical Industries, 2021). The NH_4NO_3 fertilizer is synthesized by reacting ammonia and nitric acid. The company used to produce ammonia onsite from nitrogen (N_2) produced from air separation and H_2 produced from the electrolysis of water. The plant is located close to a river with a perennial flow that would supply water to the electrolysis plant. The electrolysis plant involves 14 electrolyzers with the capacity to produce 23.1 kg/h [31,32]. The electrolyzers consume a total of 105 MW of power. The Kariba Hydro-power station supplies electricity to the plant; thus, Sable Chemicals produces green hydrogen [33].

The electrolysis plant was decommissioned in 2015 due to the high cost of power and shortages of electricity supply. The company now relies on ammonia imports from SASOL in South Africa [34]. Plans are underway to construct a solar farm that would produce 50 MW in phases and increase the power output to 400 MW at full capacity [35]. The solar farm would enable Sable Chemicals to produce green hydrogen again.

3.2.2. Secunda: Grey Hydrogen in South Africa

Sasol is a fuel and chemical company from South Africa with branches all over Africa and the Sasol Secunda plant is the one that produces ammonia and other fertilizers. At Sasol, grey hydrogen is produced in the coal gasification process as Syngas [(30–60% carbon monoxide (CO), 25–30% hydrogen (H2), 0–5% methane (CH_4), 5–15% carbon dioxide (CO_2)] and subsequently in the water gas shift reaction as a high purity gas. In addition, Sasol also produces grey hydrogen from the steam reformation of natural gas at its Sasolburg plant. The syngas is the feedstock to the Fischer–Tropsch process to produce fuel and an array of hydrocarbons. Thus, the hydrogen is used onsite, and some hydrogen is also sold as ultra-high pure hydrogen [36].

3.2.3. Sasol Hydrogen Outlook in South Africa

Sasol continues to explore ways to transition from grey hydrogen production to blue and green hydrogen [37]. Sasol has invited other partners interested in forming a consortium in a 'Request for Information' program to make carbon capture and utilization a reality from its operations in South Africa. Sasol has proposed carbon capture and utilization, which would mean that the CO_2 produced during the production of hydrogen via natural gas steam reformation would be utilized in a more beneficial way. CO_2 utilization would enable the production of blue hydrogen. In April 2021, Sasol entered a partnership with Toyota South Africa to produce green hydrogen [38].

3.2.4. PetroSA—Grey Hydrogen in South Africa

The Petroleum, Oil and Gas Corporation of South Africa (SOC) Ltd. (PetroSA) is the national oil company of South Africa. PetroSA produces hydrogen from natural gas in a gas to liquid (GTL) plant [39]. The hydrogen is thus grey hydrogen since the CO_2 is emitted into the atmosphere. The methane steam reformation method is used to produce syngas, which is subsequently used to synthesize liquid fuels and other hydrocarbon products. The GTL plant is located at Mossel Bay in the Western Cape province of South Africa. The plant was shut in December 2020 as efforts are ongoing to secure gas to feed the GTL plant [40].

3.3. Significance of Hydrogen Energy Policies

For decades, hydrogen and energy have a shared history—fueling the first motor engines more than 200 years before turning into a basic piece of the cutting-edge refining industry. Some unique properties of hydrogen that put it at an advantage over other energy types is that it is light, storable, has higher energy density than other fuels, and creates no immediate discharges of toxins, emissions, or ozone harming gasses such as carbon dioxide (CO_2). The deployment of hydrogen energy requires sound policies in place to support its advancement.

While the renewable energy sector has not enjoyed dedicated policies in Southern Africa, the green hydrogen energy sector has no dedicated policies. However, on a global level, hydrogen energy has thrived on some fair share of these policies, especially in green hydrogen leading countries such as Germany, Japan, and South Korea. However, there is a need for enhanced policy support at each stage of the three stages of green hydrogen: policy support; technology readiness; and market penetration and market growth [11,12].

By 2019, the global policy support for hydrogen only focused on the land transport sector because this sector, directly and indirectly, impacts or promotes clean energy or decarbonizes the end-use sectors: the industry, transport, buildings, and power sectors. This is because hydrogen energy complements fuel cell electric vehicles (FCEVs) to promote zero-emission vehicles. From 2019 to 2020, hydrogen energy has been perceived to be a game-changing energy for green hydrogen policies, with interest increasing globally, especially in Germany, Austria, Norway, Spain, Canada, Chile, Australia, Italy, France, Morocco, Portugal, and the Netherlands, and the European Union has made known to the public their national hydrogen strategies and post-COVID-19 recovery packages, which include green hydrogen support [11,12].

The deployment of clean hydrogen and green hydrogen comes with several barriers across the entire hydrogen energy value chain comprising hydrogen production, infrastructure, industry, aviation, and shipping sectors. Green hydrogen is still a niche area that needs policy enhancement to progress to the energy transition mainstream.

Table 1 shows some barriers to the deployment of green hydrogen in various sectors along with the green hydrogen energy value chain up to end-users, with cost emerging as the main barrier. Furthermore, policymakers should first set their priority areas and address the barriers that affect green hydrogen deployment in the different segments of the green hydrogen energy value chain.

Table 1. Barriers and policy options of the hydrogen value chain network [11].

	ELECTROLYSIS	INFRASTRUCTURE	INDUSTRY	AVIATION	SHIPPING
BARRIERS	• Capital cost • Electricity cost • Lack of hydrogen market • Barriers to power market	• Limited existing infrastructure • Technical limitations of users • Lack of investment	• High cost • Lack of demand for green products • Global competition and carbon leakage	• High cost • Procurement of sustainable CO_2 • Policies focus on biofuels	• High cost • Technical barriers
POLICY OPTIONS	• Set capacity targets • Offer loans • Introduce feed-in premiums • Allow participation in ancillary markets	• Collaborate on global trading of hydrogen • Identify priorities for conversion • Align blending targets • Provide financing	• Offer dedicated loans • Develop public procurement of green products • Phase out high emission technologies	• Set targets • Review policy focus • Expand emissions trading system	• Introduce fiscal incentives • Set targets for zero-emission vessels • Support infrastructure development

4. Results and Discussion

A hydrogen energy matrix for all the policies in SADC countries concerning renewable energy and green hydrogen would assist in showing the status of how investment-ready SADC concerns green hydrogen. Furthermore, it also helps to ensure the local and international investors include a financial cost component, associated with policy formulation in their project proposals.

From the literature review, it can be inferred that most of the green hydrogen projects implemented in Southern Africa are either privately funded or are funded by international players. The private and international community has been very instrumental in leapfrogging the sensitization of the public sector concerning hydrogen energy through projects such as the Atlas of Green Hydrogen Generation Potential (H2Atlas), which is implemented by the Southern African Science Service Center for Climate Change and Adaptive Land Management (SASSCAL) in twelve (13) SADC states [30]. An analysis of the existing hydrogen energy using a policy evaluation matrix was conducted in Table 2. The evaluation design matrix tool helps to plan and organize the existing policies in a table with one row for each evaluation question and columns that address evaluation design issues such as existing policies, renewable energy policies, or hydrogen energy policies, etc. Depending on what is prevailing, either a tick ($\surd$) or cross (X), was used to affirm the status in each SADC nation.

Table 2 shows that almost all countries have general energy policies and specific renewable energy or promulgated to incorporate renewable energy or other modern clean energy resources and technologies. It can also be seen that no SADC country has specific hydrogen energy policies in their energy policy framework, with only South Africa as the only country with hydrogen energy footprints and local initiatives. This shows that currently, all SADC nations do not have long-term hydrogen policies that can create sustainable markets for green hydrogen, and enhanced decarbonization of the current fossil fuel-based economies. Such policies are necessary to underpin investments by all energy suppliers, distributors, and users in the private and public sectors.

Table 2. Hydrogen energy policy evaluation matrix.

		Energy Policy	Renewable Energy Policy	Hydrogen Energy Policy	Country Hydrogen Energy Initiative	International/Private Hydrogen Energy Initiative
1.	South Africa (Lesotho)	√	√	X	√	√
2.	Namibia	√	√	X	X	√
3.	Botswana	√	√	X	X	√
4.	Zimbabwe	√	√	X	X	√
5.	Zambia	√	√	X	X	√
6.	Mozambique	√	√	X	X	√
7.	Mauritius	√	√	X	X	√
8.	Tanzania	√	√	X	X	√
9.	Malawi	√	√	X	X	√
10.	DRC	√	√	X	X	√
11.	Madagascar	√	√	X	X	√
12.	Angola	√	√	X	X	√
13.	Eswatini	√	√	X	X	√

Note: Lesotho is analyzed as part of the Republic of South Africa.

4.1. Policy Option Recommendations

Policy option recommendations on how to enhance hydrogen energy production to guide SADC countries to ramp their transition to a hydrogen energy-based economy can be made.

a. **Establishing the role of hydrogen within long-term energy strategies.** There is a need to have these policies embedded in national, regional, and local governments to guide future expectations. In this way, firms would have their long-term goals outlined. Some key industrial sectors that can be targeted include refineries, chemical, iron and steel, transport, buildings, and energy generation and energy storage.

b. **Stimulate commercial demand for green hydrogen.** While green hydrogen technology is available, to date, its cost remains a challenge. This shows that there is a need for countries in the SADC region to create sustainable markets for green hydrogen, reduce carbon emissions from fossil fuel-based hydrogen, and underpin the energy investments by local, private, and public investors and all supply chain distributors and end-users. Furthermore, scaling up the supply chain network of green hydrogen could lead to increased energy production, while an emphasis on clean energy would increase the production cost of energy from fossil fuel-based electricity because of carbon capture, utilization, and storage.

c. **Investment risks sharing and incentivizing.** New entrants or firms that express interest in hydrogen energy production, supply, distribution, and infrastructural development projects usually bear the highest risk at the deployment stage, especially those in the private sector. There is a need to assist the private sector with hydrogen energy mentorship, incentivize loans, provide guarantees, and tax rebates on tools, and even provide rewards.

d. **Public financial institutions support for research and development (R&D)**. This approach is necessary for the hydrogen production and supply chain network because the cost of production plays a critical role in any business. R&D is a crucial strategy that can lower the production costs, improve technology performances of electrolyzers, fuel cells, and any other hydrogen-based technologies. This can also be extended to the desalination processes, especially in countries that have a seashore. SADC countries have almost 10,000 km of a seashore from Tanzania on the east coast to the DRC on the west coast of Southern Africa. Furthermore, the actions that any government takes, especially through providing financial mechanisms for the public, are significant in promoting R&D, risk management, and attracting both international investors and private investors.

e. **Eliminate unnecessary regulatory barriers and harmonize standards.** In most SADC countries, hydrogen energy project developers may face licensing barriers due to unclear licensing requirements and regulations, and such inconsistencies are capable of retarding progress in the transition to hydrogen energy-based economies. This calls for several commitments in the form of a Memorandum of Understanding (MOU)/treaties, and dialogue among different stakeholders including the government, private sector, civil society, and the community at large.

f. **Engage internationally and track progress**. Apart from HYSA in South Africa, since there is very little research and development currently ongoing in Southern Africa, nations are encouraged to enhance their international and bilateral cooperation with firms and companies that are global leaders in hydrogen deployment to keep up with international standards, embrace knowledge sharing, lessons learnt, and adopt best practices in the hydrogen energy industry.

g. **Explore opportunities to enhance future hydrogen development progress.** By building on current policies, infrastructure, and skills, enhanced investor confidence, and lower costs, nations in Southern Africa can:

    i. Transform the existing industrial seaports into hubs for lower-cost, lower-carbon hydrogen;
    ii. Use the existing natural gas/coal infrastructure to accommodate green hydrogen energy supplies;
    iii. Improve the transport freight and fleets by making road and railway corridors that are hydrogen energy ready and build infrastructure that can, in the short-term, help export green hydrogen and in the long run, cater for fuel-cell vehicles and other hydrogen energy end-line users and make the entire value chain more competitive; and
    iv. Establish the shipping routes to kick-start the international hydrogen trade.

Furthermore, for hydrogen to enhance green energy transitions, it should be embraced in areas where it is missing, such as in power production/generation, buildings, and the transport sector. The policy recommendations on how to enhance hydrogen energy production to guide the SADC countries to ramp their transition to a hydrogen energy-based economy are made in line with the International Energy Agency (IEA) recommendations [12]. These policy recommendations will enhance hydrogen energy production and guide the SADC countries to ramp their transition to a hydrogen energy-based economy. The significance of this review goes beyond addressing the UN SDG 7, which emphasizes cleaner and affordable energy for all as well as addressed all seventeen UN SDGs.

4.2. The Role of Renewable Energy and Green Hydrogen to Achieve the UN SDGs

The Sustainable Development Goals (SDGs) stipulated by the United Nations in 2015 are the blueprints for achieving a sustainable future in which all peoples of the world thrive and are successful. The SDG targets should be achieved by 2030. Specifically, SDG 7 focuses on cleaner, modern, and affordable energy for all. Studies have indicated that whilst economic growth results in socio-economic growth, it comes with negative environmental consequences [31]. Renewable energy is characterized by fewer environmental concerns and thus will ensure economic and socio growth with minimum adverse effects on the environment. Therefore, renewable energy offers a long-term sustainable source of energy.

The price of renewable resource-based energy (i.e., wind and solar) has fallen by more than 80% in the past ten years, making them economically sustainable and ready for wide-scale deployment. Fossil-based electricity is centralized and requires infrastructure over large geographical space miles, and as a result, only 21% have access to electricity in developing nations including regions such as Southern Africa. The modular nature of solar and wind power provides an opportunity for such communities to have access to electricity with minimum power infrastructure.

Energy generation's contribution to climate change is well documented [32–34]. Much energy is generated from fossil fuels, which result in significant greenhouse gas (GHG) emissions and carbon dioxide is the most significant anthropogenic greenhouse gas (GAW, 2014). Reducing GHGs will enable the world to keep the global average temperature rise below 2 °C of the pre-industrial levels [32]. Energy is required for electricity generation, transport, production of goods and services, and the production of food. It therefore correlates that large-scale implementation and use of renewable energy is key to mitigating climate change. Climate change threatens water availability, food security, biodiversity, and human health.

Due to the threat that climate change presents, SDG 13 calls for urgent action to combat climate change and its impacts. Renewable energy will assist directly in climate change mitigation, adaptation, and reduce the vulnerability of communities to the effects of climate change [35]. SDG 13 cannot be achieved with the continued use of non-renewable energy. The link between SDG 7 and SDG 13 and SDG 12 has also been reported [36]. The study specifically investigated the synergies between renewable electricity and the various SDGs. The study showed that the price of renewable electricity had a significant impact on SDG 7 and SDG 8, which emphasize having decent work and enhanced economic growth.

Renewable energy is at the heart of the realization of many SDGs [37,38]. Previous studies by R. Madurai Elavarasan et al. of a pairwise comparison of SDGs with a formulation of SDG interaction in Table 3, shows that SDG 7 had the second-highest influence with a score of 14, after SDG 13, but had the highest interaction score of 2.333. This implies that energy underpins all the SDGs because they are all highly interactive with the energy SDG 7 than with the other SDGs.

Several renewable energy technologies support the realization of SDGs. For instance, the off-grid and modular nature of renewable energy offer many advantages, especially in developing countries, where poor governance may hamper the provision of services to the population. The modular off-grid nature allows for the urbanization of previously marginalized areas, thus reducing the rural-urban migration. This is in line with SDG 11, whose goal is to make cities resilient and sustainable. Energy is essential for the growth and development of businesses, thus improving the employment capacity of communities and settlements. When there are jobs available, then people can feed their families. Sustainable jobs will be created through renewable energy infrastructure development.

Furthermore, power is needed to pump water from boreholes and pump it through water circulation through pipes to the residential areas and homes. Affordable renewable energy plays a role in supplying clean water. The availability of clean water is crucial for sanitation, which leads to combating water-borne diseases. SDG 6 aims to provide clean water and sanitation to all people by the year 2030. The off-grid nature of renewables such as solar systems allows for clean water access in marginalized areas. Improved water availability and solar pumps enable irrigation, which improves agriculture productivity and improves food security. Irrigation and improved agriculture can improve income earnings for families and thus address SDGs 1, 2, and 3, which address poverty, hunger, and good health. Castor et al. (2020) presented a novel framework for assessing energy projects against SGDs. The results showed a clear benefit for SDGs 1, 2, and 4 for communities that previously did not have access to electricity. SDG 12 (responsible consumption and production), SDG 14 (life below water), and SDG 15 (life on land) were also shown to have a link to energy [39].

SDG 4 seeks to provide quality education for all by 2030. The provision of sustainable electricity to people improves the quality of the education they receive. As there is improved lighting, school children can do their homework and study safely at night. The provision of electricity also enables access to information through the Internet. It also allows for teacher retention in remote schools, which improves the quality of education provided to communities. Schools with energy also provide essential services to the surrounding communities such as clean water as well as a source of clean water and can be emergency centers [40].

Table 3. Pairwise comparison of SDGs and the formulation of SDG interaction index [37].

SDG	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**Influence Score**	**SDG Interaction Index**
1		1	2	0	1	0	0	0	0	1	3	0	0	0	0	0	0	**8**	**0.800**
2	0		2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**3**	**1.000**
3	0	0		0	1	0	0	0	0	1	3	0	0	0	0	0	0	**5**	**0.385**
4	1	0	0		0	0	0	2	1	0	0	0	0	0	0	1	0	**5**	**1.667**
5	1	0	1	1		0	0	0	0	3	0	0	0	0	0	1	0	**7**	**1.000**
6	0	0	1	0	0		0	0	0	0	1	0	0	0	0	0	0	**2**	**0.500**
7	2	0	0	0	0	0		1	2	0	3	0	3	0	1	0	2	**14**	**2.333**
8	3	1	1	0	0	0	1		1	0	2	0	0	0	0	0	1	**10**	**1.667**
9	0	0	0	0	0	0	2	1		0	3	1	2	0	1	0	2	**12**	**2.000**
10	1	0	1	1	3	0	0	0	0		0	0	0	0	0	1	0	**7**	**1.000**
11	1	0	1	0	0	1	1	1	2	0		1	1	0	0	1	1	**11**	**0.611**
12	0	1	0	0	0	2	−1	0	−3	0	−2		0	1	1	0	0	**−1**	**−0.250**
13	1	0	3	0	0	1	3	0	2	0	1	0		2	2	0	1	**16**	**1.455**
14	0	0	0	0	0	0	0	0	1	0	0	1	2		0	0	1	**5**	**1.250**
15	0	0	1	0	0	0	−1	0	−1	0	0	1	1	0		0	1	**2**	**0.333**
16	0	0	0	1	2	0	0	0	0	2	1	0	1	0	0		0	**7**	**1.750**
17	0	0	0	0	0	0	1	1	1	0	2	0	1	1	1	0		**8**	**0.889**
Dependency Score	**10**	**3**	**13**	**3**	**7**	**4**	**6**	**6**	**6**	**7**	**18**	**4**	**11**	**4**	**6**	**4**	**9**		

In addition, renewable energy also comes with the advantage of being health friendly. The World Health Organization (WHO) reported that two million deaths occur annually due to utilizing biomass and coal for cooking [41]. Improved access to renewable electricity would reduce air pollution-related deaths.

Green hydrogen is also essential in realizing the SGDs. For instance, SDG 2 seeks to alleviate world hunger. The production of green ammonia will enable the sustainable production of fertilizer, which would improve food security [42].

Green hydrogen production is also positively linked to SGD 8, which seeks economic growth, and this is especially true for developing countries with plenty of renewables [43]. If developing countries cease to import fuel for transport, it would result in the retention of much-needed foreign currency. Governments would then put the foreign currency into other essential sectors such as health and education. The opportunity to export hydrogen to developed countries that are not much endowed with renewable energy sources would earn these developing countries foreign currency whilst generating jobs [42].

From the discussion, it is apparent that renewable energy is central to the realization of the SGDs [44].

5. Conclusions

Green hydrogen energy is significant in decarbonizing the entire hydrogen value chain network from its generation to the end-user sectors. It can help achieve the UN Sustainable Development Goals (SDGs) and regional sustainability. However, given the pivotal role of the public service in hydrogen energy deployment, there is a need to extensively engage decision-makers in the public sector to achieve the UN SDGs. While SDG 7, which emphasizes modern and clean energy for all, can help the region transition from a fossil fuel-based economy to a green economy, its achievement influences the success of all the remaining SDGs. Without a doubt, green hydrogen has been identified to be a clean energy solution globally. However, there is a need to clearly articulate the benefits that green hydrogen brings to the specific countries and SADC region alongside the global pursuit to reduce GHG emissions that cause climate change.

The lack of clear hydrogen energy policies in Southern Africa retards a collective regional vision to achieve a green hydrogen economy. This further points to the need for dialogue and commit to the Paris Agreement targets that aim to limit global warming closer to 1.5 °C rather than 2 °C or higher, to make the Earth safer and help achieve other SDGs.

Green hydrogen energy policies should be formulated in a blended manner that incorporates the research institutions, public sector, and private sector and more focused on achieving certain specific goals such as decarbonization, alongside other economic benefits such as a scaled-up energy sector with wind, solar, and tidal infrastructure, and technology; an improved health and environment that has reduced CO_2 emissions and particulate matter; improved water sector, especially for the countries with a seashore concerning desalination technologies; an improved transport system with hydrogen vehicles and pump stations, and an improved logistics and infrastructure that introduces a new infrastructure for (1) packaging the hydrogen as a compressed gas, liquid, hydride, etc.; (2) distribution-pipelines, pipes, roads, shipping and railroads; (3) dispensing-transfer from retailers to consumers; and (4) storage-pressurized containers. Research is needed to provide accurate base data on which policies can be formulated.

Finally, to accomplish green hydrogen policy formulation in Southern Africa, governments would need to take up the following measures:

- Establish the role of hydrogen within long-term energy strategies that are embedded in national, regional, and local governments to guide future expectations. In this way, firms would clearly have their long-term goals outlined. Some key industrial sectors that can be targeted include refineries, chemical, iron and steel, transport, buildings, and energy generation and energy storage.
- Share in the investment risks by incentivizing new entrants or firms that express interest in hydrogen energy production, supply, distribution, and infrastructural development projects, through hydrogen energy mentorship, incentivized loans, provide guarantees and tax rebates on tools, and even provide rewards.
- Develop deliberate policies that enhance public financial institutional support for research and development (R&D) to reduce hydrogen production costs and enhance capacity building as production plays a critical role in any business.
- Eliminate unnecessary regulatory barriers and harmonize standards. This will help hydrogen energy project developers develop investor confidence and eliminate licensing barriers that are experienced due to unclear licensing requirements and regulations, and such inconsistencies are capable of retarding progress in the transition to hydrogen energy-based economies.
- Engage internationally and track progress to enhance their international and bilateral cooperation with firms and companies that are global leaders in hydrogen deployment to keep up with international standards, embrace knowledge sharing, lessons learnt, and adopt best practices in the hydrogen energy industry.

Most importantly, the hydrogen economy demonstrates a capability to help nations in Southern Africa (and SADC) to become major exporters of green hydrogen as an interim or short-term benefit as well as in decarbonizing the carbon-intensive emission sectors and reducing greenhouse gas (GHG) emissions and climate change in the long-run, alongside providing a future fuel for the transport sector and industries. Southern Africa stands to benefit from the deployment of hydrogen energy and become a major supplier of hydrogen globally because of its immense renewable resources, especially if it leapfrogs its hydrogen infrastructure development and hydrogen policy framework formulation.

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