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Green Hydrogen in the Northern Cape:

Investigating Sustainability Indicators for Investment and Policy Decisions

A Dissertation

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By

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Financing Equitable, Ethical, Sustainable & Collaborative Development

Declaration

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Finally, I offer my sincere appreciation to my supervisors, whose pioneering research, time, and guidance made this study possible.

ABSTRACT

This study investigated the sustainability indicators for green hydrogen in South Africa's Northern Cape Province to inform investment and policy decisions. Using an exploratory sequential mixed-method approach, the study first conducted a systematic literature review to identify relevant sustainability indicators. This was followed by a stakeholder survey of 16 individuals representing 11 stakeholder groups to validate and rank these indicators in the context of the Northern Cape. The stakeholders' responses on the relative importance of each of the identified sustainability indicators were registered using a 5-point Likert scale, and a weighted mean score was computed to rank each indicator.

This study identified 28 sustainability indicators across environmental, economic, and social dimensions. Environmental indicators were ranked highest in importance, with water use, biodiversity impact, and human toxicity potential as the top concerns. Social indicators were ranked second, with employment and skills development emerging as critical factors. Economic indicators were ranked third, with energy efficiency, local procurement, energy supply security, and economic development as the primary considerations.

The study also revealed differences in priorities between public and private sector stakeholders, with the former placing more importance on social indicators and the latter on environmental indicators, thus highlighting the need for a balanced energy technology sustainability assessment approach.

Based on the findings, this study recommended a comprehensive energy technology sustainability assessment for green hydrogen be conducted that considers the diverging stakeholder views and incorporates the key sustainability indicators established in this study. The assessment may provide results relevant to policymakers and investors alike in decision-making, thus ensuring that capital is mobilised and aligned with sustainable energy technologies, such as green hydrogen.

This study contributed to the broader fields of energy technology assessment and sustainable investment and provided sustainability indicators that researchers, policymakers and investors can consider in South Africa's emerging green hydrogen economy, with a specific focus on the Northern Cape. These findings can inform sustainable development strategies and guide future research in this field.

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LIST OF ABBREVIATIONS

CCUS – Carbon Capture Utilisation and Storage

CEFIC – The European Chemical Industry Council

DMRE – Department of Mineral Resources and Energy

EPCs – Engineering, Procurement and Construction Service Providers

EU – European Union

FID – Final Investment Decision

GDP – Gross Domestic Product

GW - Gigawatts

IEA – International Energy Agency

IPP – Independent Power Producers

IRP – Integrated Resource Plan

LCOE – Levelised Cost of Energy

LCOH - – Levelised Cost of Hydrogen

MW – Megawatts

NCEDA – Northern Cape Economic Development, Trade and Investment Promotion Agency

NGO – Non-Governmental Organisation

OEMs – Original Equipment Manufacturers

O&Ms – Operations and Maintenance Service Providers

PESTLE - Political, Economic, Social, Technological, Legal and Environmental Analysis

SADC - Southern African Development Community

SATSA - Systems Approach to Technology Sustainability Assessment

SKAO – Square Kilometre Array Observatory

TCS – Total Choice Score

TNPA – Transnet Port Authority

UK – United Kingdom

UNSDGs – United Nations Sustainable Development Goals

US – United States of America

USD – United States Dollars

WMS – Weighted Mean Score

CHAPTER 1: INTRODUCTION

1.1 Background of Study

South Africa's energy landscape has faced a significant number of challenges in recent years owing to an increased energy deficit, resulting in load-shedding coupled with the need to decarbonise the economy. This has put the country at odds with the United Nations Sustainable Development Goal 7, which aims to increase access to affordable and clean energy (United Nations, 2022), necessitating the implementation of a just transition to a low-carbon society as set out by the Presidential Climate Commission (2022).

In 2022, the country's energy supply relied heavily on fossil fuels, with coal accounting for 67%, followed by crude oil (17%) and renewable energy (11%) (Ratshomo & Nembahe, 2022). Consequently, South Africa is a significant emitter of greenhouse gases, with carbon dioxide emissions of over 390 million tons, which equates to approximately 50% of the total carbon dioxide emissions of sub-Saharan Africa (World Bank, 2024 and IEA, 2024). With the need to increase clean energy supply, South Africa has made significant strides in introducing renewable energy to the national grid, with 9,258 MW procured from 110 renewable energy independent power producers (DMRE, 2024b). However, renewable energy supplied through the grid has several inherent limitations that have been widely documented, including its intermittency and lack of feasibility in decarbonising hard-to-abate industries. Hence, it is necessary to introduce new alternative energy sources and carriers.

Green hydrogen has been touted as a panacea for these decarbonisation efforts, given its ability to be produced from renewable energy and its application in hard-to-abate industries while emitting minimal greenhouse gases. Indeed, the establishment of a green hydrogen economy could help the country attain sustainable development while also decarbonising it (Imasiku et al., 2021). However, the green hydrogen industry is still in its infancy and is riddled with uncertainty. Hamukoshi et al. (2022) and Kweinor Tetteh et al. (2024) highlighted that the possible socio-economic impacts of green hydrogen on society in South Africa are yet to be understood. This knowledge gap might explain South Africa's slow progress, despite its potential for green hydrogen production.

Recognising this potential, the South African government has taken steps to understand what a green hydrogen future would look like, culminating in the publication of South Africa's Hydrogen Society Roadmap by the Department of Science and Innovation (2021). While comprehensive, the roadmap falls short of assessing the overall sustainability of a green hydrogen economy. This presents a critical gap in research – the need for a robust green hydrogen technology sustainability assessment.

Energy technology sustainability assessment by its nature is complex and riddled with uncertainties, thus requiring a holistic and transdisciplinary approach (Kates et al., 2012). This is echoed by the Department of Science and Innovation (2021), which noted that *"the future of hydrogen in energy is fraught with varying measures of ambiguity, turbulence, uncertainty, novelty, and unpredictability."*. This is particularly the case because of the number of stakeholders involved in the development of such technology, including project developers, OEMs, EPCs, investors, local communities, O&Ms, off-takers, regulators, government, and policymakers. Therefore, the development of technology is impacted by the behaviour and actions of stakeholders.

Although a pilot study was launched by the United Nations Trade and Development in collaboration with the Department of Science and Innovation to assess the sustainability of green hydrogen electrolysers (Mlosy, 2024), it failed to assess the sustainability of the green hydrogen economy as a whole. A green hydrogen economy is more than just the technology required but encompasses the production, distribution, and utilisation of green hydrogen. To the best of our knowledge, no study has been undertaken on the sustainability of a green hydrogen economy in South Africa that considers the economic, social, and environmental factors that may impact its development and commercialisation. Given the infancy of green hydrogen technology worldwide and the uncertainty of its sustainability, there is a need for a holistic assessment that will enable policymakers and investors to understand the impact of green hydrogen on certain measures of the economy, society, and the environment.

Musango & Ouma-Mugabe (2024) developed a generic framework for assessing the sustainability of energy technologies in an African context. This study utilised this framework to assess the sustainability indicators of green hydrogen in South Africa, particularly in Northern Cape Province in order to facilitate their utilisation in assessing the sustainability of green hydrogen.

1.2 Research Problem Statement

This study investigates two research problems. First, there is uncertainty surrounding the sustainability of green hydrogen as an energy technology with lingering questions about its environmental impact, economic feasibility, and social implications (Cremonese et al., 2023). Second, there is a limited understanding of the key sustainability indicators of green hydrogen in the Northern Cape and the weight that different stakeholders place on these indicators (NCEDA, 2023). These problems limit the ability of policymakers and investors to assess the technology's sustainability while considering the complex interactions and trade-offs between the factors involved in the green hydrogen value chain. While technology assessment literature has explored the economic feasibility, technical efficiency, and social impacts of green hydrogen, this has often been done in silos as highlighted in section 2.6.1. Thus, a critical research gap existed in the assessment of the sustainability of green hydrogen from a holistic perspective. This gap requires filling in the green hydrogen technology assessment discourse, as the linkages and relationships between social, environmental, and economic variables are important in the assessment of sustainability. To address this gap, this study investigates the context of the green hydrogen economy and technology assessment and identified key sustainability indicators of green hydrogen in the Northern Cape to provide valuable insights for researchers to develop an appropriate energy technology sustainability assessment that policymakers could use develop effective strategies and investors could use to make informed decisions.

1.3 Research Questions

The research questions that this study will answer are as follows:

- What is the context of the green hydrogen economy and technology sustainability assessment in South Africa?
- What are the key sustainability indicators of green hydrogen in the Northern Cape?

1.4 Research Objectives

The purpose of this study is to:

- Describe the context of the green hydrogen economy and technology sustainability assessment in South Africa.
- Identify key sustainability indicators of green hydrogen in the Northern Cape.

1.5 Justification of the Study

The lack of research on the environmental, social, and economic sustainability of green hydrogen in the Northern Cape province of South Africa coupled with the energy transition imperative of the country underpins the need for this study.

The findings from this study offer practical insights into the development of evidence-based strategies to promote investment in green hydrogen technologies, thus contributing to the country's sustainable energy future. This is particularly important, as investors have come under increasing pressure from various stakeholders to not only maximise returns but also to ensure that investments contribute positively to sustainable development. Similarly, policymakers are required to put in place policies that not only contribute to the development of a green hydrogen economy, but also to sustainable development. Therefore, this study develops sustainability indicators relevant for researchers, policymakers and investors alike to make informed decisions regarding green hydrogen development in the Northern Cape.

1.6 Organisation of the Study

The rest of this study was organised as follows. Chapter one introduced the study with specific reference to the research problem, questions, research objectives, and justification of the study. Chapter two explored the literature to describe the context of green hydrogen and its sustainability assessment. Chapter three set out the research methodology employed in the study in terms of the research approach, design, and data collection and analysis. Chapter four discussed the findings of the data analysis. Chapter five, concluded the study and discussed recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter explores the literature to describe the context of green hydrogen and its sustainability assessment. Firstly, it discusses the properties of green hydrogen in relation to other hydrogen varieties. Secondly, the importance, applications, drawbacks, and advantages of green hydrogen and a green hydrogen economy, initially from a global perspective and then contextualised to South Africa are discussed. Thirdly, South Africa's energy policy landscape is examined. Fourthly, the theoretical and conceptual frameworks relevant to this study are discussed. The chapter concludes with a review of the literature and a discussion of the uncovered research gap.

2.2 Types of Hydrogen

Hydrogen is an abundant chemical element that is an energy carrier that can be used to produce various important fuels (Baker McKenzie, 2020). Fazioli & Pantaleone (2021) and the Department of Science and Innovation (2021) broadly set out how hydrogen is labelled based on the energy source used to produce it. In order of their respective environmental friendliness, the different types of hydrogen are brown, grey, blue, purple, and green. Brown hydrogen is produced from coal gasification. Grey hydrogen is produced from natural gas via steam methane reformation. Blue hydrogen is produced from natural gas but with carbon dioxide from the process being stored using carbon capture utilisation and storage (CCUS) technology. Purple/pink hydrogen is produced from water, which is split between oxygen and hydrogen primarily via electrolysis, which is powered by nuclear energy. Green hydrogen is produced from water via electrolysis, powered by renewable energy.

Despite its environmental benefits, green hydrogen accounted for less than 1% of the total production of hydrogen in the world (Department of Science and Innovation, 2021; International Energy Agency, 2022), with 76% being grey hydrogen and the remainder being mostly brown hydrogen (Zhiznin et al., 2023). Green hydrogen relies on the use of solar and wind technologies which are well-established energy technologies. The use of these renewable sources allows the production of green hydrogen with relatively low carbon emission over its lifecycle. Electrolysis is the most common hydrogen production method, and the International Energy Agency (2023) estimates that this method will account for 70% of green hydrogen production by 2030. Therefore, this method of production was considered in this study. Other methods of production are listed in Figure 2.1. Green hydrogen can then be converted into feedstocks such as ammonia, methanol, and synthetic hydrocarbons which are easier to store and transport than hydrogen in gas form (IEA, 2023a).

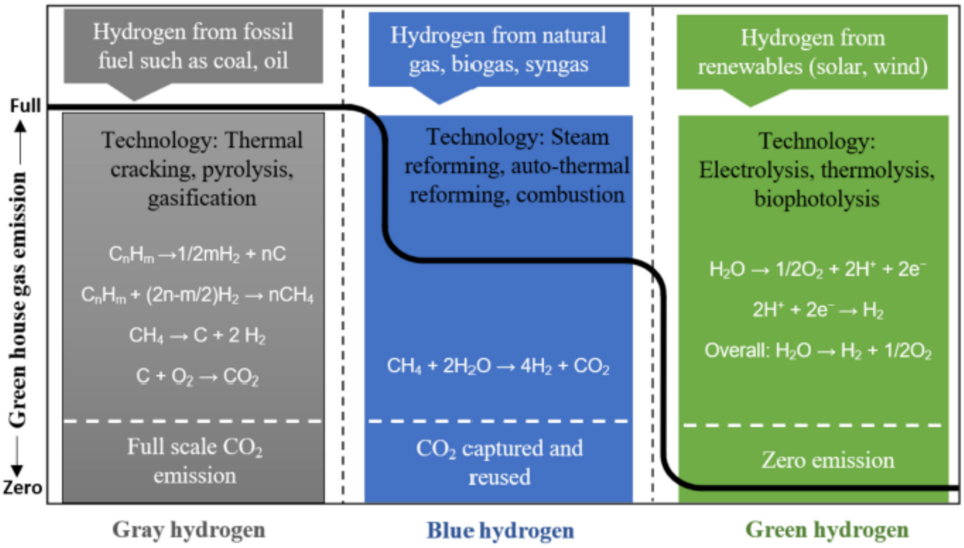


Figure 2.1: Types of Hydrogen

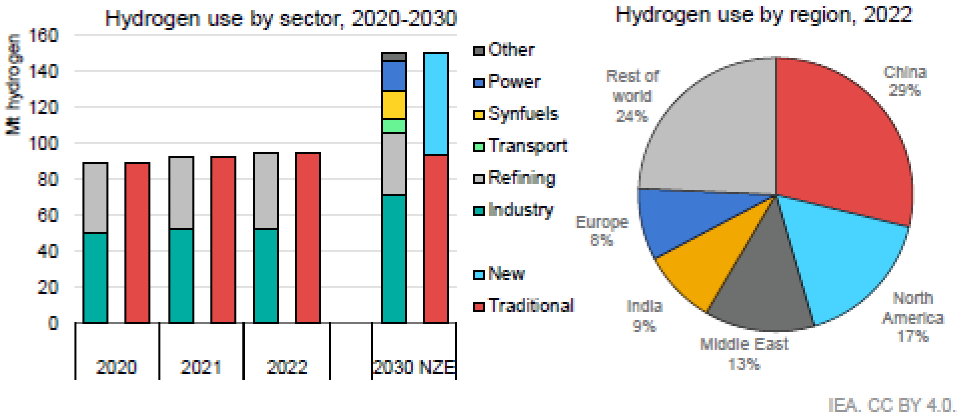
Source: (Sarker et al., 2023)

2.3 State of Global Hydrogen Production and Demand

In spite of the abundance of hydrogen, the environmental benefits of green hydrogen and its production process, fossil fuels dominate the global energy demand (Xiang et al., 2021). In 2020 the fossil fuels consumptions represented 85% of the global energy demand (Xiang et al., 2021). Therefore, it is no surprise that the insurgence in the interest in a green hydrogen economy worldwide has been a direct result of increased pressure on countries to decarbonise and meet climate targets in line with the Paris Agreement. Indeed, the International Energy Agency (2023)'s annual review of the global hydrogen landscape notes that the number of hydrogen production projects announced is increasing exponentially, albeit 94% being at the early and feasibility study stages. This increase in hydrogen projects may be a result of the general consensus among various stakeholders that decarbonisation cannot be achieved exclusively through renewable electricity, but it needs to be coupled with green hydrogen to decarbonise certain industries (Baker McKenzie, 2020). As a result, multiple green hydrogen projects are underway, such as the Neom Green Hydrogen Project in Saudi Arabia, with a production capacity of 600 tons of green hydrogen per day, which will reduce carbon emissions by five million tons per year (Air Products, 2025). More projects, such as these, will need to be undertaken for hydrogen to account for the expected 12% of the total energy consumption by 2050, and for green hydrogen to make up two-thirds of the total hydrogen consumption (Martínez de León et al., 2022).

Initial inroads are being made to achieve this target of increased contribution of green hydrogen to the energy mix. There has been a marked increase in the supply of hydrogen due to China's increased manufacturing capacity of electrolysers, with the country deploying 40% of the electrolysers used in electrolysis projects that have reached FID globally (IEA, 2023a). Manufacturers of electrolysers aim to have a manufacturing capacity of 155GW per annum by 2030 which will enable a further increase in green hydrogen supply (IEA, 2023a). This will also be supported by government initiatives put in place to incentivise the use of green hydrogen, including the US Hydrogen Production Tax Credit, EU Important Projects of Common European Interest, and the UK Low Carbon Hydrogen Business Model. However, according to the International Energy Agency (2023), despite the increased supply of hydrogen, low-emission hydrogen, such as green hydrogen, represents less than 1% of global hydrogen and thus will need to increase by over 100 times to achieve net zero by 2030. Furthermore, Europe and Australia collectively account for almost 50% of the green hydrogen projects that have been announced, with Africa having minimal contribution (IEA, 2023a).

Similarly, the demand for hydrogen has increased. According to the International Energy Agency (2023), hydrogen is predominantly used in oil refining to reduce impurities in fuel, chemicals production, as well as in ammonia, steel, and methanol production. These are the "traditional" uses of hydrogen and have historically been the driver of growth in hydrogen demand. Additionally, hydrogen is used in a variety of applications, including as a long-term storage facility for renewable energy, which is characterised by intermittent production and seasonality (Clark & Rifkin, 2006). This is made possible by the ability of hydrogen to store approximately 60% to 80% of the energy used to produce it (Sadeq et al., 2024). However, the true opportunity of hydrogen emanates from its ability to decarbonise the so-called "hard to abate industries" such as steel, cement, and chemical industries. This is because the use of renewable electricity in these industries is either difficult or non-viable (Roos & Wright, 2021). Other future applications of hydrogen include as fuel cells for road transport vehicles, specifically heavy-duty long-haul vehicles, which cannot run on electric batteries, and as a source of heating for buildings (Baker McKenzie, 2020). In particular, the use of hydrogen in road transport has increased by 45% from 2021 to 2022 albeit from a very low base of approximately 22 kilotons (IEA, 2023a). These are collectively the "new" applications of hydrogen, and despite their importance in transitioning to a low carbon further, they account for less than 0.1% of the global demand (International Energy Agency, 2023) as reflected in Figure 2.2.



Notes: NZE = Net Zero Emissions by 2050 Scenario. "Other" includes buildings and biofuels upgrading.

Figure 2.2: Hydrogen Demand by Sector and Region

Source: (International Renewable Energy Agency, 2023)

In 2023, the adoption of hydrogen faced fierce competition from natural gas (Panchenko et al., 2023), which is considered a more environmentally friendly fuel than coal and oil, but cheaper than hydrogen. The capital-intensive nature of the technology means that significant capital and financing costs hamper the bankability of projects and the competitiveness of the fuel (IEA, 2023a). Thus, for green hydrogen to be cost-competitive, a reduction in the cost of renewable electricity and electrolysers as well as increased efficiency needs to be achieved. Other obstacles to the use of green hydrogen include demand uncertainties, lack of infrastructure, and lack of clarity on regulations and skills, as evidenced by the fact that in more than 100 hydrogen projects, only 4% have reached a final investment decision (IEA, 2022). The IEA recognized that these challenges are interlinked and cannot be addressed independently or sequentially. Therefore, a coordinated strategy is required.

Despite the aforementioned obstacles to green hydrogen as a competitive fuel, it has some advantages such as indefinite storage (whereas batteries are suitable for short-term storage), high energy density and content of 142 MJ/kg (Sarker et al., 2023) as shown in Figure 2.3, and lack of harmful gas emissions (Imasiku et al., 2021;Fazioli & Pantaleone, 2021). Additionally, it is complementary to electricity and suitable for providing heat, light, and mechanical work, which are basic energy requirements (Posso et al., 2022). Nonetheless, the key advantages and disadvantages of green hydrogen from a sustainability perspective still require understanding.

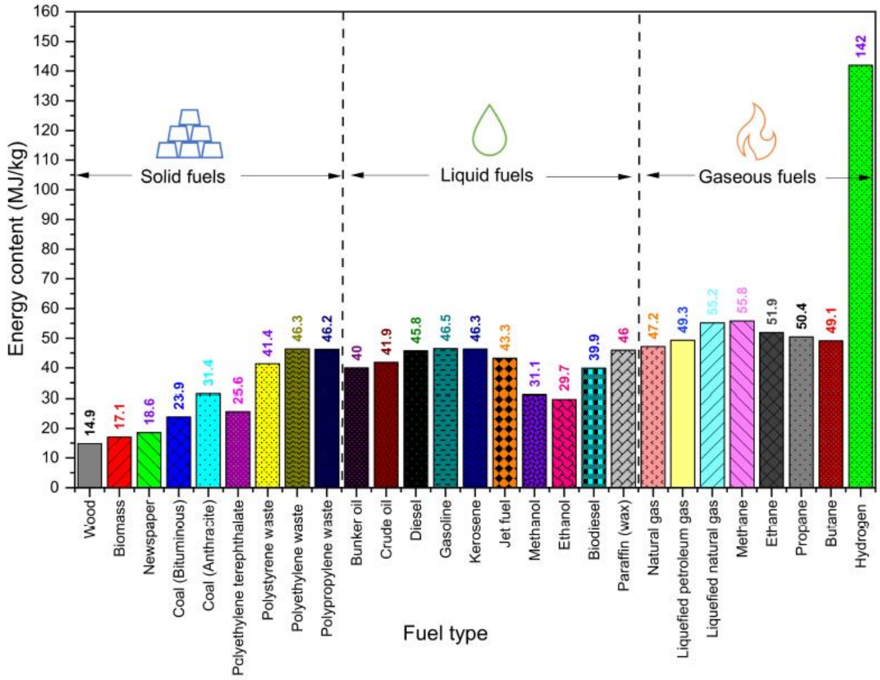


Figure 2.3: Green Hydrogen Energy Content

Source: (Sarker et al., 2023)

2.4 State of South African Hydrogen Production and Demand

Similar to global trends, South Africa predominantly relies on fossil fuels. South Africa’s energy landscape has historically been characterised by reliance on fossil fuels with coal and oil products, accounting for approximately 86% of the country’s energy supply in 2019 (Ratshomo & Nembahe, 2022) , as shown in Figure 2.4, making it the world’s 14th largest emitter of greenhouse gases (McSweeny & Timperley, 2018; Mostefaoui et al., 2024).

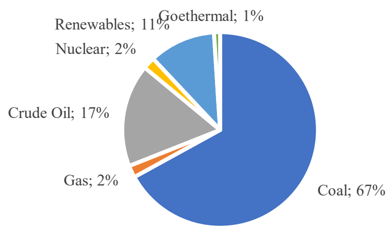


Figure 2.4: Primary Energy Supply (2019)

Source: (Ratshomo & Nembahe, 2022)

The key drivers of these greenhouse gas emissions were energy, transport, and industry, which collectively contribute to over 80% of the emissions (Department of Science and Innovation, 2021). This does not bode well for South Africa, as a Paris Agreement signatory that has committed to reducing its carbon emissions. In addition, South Africa experiences an energy deficit, which causes ongoing power outages, resulting in significant economic losses. Therefore, diversification of energy supply is required, particularly in energy-intensive industries that made up 41% of the primary energy demand as shown in Figure 2.5, and this diversification should include hydrogen.

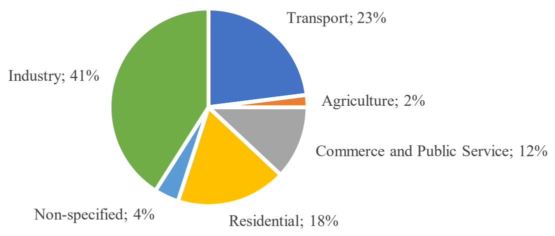


Figure 2.5: Primary Energy Demand (2019)

Source: (Ratshomo & Nembahe, 2022)

However, to date, the footprints of hydrogen in South Africa have been primarily grey hydrogen, predominantly produced by Sasol for its use as feedstock in the production of synthetic fuels using its Fischer-Tropsch technology (Department of Science and Innovation, 2021). Thus, government intervention is needed to introduce green hydrogen into the energy mix, specifically for use in the hard to abate and hard to electrify industries such as steel, iron and chemicals.

South Africa has designated hydrogen as a priority substitute energy source (Engie Impact, 2021). According to the Hydrogen Society Roadmap, South Africa aims to double its green hydrogen market share (currently 2%) by 2050 and capture 10% of the EU and Asian import markets (NCEDA, 2023). Several initiatives have been put in place, most notably in the proposed South African Hydrogen Valley, which aims to leverage the availability of infrastructure, hydrogen demand, hydrogen production, and renewable energy in Johannesburg, Mogalakwena, and Durban to create a green hydrogen economy (Engie Impact, 2021). Another key initiative is the proposed development of a green hydrogen economy in the Northern Cape. South Africa's vast solar and wind resources (which are used to generate electricity) and platinum group metal resources (which are key components of electrolysers) present an opportunity to further explore green hydrogen. However, The Department of Trade Industry and Competition (2022) rightly noted that the success of a green hydrogen economy requires an investor-friendly environment with clear government support, as it estimates that a total of USD 18.4 billion in capital will be required between 2023 and 2027 to kickstart the green hydrogen economy. Initial progress has been made in this regard, with feasibility studies being conducted by local investors such as Sasol, on green hydrogen projects in South Africa (NCEDA, 2023).

Green hydrogen may find applications in the industrial sector, such as chemical, iron, and steel manufacturers in Sasolburg; pulp and paper manufacturers in Durban; heavy-duty trucking sectors such as the N3 freight route; mining sector trucks in Limpopo; and public buses and buildings in metropolitan areas (Engie Impact, 2021). Most applications of hydrogen may be in the form of power fuels, which are liquid fuels made from green hydrogen that are required in hard-to-abate industries (Roos & Wright, 2021). Similar to the global challenges, South Africa's green hydrogen is impacted primarily by its lack of competitiveness. For example, the total cost of ownership of a heavy-duty truck that runs on hydrogen fuel is 10-45% higher than that of a diesel truck (Department of Science and Innovation, 2021).

Besides the obvious environmental benefits, a green hydrogen economy may contribute to sustainable development. In the South African context, socioeconomic considerations are important, and a green hydrogen economy promises multiple advantages. According to Engie Impact (2021), a hydrogen economy will have a positive effect on GDP and job creation. There is also an opportunity to localise the value chain including the beneficiation of platinum group metals, production of electrolysers, fuel production and recycling technology (The Department of Trade Industry and Competition, 2022). Furthermore, hydrogen may reduce the extent to which South Africa needs to import crude and refined oil, thus improving the country's balance of payments and reducing its dependence on foreign oil (Department of Science and Innovation, 2021). Although these environmental, economic, and social impacts have been reported in the literature and government reports, minimal attention has been paid to the interaction of these factors and whether they are key indicators of sustainability, which further indicates the need for this study.

The Northern Cape is particularly important in South Africa's aim to create a green hydrogen economy, as it is a province endowed with the availability of land, solar, and wind resources and with an ambition to be a leader in sustainable energy production. Figure 2.6 visualises the green hydrogen potential in the Northern Cape province.

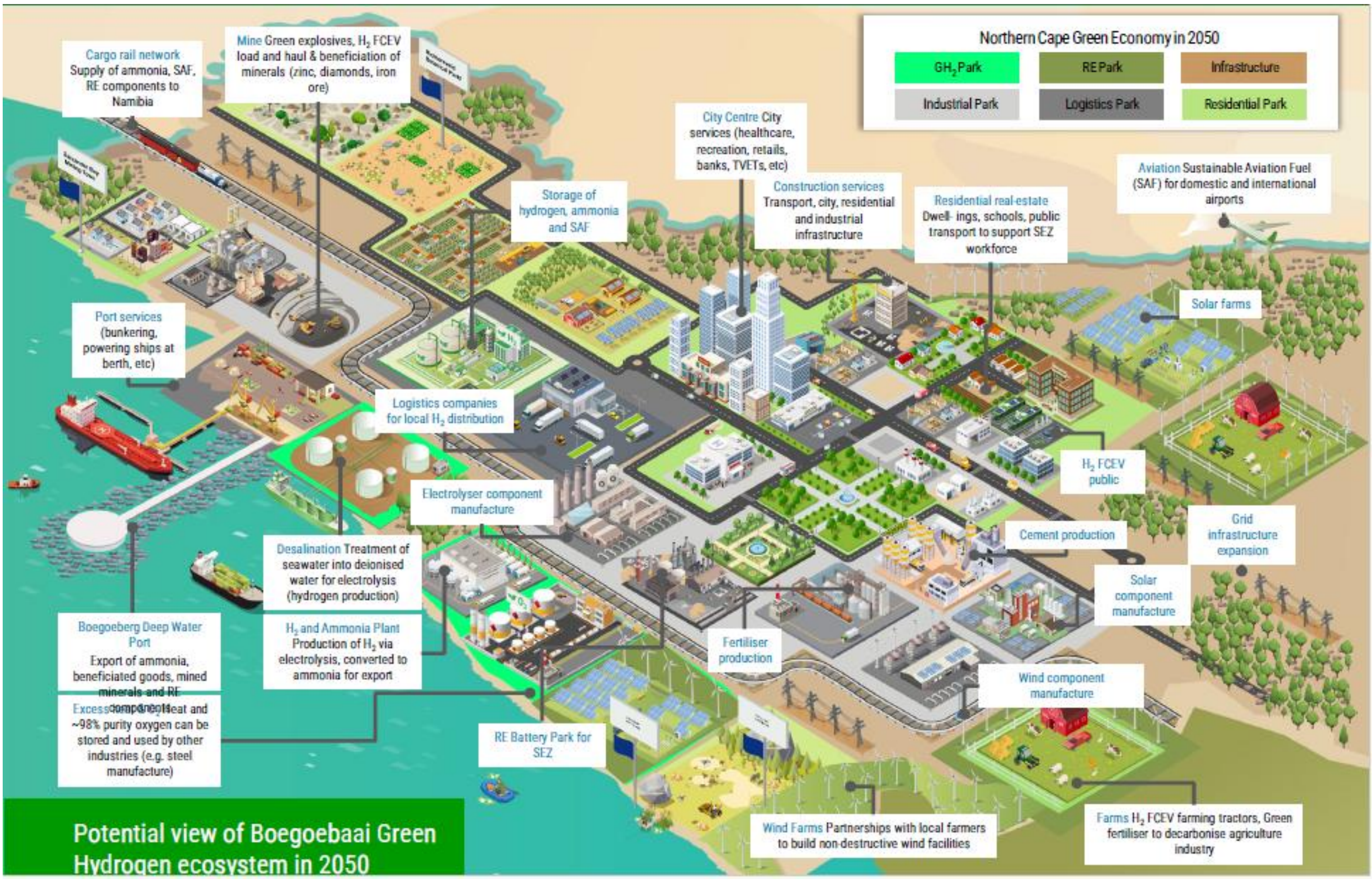


Figure 2.6: Northern Cape Green Hydrogen Economy

Source: (NCEDA, 2023)

According to the province's green hydrogen master plan (NCEDA, 2023), it aims to be a low-cost ammonia supplier to export and local off-takers and create a 40GW electrolyser capacity by 2050 while catalysing the localisation of the manufacturing of green hydrogen and renewable energy products in a designated special economic zone. The master plan highlights the anticipated socio-economic benefits of building a green hydrogen economy in the province, including job creation, skills development, GDP growth, and enterprise development. However, an in-depth study to understand the socioeconomic potential of the master plan has not yet been undertaken (NCEDA, 2023). Given the province's intentional strategy to be the leader in green hydrogen production, it is the focus of this study.

2.5 South Africa Policy Landscape

South Africa's broader energy policy framework has evolved, with green hydrogen becoming prominent only in recent years. The White Paper on the Energy Policy of the Republic of South Africa (DMRE, 1998) was the first attempt to provide policy directions for the energy landscape of the country. It envisaged the diversification of energy sources to ensure energy security and sustainability with particular policy objectives for supply from electricity, nuclear, oil and gas, liquid fuels, coal, renewable energy, and low-smoke fuels. This initial policy did not specifically consider the integration of green hydrogen into the energy system but mentioned the opportunity to utilise hydrogen in transport technologies. Following the White Paper, various Integrated Resource Plans (IRP) were published to act as roadmaps for the country's electricity needs. Although the first IRP was published in 2010 (DMRE, 2010), hydrogen was only considered in 2019 (DMRE, 2019) as a storage technology complementary to renewable energy, that should be further researched. The draft 2023 IRP (Department of Mineral Resources and Energy, 2023) builds on this by emphasising that green hydrogen will be required to transition to net-zero and that South Africa is primed to pursue a hydrogen economy due to its expertise in the Fischer-Tropsch process and the availability of required critical minerals and renewable energy sources. The draft 2023 IRP was further amended in 2024, to address the concerns that it was not aligned with other national policies such as the green hydrogen commercialisation strategy and the country's climate goals (DMRE, 2024a). The 2024 draft IRP that took these amendments into account was not yet available for review at the time of completion of this study. The 2016 Integrated Energy Plan (DMRE, 2016) similar to the White Paper, set out the government's policy to diversify energy supply and sustainably ensure supply security. This 2016 Integrated Energy Plan envisaged hydrogen and fuel cell technologies as a source of energy and similarly highlighted the advantages South Africa has in developing a hydrogen economy (Department of Mineral Resources and Energy, 2023). Five specific hydrogen and fuel cell systems were considered as part of the 2016 Integrated Energy Plan: standalone power systems, storage for renewable energy, combined heat and power units, back and prime power units, and hydrogen-fuelled rail vehicles (Department of Mineral Resources and Energy, 2023). The aforementioned policy documents, despite being critical in the country's energy landscape, did not delve deeper into the sustainability of green hydrogen, as the focus of these documents was the primary energy supply. This necessitated the development of hydrogen-specific strategies.

In South Africa, two key strategy documents are relevant to the development of a green hydrogen economy: the Hydrogen Society Roadmap for South Africa which is the government's hydrogen economy roadmap and policy direction intended to bring various stakeholders together and set out how green hydrogen will be deployed (Department of Science and Innovation, 2021), and the Green Hydrogen Commercialisation Strategy for South Africa which builds on the roadmap and outlines the commercial opportunity for green hydrogen (The Department of Trade Industry and Competition, 2022). In the Northern Cape, specifically, the Green Hydrogen Masterplan (NCEDA, 2023) sets out the vision that the province has for a green hydrogen society. Despite not being considered a hub as part of the proposed hydrogen valley, the Northern Cape put in place a policy to create an investment conducive environment. However, given the infancy of the green hydrogen sector in the world, one could describe these attempts as taking a "shot in the dark", as no country has yet fully commercialised green hydrogen. Therefore, this section of the literature review was conducted to understand the context of green hydrogen economy in South Africa. The following section conducted literature review to understand the context of technology sustainability assessment in South Africa.

2.6 Frameworks Relevant to the Assessment of Green Hydrogen

Multiple frameworks were relevant for energy technology assessment that could be applied in assessing the sustainability of green hydrogen in the Northern Cape. Therefore, this section discussed the theory and frameworks relevant to this study, particularly energy technology assessment, Systems Approach to Technology Sustainability Assessment (SATSA) (Musango & Brent, 2011) and Musango and Ouma-Mugabe's (2024) generic technology assessment framework for sustainable energy transitions. These frameworks enabled us to understand the context of technology sustainability assessment in South Africa as well as to identify sustainability indicators.

2.6.1 Energy Technology Assessment

Technology assessment can be defined as policy studies that provide decision-makers with information about the potential consequences of adopting a new or significantly altered technology, including both direct and indirect effects, benefits, drawbacks, and uncertainties. This approach also aims to assist decision-makers in making informed choices by providing a structured analysis of policy options and their implications for the economy, environment, social, political, and legal processes and institutions (CEFIC, 1997). Energy technology assessment is characterised by a systematic examination of the consequences associated with various technological alternatives for meeting society's energy demands, or more aptly defined by Musango & Ouma-Mugabe (2024) as *"a deliberate endevour to assess the potential and impact of technological change in an evolving energy system to advance sustainability, design selection and utilisation of resources"*. Energy technology assessment can be used to inform energy transition decisions and to address societal challenges in certain contexts (Musango, 2024), as well as to assess sustainability (Musango, 2025) ,therefore this framework was relevant in assessing the sustainability indicators of green hydrogen in the Northern Cape.

Researchers, such as Halicka (2016) and Musango & Ouma-Mugabe (2024), have investigated the varying forms that energy technology assessments have taken over the years for different purposes. It was evident that despite the broad definition of energy technology assessment and its focus on implications on various facets of processes and institutions, policymaking and literature had predominantly focused on only narrow implications of new energy technologies. Tran & Daim (2008) summarised general technology assessment methods that may find application in energy technology assessments such as economic analysis, decision analysis, systems analysis, technology forecasting, information monitoring, technical performance assessment, risk assessment, market analysis, and externality analysis. However, the field of energy technology assessment has not been developed yet. Indeed Musango & Ouma-Mugabe (2024) called for the development of the energy technology assessment field as it was not yet a unique field but remained rooted in the field of technology assessment (Musango, 2024).

Applications of general technology assessment methodologies can be found in hydrogen related literature. The literature primarily emphasised techno-economic analyses, such as Net Present Value and Levelised Cost of Energy determinations. This was exemplified by studies such as Matute et al. (2023), who developed a techno-economic model to assess the feasibility of green hydrogen projects using the NPV formula. Other techno-economic studies in the field include Achour et al. (2023)'s techno-economic model focusing on determining the Levelised Cost of Energy and Levelised Cost of Hydrogen using different solar photovoltaic technologies in Morrocco, Ayodele & Munda (2019)'s model using wind energy in South Africa and Gado et al. (2024)'s model using solar energy in numerous African countries. Having identified the uncertainties in the development of green hydrogen, Fazeli et al. (2022) developed a framework that integrated techno-economic models with Monte Carlo simulations to evaluate critical factors impacting the timing of the transition to green hydrogen. This approach also utilised a dynamic simulation model to understand the development of hydrogen production similar to the approach used in SATSA. These studies, although helpful in assessing the economic feasibility of the technology, failed to encapsulate the holistic nature of technology assessment from a sustainability perspective. Musango & Brent (2011)'s literature review on renewable energy technology analysis highlighted a similar dominance of economic perspectives that often neglected the dynamic nature of technological development.

Other studies went beyond merely economic metrics and assessed the socio-economic impact of the technology, such as Hamukoshi et al. (2022), who analysed the socio-economic impacts of the green hydrogen value chain. Furthermore, some have assessed the environmental impact, such as Zhang et al. (2022), who carried out a lifecycle assessment of hydrogen and examined the environmental impact of technology over its entire lifecycle, from the extraction of raw materials to the disposal of the technology.

The literature contained some examples of green hydrogen technology assessments that provided a holistic approach. Agyekum (2024) identified opportunities and challenges facing the development of hydrogen in Africa by utilising a best-worst method multi-criteria decision-making approach. However, by its nature, the study relied on experts' judgements and did not provide any evidence of how the highest-ranked opportunities and barriers would affect technology development. Mukelabai et al. (2022) went a step further and evaluated the PESTLE conditions instrumental in the development of hydrogen technologies in Africa whilst utilising Kate Raworth's doughnut model. However, this study also failed to analyse the interaction of these spheres of the system and did not account for causal loops between elements. Ma et al. (2010) deployed a system dynamics model to understand how the future economic development of China would impact the future demand for hydrogen.

Energy technology assessment can be helpful in assessing the implications of energy transition technologies and providing insights at any stage of development of the technology (Musango, 2024) , such as early-stage green hydrogen. The various technology assessments found in literature were indeed helpful in this study as they provided an indication of the various dimensions that one needs to consider when assessing a technology, beyond just economic metric. However, what was clear from the above literature review was that there was a gap in the assessment of green hydrogen technology from a systematic perspective. This necessitated a systems view of technology assessment, that is, the system analysis approach. Halicka (2016) classified this approach as an exploration research method of Future-Oriented Technology Analysis and concluded that it was useful in understanding factors that affect the development of a technology. This therefore required us to look at a specific framework for energy technology assessment which not only considered technology development but also explicitly takes sustainability into account, namely the SATSA.

2.6.2 Systems Approach to Technology Sustainability Assessment (SATSA)

Musango & Brent (2011a) developed a technology assessment framework that incorporates the concepts of technology development, sustainable development and dynamic systems approach in assessing the sustainability of energy technologies, particularly bioenergy as visualised in Figure 2.7.

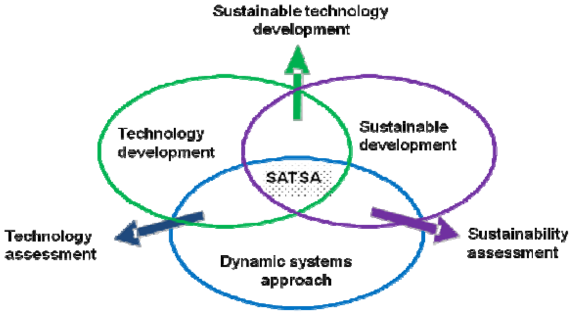


Figure 2.7: SATSA Framework

Source: Musango & Brent (2011a)

This framework enabled the utilisation of a holistic approach to determine the sustainability of a specific energy technology. This framework interlinked with other frameworks discussed in this chapter including energy technology assessment (discussed in section 2.6.1) and sustainability assessment (discussed in section 2.6.4) thus provided useful insights in understanding the context of technology sustainability assessment.

This framework is particularly important in a development finance setting wherein the economic sustainability of technology needs to be supported by social and environmental sustainability to drive sustainable development in line with the United Nations Sustainable Development Goals. Indeed Musango (2012) found that this framework can be applied to the sustainability assessment of other renewable energy technologies, of which green hydrogen is one. Although no system dynamics modelling is undertaken as part of this study, SATSA provides a clear insight into the intersection of technology development, sustainable development, and system dynamics, and is indeed a sound theoretical foundation for investigating the sustainability of green hydrogen in the Northern Cape and understanding the context of energy technology sustainability assessment in South Africa.

2.6.3 Generic Technology Assessment Framework for Sustainable Energy Transitions

Musango & Ouma-Mugabe (2024)'s 3-phased framework for action-oriented energy technology assessment for sustainability as summarised in Figure 2.8, provided a sound basis for undertaking energy technology assessment in an African context. As discussed earlier, the assessment of the sustainability of green hydrogen required one to understand the views of various participants in the green hydrogen economy in the geographical location where it is to be implemented. This framework was particularly helpful in the context of this study as it was premised on inclusive stakeholder engagement in a transdisciplinary manner.

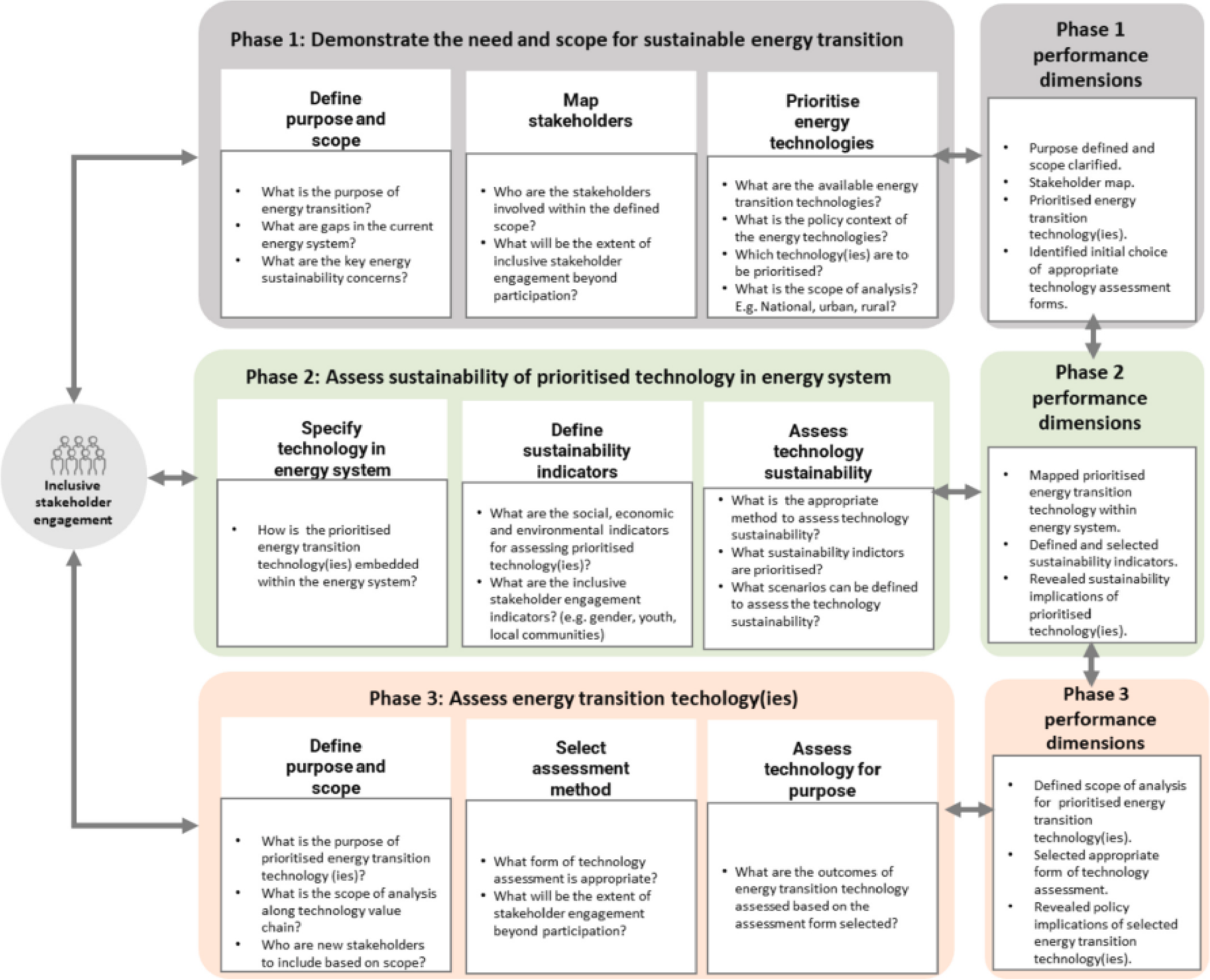


Figure 2.8: Generic Technology Assessment Framework

Source: (Musango & Ouma-Mugabe, 2024)

2.6.4 Sustainability Assessment of Green Hydrogen

The three phases proposed in the framework, included firstly demonstrating the need and scope for sustainable energy transition. Secondly, assessing the sustainability of priorities technology in the energy system. Lastly, assessing the energy transition technology. Based on the research objectives of this study, only phase one and phase two were relevant for this study and were therefore discussed herein.

Phase 1 of this framework was used to answer the first research question. This is because this phase required a comprehensive understanding of the context of energy technology as well as the greater energy system. This was done by assessing the energy system as it included its sustainability pitfalls and gaps, mapping the stakeholders relevant to the energy technology assessment, and prioritising an energy technology for further assessment as part of Phase 2.

Phase 2 of the framework was used to answer the second research question. This was particularly so because it required a system assessment of the sustainability dimensions and indicators of the prioritised energy technology, in this instance, green hydrogen. The United Nations Trade and Development pilot program did not consider this (Mlosy, 2024) , and therefore, this presented a research gap in the green hydrogen sustainability assessment in South Africa.

The energy technology assessments discussed in 2.6.1 need to consider social, economic and environment in order for them contribute to sustainability (Musango, 2025). Therefore, this necessitated the discussion of sustainability assessment. According to Kates et al. (2001), sustainability assessment entails evaluating integrated environmental, economic, and social systems from a long- and short-term viewpoint. In other words, it is a process of evaluating the impact of a project, initiative, or activity on the sustainability of society (Pope et al., 2004). It forms part of the broader impact assessment field. There are a multitude of sustainability assessment methodologies in practice which were adequately summarised by Singh et al. (2009) and Ness et al. (2007) and were therefore not covered here. Bond et al. (2012) found that sustainability assessment in practice had several advantages such as acknowledgement of context and pluralism, promised more direct attention to interactions of social, economic and environmental factors, and is holistic in nature. This is particularly the case for system-dynamics-based sustainability assessments. However, these types of assessments are uncommon in the literature. Studies that have attempted to assess the sustainability of hydrogen have typically been conducted based on a limited set of criteria such as cost and carbon emissions (McDowall & Eames, 2007). This further highlights the need for more comprehensive criteria. Criteria and indicators to assess sustainability are widely used in multiple branches of science (Diaz-Balteiro et al., 2017) and were therefore utilised in this study.

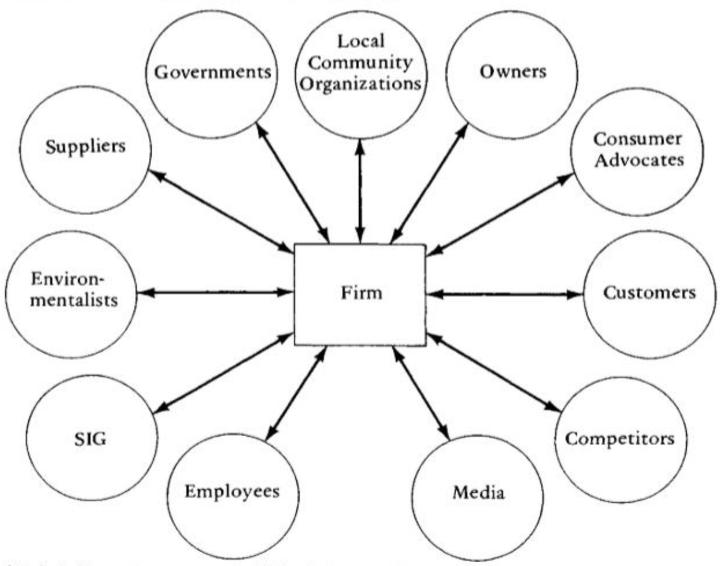
Although the reviewed literature on green hydrogen includes energy technology assessments, these assessments rarely assessed the technology from a wider sustainability perspective as highlighted in section 2.6.1. The few that did include multi-criteria by Hong et al. (2023) and Das et al. (2024) that both assessed the sustainability of green hydrogen using a multi criteria decision making analysis. Life cycle assessments (social and environmental) were also used in literature to assess sustainability of green hydrogen processes including by Barbera et al. (2022) and (Akhtar et al., 2023). Indeed Musango (2025) found these two types of analyses to be prevalent in energy technology assessments, with the added benefit of their assessment of sustainability.

In addition, to its important in energy technology assessments, sustainability assessment has become increasingly important in investment decisions, as asset owners and managers are under pressure to not only consider economic metrics but also evaluate investments against their environmental and social impacts. Indeed, the rise of sustainability-themed capital markets and instruments/products highlights the importance of sustainability to investors. Therefore, for new technologies to reach FID, the technology must be sustainable. Thus, making sustainability assessment of green hydrogen important for this study.

2.7 Framework Relevant to Sustainable Investment: Stakeholder Theory

This study identified the stakeholder theory as relevant in the field of sustainable investment, when identifying key stakeholders. This theory provided a sound basis to approach the research questions and to undertake this study as further discussed in this section.

Stakeholder theory is a sound theoretical framework through which sustainable investment can be viewed. This theory finds its roots in the management discipline and was formally established by R. Edward Freeman's seminal work Strategic Management: A Stakeholder Approach which was first published in 1984 (Freeman, 2010b). This theory argues that businesses and investors should consider the interests of all stakeholders that are impacted or that can impact their activities (Freeman, 2010a) including capital providers, employees, customers, communities and suppliers as highlighted in Figure 2.9. This links with energy technology assessment as Musango (2025) found that one of the roles of technology assessment includes the integration of knowledge from various stakeholders. In addition, stakeholder engagement is a critical part of the generic technology assessment framework further highlighting the relevance of this theory.



*Stakeholder = Any group or individual who can affect or is affected by the achievement of the firm's objectives. The groups listed here are examples of categories of stakeholders.

Figure 2.9 Stakeholder Theory Framework Theory

Source: (Freeman, 2010a)

Freeman (2010a) found this theory to be gaining traction with finance researchers and being applied to numerous finance related questions. This theory has also developed over time into a number of disciplines including in systems theories (Freeman, 2010b) such as those discussed in 2.6. This makes it particularly relevant in sustainable investment and this study as it highlights the need to consider the social, economic and environmental impacts of investment on all stakeholders. Indeed, Dzomonda & Fatoki (2020) found this theory to be significant, as it set a precedent for understanding the sustainability commitments of investors who have to respond to stakeholder interests.

In assessing the sustainability of green hydrogen in the Northern Cape to facilitate investment decisions, this theory was used to map the relevant stakeholders in the green hydrogen economy in the region for the purposes of collecting their views on sustainability indicators as discussed further in Chapter 3 of this study.

2.8 Summary of Literature

In conclusion, this literature review provided a comprehensive overview of green hydrogen, encompassing its production methods, global landscape, applications, challenges, and opportunities. This highlighted the critical role that green hydrogen can play in achieving decarbonisation goals and emphasises the need for its widespread adoption. The South African green hydrogen economy context was also explored, revealing its dependence on fossil fuels and potential to become a leader in green hydrogen production.

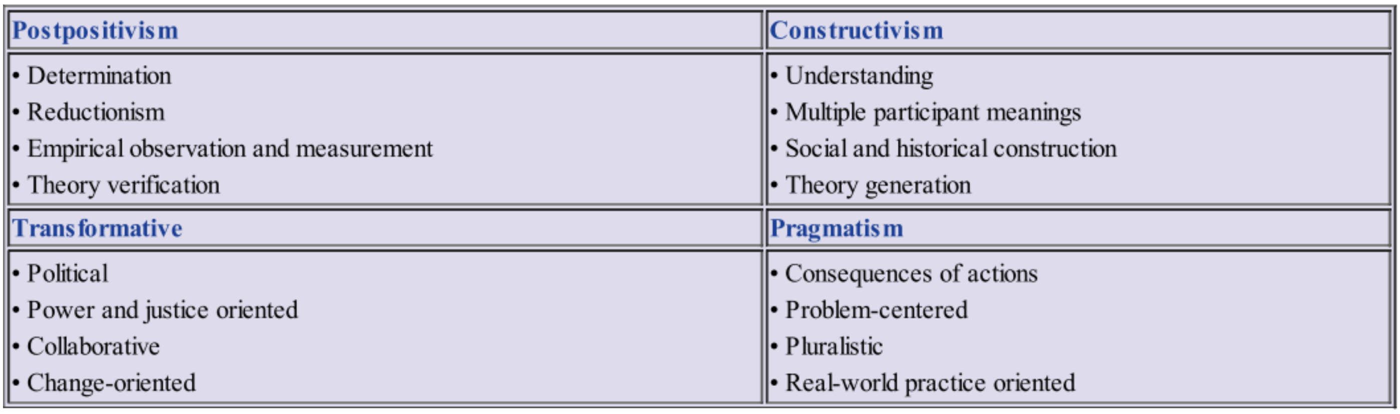
However, the review also identified a gap in the existing research. Although techno-economic analyses of green hydrogen are plentiful, there was a lack of holistic assessments that considered the complex interplay between economic, environmental, and social factors. This showed the need for developing sustainability indicators that can support undertaking a technology assessment sustainability of the green hydrogen economy.

CHAPTER 3: RESEARCH METHODOLOGY

This chapter firstly describes the research methodology used to investigate the sustainability indicators of a green hydrogen economy. An examination of the underlying philosophical assumptions was undertaken to establish a solid foundation for this study. This examination entailed an analysis of ontology, epistemology, and axiology, which collectively constituted a worldview of research. By scrutinising these philosophical principles, the most appropriate research approach was identified. Secondly, the specific research design, including the data collection and analysis techniques, were detailed. This systematic approach ensured comprehensive and rigorous exploration of the multifaceted issue of green hydrogen sustainability.

3.1 Research Approach

Three primary research approaches can be utilised in conducting a study: quantitative, qualitative, and mixed-method approaches, which are underpinned by the philosophical assumptions underlying the research and how the author views the world (Creswell, 2014). A quantitative approach uses numerical data, whereas a qualitative approach uses descriptive data, with a mixed-method approach that uses both. The appropriate research methodology for this study was determined with reference to its ontology, epistemology, axiology, and the worldview that the author brings to the study, as summarised in Figure 3.1. Based on this, a mixed-method research method was undertaken because of the pragmatic worldview that underpins this study. This worldview acknowledges the subjectivity of energy technology sustainability assessments and varying views of stakeholders in specific social, historical, political, and other contexts. Accordingly, both quantitative and qualitative methods were employed.



Postpositivism	**Constructivism**
• Determination • Reductionism • Empirical observation and measurement • Theory verification	• Understanding • Multiple participant meanings • Social and historical construction • Theory generation
Transformative	**Pragmatism**
• Political • Power and justice oriented • Collaborative • Change-oriented	• Consequences of actions • Problem-centered • Pluralistic • Real-world practice oriented

Figure 3.1: Four Worldviews

Source: Creswell (2014)

3.1.1 Ontology

Ontology considers what the author's view of reality is and which can either be that there is only one objective reality (objectivism), there are multiple subjective realities (subjectivism), or there is a combination of both singular and multiple realities that are external (Saunders et al., 2009). The development of a green hydrogen economy is a function of the interactions of different actors with varying experiences, values, and biases and therefore their assessment of the sustainability of the technology will differ. Indeed McDowall & Eames (2007) and Diaz-Balteiro et al. (2017) highlighted that there were conflicting views on the sustainability of energy technologies. Therefore, this study adopted a subjectivism position framework in terms of which there are multiple constructed realities.

3.1.2 Epistemology

Epistemology considers what the author's view on what is considered acceptable knowledge is and which can be that only evidence that is observed provides acceptable knowledge; knowledge can be subjective and thus interpreted and understood in various ways; or that both observable evidence and subjective interpretations can be acceptable knowledge (Saunders et al., 2009). The research objectives of this study required the integration of knowledge from various sources. Indeed, the subjective views of stakeholders in green hydrogen development needed to be considered to truly understand this complex system.

3.1.3 Axiology

Axiology considers what the author's view on the role of values is and which can be that the author must be independent of the data and have an objective viewpoint, that the author is part of the subject matter and therefore will be subjective, or that the author can be both subjective and objective (Saunders et al., 2009). The author's view is that, by its very nature, sustainability is value-laden, and therefore, the author cannot be seen as independent of the phenomena. This is echoed by McDowall & Eames (2007) who found that in instances of uncertain long-term technological assessments, it is appropriate to consider value-based perspectives. However, being impartial is still key to undertaking research in an unbiased manner; therefore, values should be controlled as much as possible. This can be achieved through the validation of research outcomes and by ensuring that a wide engagement of stakeholder input is considered, which was undertaken in this study.

3.1.4 Methodology

Methodology considers the applicable research process which can be either deductive in that it tests existing theories, inductive in that it uses the views found to identify themes or can be both inductive and deductive (Saunders et al., 2009). This study used both deductive and inductive approaches. A literature review was undertaken from a qualitative perspective to source sustainability indicators in the literature, and a quantitative survey was undertaken to supplement these findings. This is in line with some of the reasons provided by Saunders et al. (2009) for utilising mixed methods, including the need to corroborate research findings and to use one data collection method to aid another. The research methodology applied herein was, therefore, an exploratory sequential mixed method, as it involved a qualitative approach followed by a quantitative approach, followed by the integration of the two.

3.2 Research Design

The research objectives of this study lend themselves to an exploratory study as it aimed to seek new insights regarding green hydrogen sustainability. According to Saunders et al. (2009), there are multiple ways in which one can conduct this type of study, including searching the literature and conducting interviews or surveys. To answer the two research questions firstly “what is the context of the green hydrogen economy and technology sustainability assessment in South Africa?” and secondly “what are the key sustainability indicators of green hydrogen in the Northern Cape?” a literature review and survey were conducted. Surveys are particularly helpful in answering “What” type of questions as this study aimed to do in answering the second research question (Saunders et al., 2009). The following is a discussion of the research design undertaken to achieve the research objectives set out in Chapter 1. The sequence of this was to first perform a literature review to determine a broad list of sustainability indicators and then quantitatively survey stakeholders to adjust and rank the various indicators while using the qualitative aspects of the open-ended questions in the survey to understand other indicators not found in the literature.

3.2.1 Qualitative Literature Review

A three-step systematic review was utilised to search for, analyse, and synthesise research on green hydrogen sustainability indicators. This approach is qualitative and has been used in the field of sustainability assessment (Lindfors, 2021). The systematic literature review has the benefit of improving the ability to understand the consistency of findings in literature and provides evidence of robustness and transferability of these findings (Ahmad, 2022). Furthermore, this literature review method was particularly useful in areas of uncertainty, such as the sustainability of green hydrogen. Therefore, despite its limitations in that it focuses only on peer-reviewed documents, this method is appropriate for undertaking this study and investigating sustainability indicators of green hydrogen.

3.2.1.1 Literature search criteria

A systematic literature review was conducted to search, collect, analyse, and compile the sustainability indicators of green hydrogen. The first step included a literature search of the Scopus database from 1997 to September 2024, using the keywords and search criteria highlighted in table 3.1.

Table 3.1: Keywords and search query criteria

Last date of search	**Search Terms**		**Search Query Strings**
13 Aug 24	Green hydrogen	Assessment	"green hydrogen"
	Sustainability	Assess*	"green hydrogen" AND sustain*
	Sustain*	Evaluation	"green hydrogen" AND indicator*
	Indicators	Evalu*	"green hydrogen" AND assess*
	Indicator*	Technology assessment	"green hydrogen" AND evalu*
	Technology assess*	Sustainability evaluation	"green hydrogen" AND "sustain* indicator*"
	Technology evaluation	Sustainability evalu*	"green hydrogen" AND "sustainability assess*"
	Technology Eval*	Sustain* evalu*	"green hydrogen" AND "sustain* evalu*"
	Sustainability assessment	Sustainability indicators	"green hydrogen" AND "technology assess*"
	Sustainability assess*	Sustain* indicator*	"green hydrogen" AND "technology evalu*"

Scopus is the largest database of peer reviewed publications (Schotten et al., 2018) and therefore provided extensive peer reviewed papers to support some of the insights and sustainability indicators from grey literature discussed in chapter 2. Green hydrogen research has recently garnered attention. Figure 3.2 shows the trend in green hydrogen-related publications, indicating a significant increase in research from 2020 onwards.

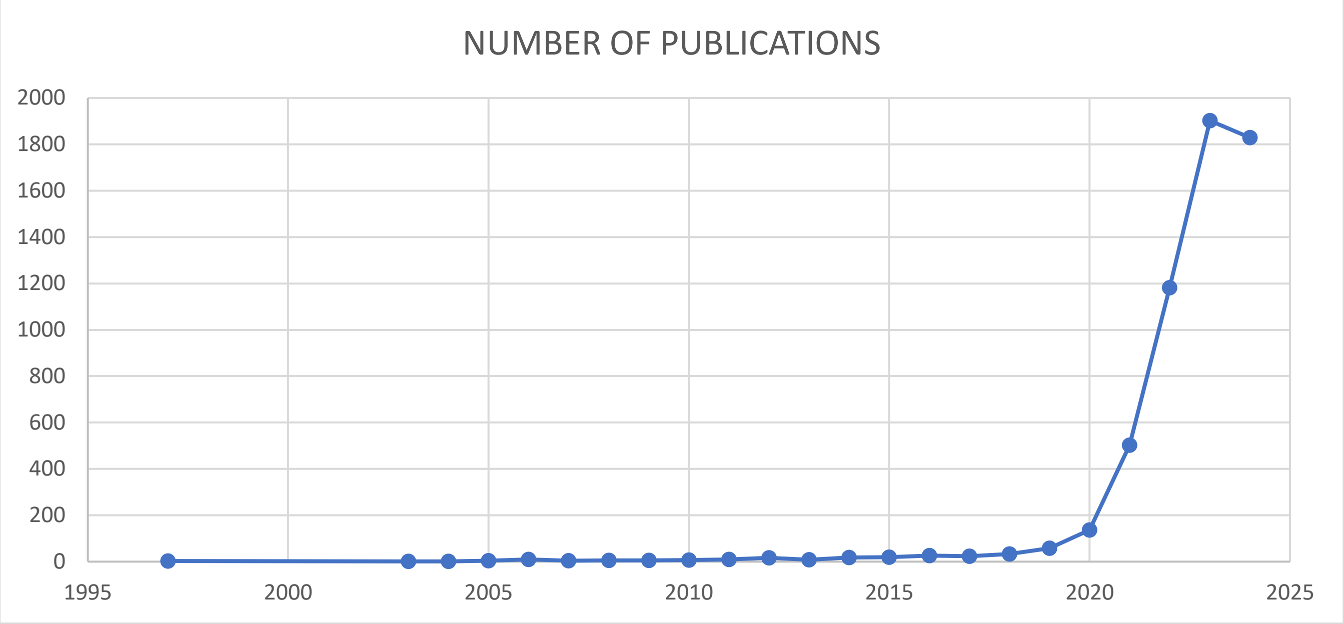


Figure 3.2: Publications using the keyword "Green Hydrogen"

Source: Author

This increased focus on green hydrogen research emphasised the importance of this field in the current energy discourse, thus necessitating research in this area. Furthermore, the importance of green hydrogen in the energy transition has necessitated further research to answer some of the questions currently riddling it and reduce uncertainties.

However, the research output is not evenly distributed geographically. Figure 3.3 highlights the concentration of research in China, the EU, India, North America, and the United Kingdom, with limited research undertaken in Africa.

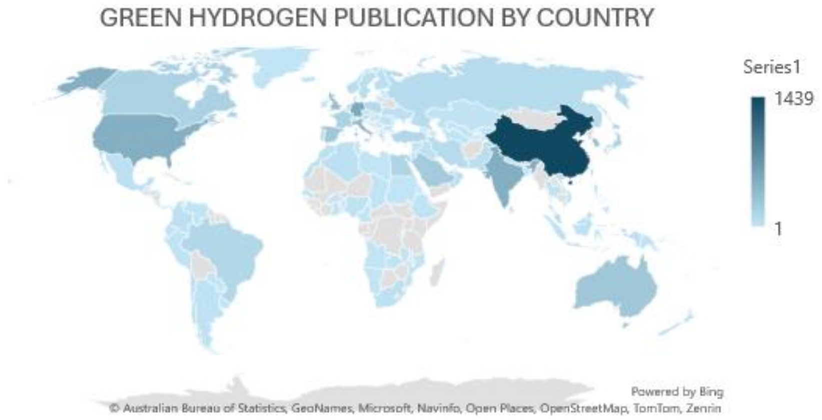


Figure 3.3: Publications by Country using keyword "Green Hydrogen"

Source: Author

However, this concentration is not surprising, as these are the regions with the highest hydrogen demand, as discussed in Chapter 2. The lack of significant peer-reviewed African research in comparison to other regions further highlights the research gap that exists on the continent, as the literature is not contextualised to African society. This may lead to the assessment of green hydrogen sustainability found in the literature, not fully considering the nuances of African countries and the Northern Cape province. This study therefore aimed to contribute to the African based green hydrogen studies.

3.2.1.2 Literature eligibility and screening criteria

Figure 3.4 sets out the literature review search and screening strategy deployed by the author.

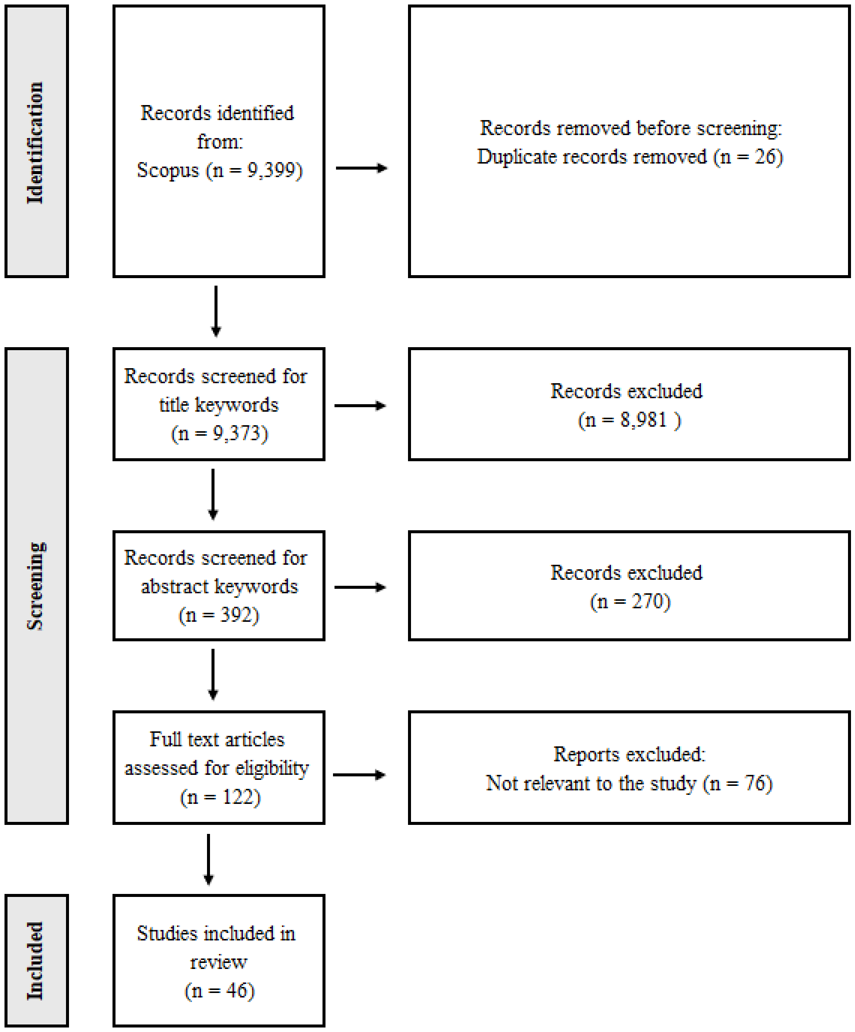


Figure 3.4: Diagram of the literature review search and screening strategy

Source: Author based on the Preferred Reporting Items for Systematic Reviews and Meta Analysis flowchart (Moher et al., 2009)

The initial search resulted in 9,399 publications being found. The second step included screening the literature to identify the publications to be included in the analysis. First, 26 duplicate publications were excluded. Second, 8,981 articles that were irrelevant to the research question were excluded based on their titles. Third, the abstracts of the remaining publications were read and 270 publications with abstracts not relevant to the research question were excluded. Finally, the remaining publications were read in full and 76 irrelevant publications were excluded. This resulted in 46 studies being included in the review as shown in Appendix A. The relevance was determined based on whether the publications covered green hydrogen sustainability indicators or assessment. This approach resulted in a saturation point being reached resulting in similar indicators being found. The sustainability indicators found in the final literature selected were therefore summarised, analysed, and set out in Chapter 4 of this dissertation.

3.2.2 Surveys

A survey was undertaken to corroborate the findings from the literature review in line with the approach set out by Saunders et al. (2009) whilst adding geographical context to the research. According to (Saunders et al., 2009) surveys helped to answer "What" type of research questions as this study aimed to do therefore making this approach justifiable.

The survey was conducted first by mapping and sampling stakeholders to the survey, and second by designing both quantitative and qualitative survey questions while ensuring the credibility of the survey. The self-administered survey was conducted using the online survey platform Survey Monkey which enabled efficient surveying of participants in various geographical locations with varying availability. The link to the survey was sent to respondents via email as well as via a LinkedIn direct message, with reminders sent to participants.

3.2.2.1 Mapping and Sample

The scoping and mapping of stakeholders were initially undertaken by assessing the various stakeholders in the green hydrogen economy, including those involved in its development and those impacted by its development, including stakeholders found as part of the literature review. Similar to the approach undertaken by McDowall & Eames (2007) which included mapping the relevant stakeholders by evaluating participants in the hydrogen economy. This mapping ensured that there was a sufficient representation of hydrogen production, distribution, users, policymakers, and civil society stakeholders. The Northern Cape green hydrogen master plan envisages the government (local, regional, national, and provincial), participants across the value chain, infrastructure developers, and civil society collaborating to create an action-oriented plan (NCEDA, 2023). This is echoed by the sentiments in Lindfors (2021) that a wide range of stakeholders, as well as experts with technical expertise, should be considered. Furthermore, the exclusion of NGO's and local community consultations can lead to procedural injustices (Kalt et al., 2023). The mapping process undertaken resulted in several of stakeholder groups being identified and contacted as set out in Table 3.2.

Table 3.2: Stakeholder Mapping and Sample

Stakeholder Group	**Group Description**	**Number of Stakeholders Contacted**	**Number of Stakeholders Participated**
National government	National, provincial and local government organisations, departments or authorities.	5	1
Provincial government		4	1
Local government		6	1
Project developers	Solar and wind energy companies that generate electricity required for electrolysis as well as green hydrogen producers.	8	2
Value chain participants	Companies offering necessary offtake, infrastructure and manufacturing capacity to the green hydrogen economy.	11	1
Local community	Individuals or businesses domiciled in the Northern Cape.	5	1
Civil society	Organisations focused on environmental protection and sustainability	6	1
Media	Journalists that report on energy technologies	2	1
Academia	Researchers with specific interest in green hydrogen and/or sustainability.	4	1
Consultants/Advisors	Providers of consultancy services (legal, technical or financial) to stakeholders of the green hydrogen economy.	5	4
Funders and investors	Potential funders of green hydrogen projects.	4	2
Total Participants		**60**	**16**

After mapping the stakeholders, a non-probabilistic self-sampling was used to select participants, suggested by Saunders et al. (2009) in exploratory studies by way of purposeful sampling. Specifically typical case purposeful sampling is used as stakeholders in typical green hydrogen stakeholder groups are selected and are knowledgeable participants (Emmel, 2014). This sampling method had the benefit of ensuring that the selected stakeholders provided the best insights into the research questions.

This sampling method's main drawbacks arose due to the fact that it was non-probabilistic. The first drawback was that it could lead to researcher bias through the selection of participants, however this was mitigated by ensuring participants were of varying professions, backgrounds and ages. The second drawback was that the sample selection was based on the author's subjective criteria which may make it difficult for another researcher to replicate, however this was mitigated by clearly outlining how the sample was selected in this study. The last drawback was that it did not enable statistical generalisability

(Emmel, 2014). However, the purpose of sampling in this study was not to ensure that the sample is representative of the population or for generalisation purposes; but to understand the views of key stakeholders in the green hydrogen economy therefore, this approach was appropriate. The sample size was determined based on the author's judgement of the relevant stakeholders involved in green hydrogen production in the Northern Cape Province, following the 3 phased generic framework. Further guidance was provided in Baker & Edwards (2012) which suggested that a sample of 15 or more participants was sufficient for a study that relied on expert participants like this one. The results of the mapping and sample selection are listed in Table 3.2.

The individuals in the stakeholder groups listed in Table 3.2 were selected based on their active participation in green hydrogen-related LinkedIn groups, conferences, and webinars in South Africa, including the Devac Hydrogen-H Indaba (17 – 18 September 2024), the Infrastructure Africa Conference (16 – 17 July 2024) and the green hydrogen economy webinar hosted by Creamer Media (9 October 2024). Furthermore, the individuals chosen were either those that are in a position to influence decision-making or policy in the green hydrogen economy or those that can be directly impacted by these decisions or policies. Due to the confidentiality of the participants, the names and organisations that they were employed by were not disclosed in this study only their position, age, gender, stakeholder group and sector as shown in Table 3.3. In this process, 60 individuals were identified and contacted. Of these, 16 responded to and participated in the survey indicating a response rate of 26.6% which is greater than the 11% likely response rate for internet-based questionnaires according to Saunders et al. (2009). Most participants were between the ages of 35 and 55 years and included key individuals in both public and private sector organisations that will participate or be impacted by the green hydrogen economy in the Northern Cape province.

Table 3.3: Surveyed Participants

	Position	Age	Gender	Stakeholder Group	Sector
1	Chief Executive Officer	35 to 44	Male	Government	Public
2	Head: Project Development	55 to 64	Male	Funders and Investors	Public
3	Director	45 to 54	Male	Project Developers	Private
4	Energy Manager	35 to 44	Female	Government	Public
5	Director: Sector Head	35 to 44	Male	Consultants and Advisors	Private
6	Senior Deputy Editor	55 to 64	Male	Civil Society	Private
7	Technical Director	25 to 34	Female	Consultants and Advisors	Private
8	Professor	65 to 74	Male	Academia	Private
9	Technical Development Engineer	25 to 34	Male	Project Developers	Private
10	Sustainability/Carbon specialist consultant	45 to 54	Male	Consultants and Advisors	Private

11	Technical Advisor	35 to 44	Female	Funders and Investors	Public
12	Chief Financial Officer	25 to 34	Male	Local Community	Private
13	Senior Manager Corporate & Community Services	45 to 54	Male	Government	Public
14	President	45 to 54	Male	Value chain participants	Private
15	Senior engineer	35 to 44	Female	Consultants and Advisors	Public
16	Implementation Manager	55 to 65	Female	Funders and Investors	Public

3.2.2.2 Survey Utilised

Once the stakeholders were mapped and sampled, 16 were surveyed to appraise the sustainability of the green hydrogen economy, particularly the indicators identified in the literature. The surveys conducted on the Survey Monkey platform took an average of 10 minutes to complete. The survey questionnaire was included as Appendix B. The survey utilised was Internet-mediated which has the following benefits (Saunders et al., 2009):

a. Higher confidence that the right person responded,
b. Likelihood of distortion of respondent’s answer was low,
c. Sample could be geographically dispersed,
d. Suitable for closed questions, such as those this study aimed to answer.

Indeed, these benefits were realised as part of this study. The indicators determined through the literature review were used to frame the survey questionnaire, a methodology used by other researchers such as Das (2023). The responses of the sampled stakeholders were registered using a 5-point Likert scale, which attached a number to each given response. Indeed, Likert-style rating questions were useful for collecting opinion data (Saunders et al., 2009) which was essential for understanding the viewpoints of various stakeholders in the green hydrogen economy. Respondents to the survey were asked to indicate the extent to which they believed each sustainability indicator was important to them, from not important at all (1) to extremely important (5). Thereafter, the Total Choice Score (TCS) for each indicator and its proportional contribution to the total weighted score were determined, with the derived TCS for all indicators changed to their respective weighted mean scores (WMS). Based on the WMS, the indicators were ranked in order of their importance to stakeholders. This helped determine the key indicators of the sustainability of the green hydrogen economy in the Northern Cape.

3.2.2.3 Credibility of Survey

Threats to the reliability and validity of the data collected in the survey were mitigated throughout the process by making use of the guidelines provided by Saunders et al.(2009). The actions undertaken in this study can be summarised as follows:

a. The author ensured that he was knowledgeable about the green hydrogen economy in Northern Cape prior to undertaking the survey through an in-depth literature review, as discussed in Chapter Two this study.
b. Supplied relevant information to participants before the survey, including what the research topic was and what the research objective was.
c. The survey was conducted in an appropriate place where participants felt comfortable owing to the self-administered nature of the survey.
d. Demonstrated credibility and friendliness before the survey commenced through the initial email or LinkedIn message sent to the participants to explain the process.
e. Utilised a neutral tone in the survey questions, with limited use of jargon, and ensuring that each indicator was adequately described.
f. The questionnaire was piloted using three friends who completed the survey using dummy responses and provided feedback on whether the questions were easy to understand, and the logic of the questionnaire was sound.

Therefore, the survey was reliable in that it was consistent and produced consistent results. This was supported by the reliability test performed by the author using an alternative form test. In this test, the participants were asked an open-ended question on which indicators that were part of the survey were not relevant to green hydrogen economy sustainability in the Northern Cape. The responses to these questions were then compared to previous responses. There were no instances where an indicator marked as irrelevant by a participant was given a high rating as part of the Likert-scale styled question of the indicator by the same participant.

CHAPTER 4: DISCUSSION OF FINDINGS

This chapter discussed the results of the systematic literature review, and the sustainability indicators found therein followed by a discussion of the findings from the stakeholder survey to understand what the key sustainability indicators in the Northern Cape were.

4.1 Green Hydrogen Sustainability Indicators from Literature Analysis

Based on the systematic literature review a total of twenty-eight sustainability indicators were identified: eleven being environmental indicators, nine being economic indicators and eight being social indicators (Table 3). As part of the analysis of sustainability indicators, indicators that measure similar goals were grouped to make the list concise. This is because less complicated frameworks with select lead indicators are more desirable, as they are easier to interpret and are more useful for decision-making purposes (Musango et al., 2012).

Table 4.1: Literature Sustainability Indicators

Indicator	**Symbol**	**Description**	**References**
ENVIRONMENTAL			
Land Use	ENVIRO1	Measures the amount of land required for green hydrogen production facilities, including electrolyzers, renewable energy sources (solar panels, wind turbines), and transportation infrastructure.	Dagnachew et al. (2024), Kalt et al. (2023), Apata (2024), Shen et al. (2024), Virens (2024), Chigbu & Nweke-Eze (2023), Blohm & Dettner (2023), Olabi et al. (2023), Agyekum (2024b), Vinardell et al. (2023), Cremonese et al. (2023), Weidner et al. (2023) and Barbera et al. (2022)
Water Use	ENVIRO2	Measures the water consumption for electrolysis, cooling systems, and potential cleaning processes.	Dagnachew et al. (2024), Kalt et al. (2023), Apata (2024), Shen et al. (2024), Virens (2024), Chigbu & Nweke-Eze (2023), Blohm & Dettner (2023), Olabi et al. (2023), Borge-Diez et al. (2024), Cremonese et al. (2023), Weidner et al. (2023) and Barbera et al. (2022)
Air Pollution, Carbon Emissions & Greenhouse Emissions	ENVIRO3	Measures the amount of air pollutants, carbon dioxide, and other greenhouse gases released due to green hydrogen production and consumption.	Kweinor Tetteh et al. (2024), Ellaythy et al. (2024), Shen et al. (2024), Blohm & Dettner (2023), Gupta et al. (2023), Das et al. (2024), Mneimneh et al. (2023), Neri et al. (2024), Wei et al. (2024), Ahrens et al. (2022), Fazli-Khalaf et al. (2020), Hamukoshi et al., (2022b), Hong et al. (2023), Olabi et al. (2023), Agyekum (2024b), Maimaiti et al. (2023), Weidner et

			al. (2023) and Guarieiro et al. (2022)
Marine Life Destruction & Water Pollution	ENVIRO4	Represents the potential impact of green hydrogen production facilities on marine ecosystems and water quality. This includes potential spills, discharges, and disruptions to marine life.	Kalt et al. (2023), Olabi et al. (2023), Mneimneh et al. (2023), Vinardell et al. (2023), Weidner et al. (2023), Maimaiti et al. (2023) and Barbera et al. (2022)
Resources, Minerals and Metals Use	ENVIRO5	Measures quantities of resources (for example, platinum group metals) needed for electrolyzers, renewable energy infrastructure, and associated equipment.	Shen et al. (2024), Chigbu & Nweke-Eze (2023), Olabi et al. (2023), Vinardell et al. (2023), Cremonese et al. (2023), Ahrens et al. (2022) and Barbera et al. (2022)
Noise Emissions	ENVIRO6	Measures the noise pollution generated by electrolyzers, renewable energy sources, and transportation of equipment.	Blohm & Dettner (2023) and Olabi et al. (2023)
Human Toxicity Potential	ENVIRO7	Measures the potential risks of green hydrogen production on human health, including exposure to toxic materials used in equipment or potential leaks.	Olabi et al. (2023), Maimaiti et al. (2023), Blohm & Dettner (2023) and Barbera et al. (2022)
Waste Generated	ENVIRO8	Measures volumes of waste generated during green hydrogen production, such as hazardous materials, used equipment, and water treatment residuals.	Olabi et al. (2023)
Impact on Biodiversity	ENVIRO9	Measures potential negative impacts on plant and animal life caused by green hydrogen production facilities and their land use.	Olabi et al. (2023), Cremonese et al. (2023), Weidner et al. (2023) and Ahrens et al. (2022)
Fossil Fuel Use	ENVIRO10	Measures the amount of fossil fuels used in the entire green hydrogen production chain, including construction, operation, and maintenance.	Vinardell et al. (2023), Ahrens et al. (2022), Maimaiti et al. (2023) and Barbera et al. (2022)
Soil Pollution	ENVIRO11	Evaluates the potential for soil contamination from spills, leaks, or improper waste disposal during green hydrogen production.	Maimaiti et al. (2023)
ECONOMIC			
Cost of Green Hydrogen	ECONO1	Measures the cost of green hydrogen production based	Dagnachew et al. (2024), Kweinor Tetteh et al. (2024), Ellaythy et al.

		on the Levelised Cost of Energy (LCOE).	(2024), Kalt et al. (2023), Apata (2024), Kanakana-Katumba et al. (2023), Park et al. (2024), Hong et al. (2023), Virens (2024), Olabi et al. (2023), Agyekum (2024b), Das et al. (2024), Vinardell et al. (2023), Guarieiro et al. (2022), Weidner et al. (2023), Wei et al. (2024), Lozanovski et al. (2018), Neri et al. (2024) and Barbera et al. (2022)
Economic Growth	ECONO2	Measures the impact on economic activity as measured by the GDP per capita.	Hamukoshi et al. (2022b), Apata (2024), Olabi et al. (2023), Gupta et al. (2023), Mneimneh et al. (2023) and Akhtar et al. (2023)
Import Dependency	ECONO3	Measures the reliance on imported resources for green hydrogen production and the potential for domestic manufacturing.	Hong et al. (2023)
Generation of Tax Income	ECONO4	Measures the potential tax revenue generated from green hydrogen production facilities and associated industries.	Chigbu & Nweke-Eze (2023) and Olabi et al. (2023)
Generation of Foreign Currency	ECONO5	Measures the potential foreign currency revenue generated from green hydrogen exports.	Chigbu & Nweke-Eze (2023)
Local Procurement	ECONO6	Measures the extent to which green hydrogen production utilises local resources, labour, and services to promote local economic development.	Olabi et al. (2023)
Energy Supply Security	ECONO7	Measures the potential of green hydrogen to diversify energy sources and reduce reliance on imported fossil fuels.	Olabi et al. (2023) and (Hong et al., 2023)
Economic Development	ECONO8	Evaluates the broader economic benefits of green hydrogen production, such as stimulating innovation and creating new industries.	Mneimneh et al. (2023) and Akhtar et al. (2023)
Energy Return on Energy Invested (EROEI) & Energy Efficiency	ECONO9	Measures the efficiency of green hydrogen production. EROEI compares the energy output (green hydrogen) to the energy input (renewable electricity) used in the process.	Hong et al. (2023), Blohm & Dettner (2023), Olabi et al. (2023), Ahrens et al. (2022) and Barbera et al. (2022),
SOCIAL			

Employment	SOCIO1	Measures the number of potential jobs created in green hydrogen production, operation, maintenance, and associated industries.	Hamukoshi et al. (2022b), Kalt et al. (2023), Apata (2024), Kanakana-Katumba et al. (2023), Chigbu & Nweke-Eze (2023), Blohm & Dettner (2023), Olabi et al. (2023), Gupta et al. (2023), Mneimneh et al. (2023), Neri et al. (2024), Fazli-Khalaf et al. (2020) and Akhtar et al. (2023)
Skills Development & Skills Transfer	SOCIO2	Evaluates the new skills and training programs gained by the local community.	Hamukoshi et al. (2022b), Apata, 2024), Chigbu & Nweke-Eze (2023), Blohm & Dettner (2023), Olabi et al. (2023), Agyekum (2024b) and Mneimneh et al. (2023)
Social Acceptance	SOCIO3	Evaluates public opinion and acceptance of green hydrogen production facilities in local communities.	Gordon, Balta-Ozkan, Haq, et al. (2024), Häußermann et al. (2023), Lozanovski et al. (2018), Cremonese et al., (2023), Gordon, Balta-Ozkan, & Nabavi (2024) and Vallejos-Romero et al., (2023)
Energy Poverty	SOCIO4	Evaluates the potential of green hydrogen to contribute to alleviating energy poverty by providing access to clean energy for disadvantaged communities.	Blohm & Dettner (2023)
Employee Diversity	SOCIO5	Measures the diversity and inclusivity of the workforce involved.	Olabi et al. (2023) and Akhtar et al. (2023)
Wage Fairness	SOCIO6	Evaluates whether wages paid to workers in the green hydrogen industry are equitable and comparable to similar roles in other industries.	Olabi et al. (2023) and Akhtar et al. (2023)
Stakeholder Involvement	SOCIO7	Measures the extent to which various stakeholders (e.g., local communities, environmental groups, government agencies) are involved in the decision-making process related to green hydrogen projects.	(Olabi et al., 2023) and (Mneimneh et al., 2023)
Food Security	SOCIO8	Evaluates the potential impact of green hydrogen production on food security, particularly in regions where agricultural activities may be affected by land use changes or resource competition.	(Borge-Diez et al., 2024)

Compiled by author

4.1.1 Environmental Indicators

The study identified a total of eleven environmental indicators as shown in Table 4.1 above and discussed further in this section. Indicators related to the environmental dimension of sustainability assessments have been widely documented in the literature. Given the environmental benefits of green hydrogen in comparison to fossil fuels and the need to decarbonise the world economy, it is evident that researchers have predominantly focused on this dimension, particularly on the indicators relating to carbon and greenhouse gas emissions. Other prominent environmental sustainability indicators in the literature include water use (a function of the significant water requirements of the electrolysis process), marine life destruction, water pollution (a function of the infrastructure development process), and land use (a function of the land required for renewable energy power generation plants and electrolysis plants).

Land usage is a key consideration in the development of a green hydrogen economy as it requires large amounts of land. Thus, the demand for land may result in increased competition, which may be further complicated by sociocultural customary user rights (Dagnachew et al., 2024). This is echoed by Kalt et al. (2023) and Chigbu & Nweke-Eze (2023), who found that large-scale land acquisitions for solar and wind farms may create land conflicts and potentially dispossess communities of their land. Additionally, this land may be arable and utilised by local communities for agricultural purposes and, therefore, should be considered in the assessment of sustainability (Evans et al, 2009). However, in the context of the Northern Cape, concerns relating to arable land may be less applicable, as the province has 84% of its land undeveloped and 57% of its land suitable for solar and wind farm construction (NCEDA, 2023). What could be critical for this province, however, is the issue surrounding the ownership of land earmarked for green hydrogen. Most of the land in the Northern Cape is privately held (Department of Rural Development & Land Reform, 2017) and therefore cannot be utilised for the furtherance of the green hydrogen economy without compensating landowners. The 2017 land audit found that of this privately held land, 47% was owned by individuals with the balance mostly owned by companies and trusts (Department of Rural Development & Land Reform, 2017). Furthermore, the land issue in the Northern Cape is reflective of the country's unjust past with 72% of land owned by individuals being held by white owners and 72% held by males (Department of Rural Development & Land Reform, 2017)s. These racial and gender injustices add complexity to land usage. Historically, land leases have been entered between landowners and renewable energy project developers, and a similar approach may be adopted in the development of the green hydrogen economy. To the extent that the government would seek to expropriate land to develop green hydrogen-related infrastructure, this will likely be significantly contested. Displaced communities would need to be provided alternative options congruent with their current lifestyles to mitigate the impacts of their replacement (NCEDA, 2023). Therefore, consideration of land usage and property rights is key to assessing the sustainability of the green hydrogen economy.

Water use is important because it is not sustainable to have high water consumption when water shortages are problematic (Evans et al. 2009). If water usage is not adequately managed, there could be increased local competition for water which is essential for agriculture, industry, and households (Dagnachew et al., 2024). This could potentially be problematic in the Northern Cape if the green hydrogen economy is reliant on piped water. The province has only 80.13% of its households with access to piped water supply as a result of inadequate bulk water supply, dilapidated wastewater treatment facilities, and dilapidated infrastructure, resulting in high water loss (Lekalake, 2023). However, the provincial government aims to eliminate constraints on freshwater access by ensuring that desalination takes place on the South Atlantic Ocean coast, thus minimising competition for water and ensuring the sustainability of the green hydrogen economy (NCEDA, 2023). Therefore, a green hydrogen economy needs to include the development of desalination facilities to ensure sustainability.

Carbon and greenhouse gas emissions must be considered as they are key parameters in defining sustainability. As discussed in Chapter 2, green hydrogen is an energy carrier with minimal emission when utilised. Furthermore, various life cycle analyses have shown that the use of green hydrogen has a lower life-cycle emission footprint compared to alternative fuels (Shen et al., 2024). These limited emissions have seen green hydrogen being touted as an energy carrier that will be key in decarbonising the world, particularly in hard-to-abate industries. This is supported by various studies, including that of Jayachandran et al. (2024) who affirmed that green hydrogen production could abate sixty gigatons of greenhouse gas emissions. However, it is important that the hydrogen is produced from renewable energy sources, as production from a predominantly coal-powered grid would yield significantly higher emissions (Hong et al., 2023). Therefore, a green hydrogen economy requires investment in renewable energy for it to be sustainable, which is possible for the Northern Cape given its favourable availability of solar and wind resources.

Marine life destruction and water pollution are key considerations in the development of a green hydrogen economy. Life cycle environmental impact assessments, such as those undertaken by Maimaiti et al. (2023), assess the impact of green hydrogen production on water pollution. Activities such as extracting water for electrolysis or constructing infrastructure can damage marine ecosystems and pollute water bodies and therefore should be considered in the assessment of sustainability. Kalt et al. (2023) showed that marine life could be disrupted as a result of the development of port infrastructure and desalination facilities. This is particularly an issue on the Boegoebaai coastline in the Northern Cape, where a deep-water port and desalination facility may be located for the purposes of a green hydrogen economy (NCEDA, 2023). Therefore, marine life should be protected, and water pollution should be minimised for green hydrogen to be sustainable.

Use of natural resources, minerals and metals requires consideration in the assessment of a green hydrogen economy. Manufacturing electrolysers, solar panels, wind turbines, batteries, and associated equipment requires critical minerals such as platinum group metals, silicon, silver, neodymium, dysprosium, copper, lithium, cobalt, manganese, and graphite. Excessive use can deplete resources and, therefore, threaten sustainability, especially in instances where these resources are scarce. Shen et al., (2024) found that green hydrogen deployment may shift the environmental pressure from fossil fuel use to mineral resources use. However, South Africa is endowed with these critical minerals particularly platinum with about 70% of the world supply of platinum metal groups in 2023 (Metals Focus, 2024; USGS, 2023) (a key component of electrolysers) being found in the country (Chigbu & Nweke-Eze, 2023). Additionally, South Africa's mineral exploration strategy has identified an opportunity to explore known prospects of copper, nickel, chrome, cobalt and lithium in the Northern Cape (DMRE, 2022). This significant availability of natural resources may help mitigate the risk of unsustainable resource use.

Noise emissions may arise in both the construction and operational phases of green hydrogen facilities which may result in disturbances. This noise may arise from land clearing activities, drilling and blasting, concrete mixers and cranes and other construction-related noises as well as electrolyser unit noise, blowers and compressors, motors and pumps and other operations related noises (Nadar & Strong, 2022). Noise emissions should therefore be considered and limited, particularly if production occurs in close proximity to residential areas and should not exceed 40 decibels (Blohm & Dettner, 2023). High noise emissions above the threshold may detract from the sustainability of green hydrogen, and therefore noise should be lowered to a minimum (Olabi et al., 2023).

Human toxicity potential is essential to consider, as it measures the potential risks of green hydrogen production on human health, including exposure to toxic materials used in equipment or potential leaks over the life cycle of the technology. South Africa's constitution gives people the right to an environment that is not harmful to their health, thus further emphasising the need to assess the human toxicity potential of this technology. It is therefore important to assess the potential impact of green hydrogen projects on humans' health as part of the impact assessment prior to construction of green hydrogen facilities (Blohm & Dettner, 2023). This can be achieved by utilising a life cycle assessment (Olabi et al., 2023), which has been performed in numerous green hydrogen studies including Barbera et al. (2022).

Waste generated, if not appropriately separated, stored, managed, or recycled, may result in the contamination of soil, groundwater, surface water and may attract pest species (WSP Group, 2022). Different types of waste, including general waste (such as building rubble, biomass and metal waste) and hazardous waste (such as used lubricants, dewatered brine and hydraulic oils), must be managed for sustainable green hydrogen production. This could be achieved by minimising the waste generated as well as adding value to the waste through recycling (Olabi et al., 2023).

The impact on biodiversity is important to consider, as the development of green hydrogen-related infrastructure can result in the disruption or change in biodiversity in a region (Evans et al., 2009). The Northern Cape is a biodiverse region with numerous biomes, including Savanna, Nama-Karoo, Succulent Karoo, and Fynbos, and it has a variety of wildlife and vegetation. This biodiversity can be disrupted due to a number of factors including deforestation, enhanced erosion, and ecological imbalances, thus adversely affecting natural habitats (Chigbu & Nweke-Eze, 2023). The biodiversity loss index as utilised by Ahrens et al. (2022) helps to analyse the extent to which biodiversity is disrupted as a result of green hydrogen economy development.

The use of fossil fuels throughout the green hydrogen production chain needs to be considered, as a high usage of fossil fuels would be unsustainable. Indeed, a significant reduction in the use of fossil fuels is required to meet the international greenhouse gas emission targets (Barbera et al., 2022). This is evidenced by fossil fuel use and depletion being a key indicator in life cycle assessments of green hydrogen such as by Vinardell et al. (2023) and Maimaiti et al. (2023). The use of green hydrogen reduces the environmental impacts associated with fossil resources use such as crude oil (Vinardell et al., 2023). Therefore, a green hydrogen economy will result in less fossil fuel use and, thus, contribute to sustainability.

Soil pollution has also been included in life-cycle assessments including the green hydrogen assessment conducted by Maimaiti et al. (2023). Soil pollution could result in soil degradation which may lead to loss of agricultural potential of the land in the area (Nadar & Strong, 2022). Therefore, it is important to consider their potential impact on biodiversity and food security.

4.1.2 Economic Indicators

The study identified a total of nine economic indicators, as set out in Table 4.1 and discussed further in this section. Historically, economic indicators have been the focal point of decision-making for both investors and policymakers. However, the social and environmental dimensions have become increasingly important in ensuring sustainable development. However, economic indicators remain relevant for assessing the sustainability of energy technology. This is evidenced by the significant literature on these indicators, particularly the cost of green hydrogen and associated economic growth.

The **cost of green hydrogen** must be considered as unfavourable economics of green hydrogen are not sustainable (Evans et al., 2009). As discussed in Chapter 2, the current high cost of green hydrogen is one of the reasons that has impacted its commercialisation and remains a key challenge if a green hydrogen economy is to be sustainable. Multiple studies have investigated the levelised cost of hydrogen including (Agyekum, 2024b; Das, 2023; Guarieiro et al., 2022; Hong et al., 2023). Green hydrogen is expected to remain expensive in the short term until a significant level of deployment is achieved. If the deployment is in line with the International Energy Agency's net zero emissions by 2050 scenario, then the cost of green hydrogen is expected to fall to USD2-9/kg by 2030 which is half of 2024's cost (IEA, 2024a). The Northern Cape aims to position itself as a cost-competitive producer of green hydrogen, a function of high solar and wind load factors, lower shipping costs, and government incentives (NCEDA, 2023). This may result in the province producing green hydrogen at the lower end of the price range, thus enabling its sustainability.

The impact of the green hydrogen economy on **economic growth**, as measured by GDP per capita, is a key consideration, particularly in South Africa, which has been on a declining trend. Green hydrogen is expected to position South Africa as a major global energy market player and thus fueling local economic growth (Apata, 2024). However, policy formulation will be key in fostering green hydrogen driven economic growth, as there are trade-offs with other industries, such as fossil fuels, whose contribution to economic growth will be reduced (Hamukoshi et al., 2022b). The Northern Cape's intends to achieve this economic growth by driving demand for goods and services, providing cost-effective feedstock for downstream beneficiation industries, promoting the availability of by-products at a low cost, stimulating investment, and generating demand for supporting industries (NCEDA, 2023). This is estimated to increase the annual GDP by USD8 billion and positively impact the economy of the province, thus contributing to the economic sustainability of the green hydrogen economy.

Import dependency is key in assessing energy security and, thus, the sustainability of a green hydrogen economy. An economy that exacerbates a country's position as a net importer of fuel would not be sustainable and would expose the country to commodity and foreign exchange risks. South Africa is a net importer of crude oil, refined oil and natural gas thus increasing its dependency on countries such as Saudi Arabia, Nigeria, United Arab Emirates and United States of America (Mokwena, 2023). Therefore, reducing energy import dependency is critical for the country. Hong et al. (2023) identified import dependency as a key indicator in evaluating the sustainability of a green hydrogen economy in South Korea and similarly this applies to South Africa and the Northern Cape.

Tax income generated by the government is an important consideration, as it provides a source of revenue for governments to fund important expenditures such as education, health, and infrastructure which are critical in achieving the UNSDGs such as no poverty (Olabi et al., 2023). This is indeed important for South Africa, which has a narrowing tax base and sustained fiscal deficits. There is evidence that development of renewable energy-based technologies can positively impact the generation of tax income (Chigbu & Nweke-Eze, 2023). The Northern Cape estimates that the annual tax revenues resulting from the establishment of a green hydrogen economy will be USD 2 billion (NCEDA, 2023), which may positively impact the economic sustainability of the province.

The potential export of green hydrogen as envisaged by the province's masterplan will **generate foreign currency** for the region. These can be used to bolster much needed foreign currency reserves of the country and ensure availability of foreign currency denominated income to repay external debt. Furthermore, the generation of foreign exchange has the potential to contribute to the socio-economic development of the Northern Cape (Chigbu & Nweke-Eze, 2023).

Local procurement is an important consideration when assessing sustainability. Olabi et al. (2023) found that local procurement of products and services is an indicator that positively contributes to the attainment of UNSDG 8 "Decent work and economic growth". The Northern Cape aims to achieve this by localising the green hydrogen supply chain and enabling local SME growth (NCEDA, 2023). This ensures that the region does not source all high-value products from the international markets. Therefore, local procurements requires careful consideration.

Energy supply security is critical in every country as it can be described as the lifeblood of the economy and is forms a foundational part of the energy trilemma index (Hong et al. 2023). By producing its own energy, the Northern Cape will ensure energy supply security for itself and for the country. Furthermore, reducing exposure to oil price instability and interruptions can also enhance energy security (Olabi et al., 2023). The Northern Cape aims to improve energy supply by utilising the renewable energy from the green hydrogen economy to balance the grid and supply power during peak times (NCEDA, 2023). However, there is a risk that the transition to green hydrogen may result in the complete abandonment of fossil fuels which may threaten energy security. Therefore, an assessment is required to determine the sustainability of a green hydrogen economy.

A green hydrogen economy will be sustainable if it results in broader economic benefits, such as creating or supporting new industries (i.e. **economic development**). It can contribute by developing and improving infrastructure to support economic development and develop other sectors such as transportation (Mneimneh et al., 2023). The Northern Cape aims to establish a large-scale export-focused green hydrogen special economic zone (NCEDA, 2023). This focus on export markets may have unintended consequences for economic development, and thus, the sustainability of the green hydrogen economy. Kalt et al. (2023) found that the green extractivist approach to green hydrogen may reproduce neocolonial patterns resulting in the re-primarisation of South Africa's economy towards lower value-added products. Therefore, it is important for a country to build its industrial capacity across the value chain. This would explain why the Northern Cape masterplan envisages the development of industrial capacity in electrolysers, batteries, renewable energy components, and fertiliser production, along with the development of markets for green hydrogen by-products such as desalinated water, brine, oxygen, heat, and industrial gases (NCEDA, 2023). Therefore, the realisation of this strategy may contribute to the sustainability of a green hydrogen economy.

Energy efficiency must be considered for meaningful comparisons with other energy sources and carriers, as more efficient processes tend to have fewer process requirements and costs, thus impacting sustainability (Evans et al., 2009). Due to its role as an energy carrier and not as an energy source, green hydrogen has a low return on energy investment compared to other fuels owing to the significant energy required to power the electrolysis process (Hong et al., 2023). Therefore, it is reasonable that this is one of the key indicators used in decision making and the assessment of the sustainability of green hydrogen (Barbera et al., 2022).

4.1.3 Social Indicators

The study identified a total of eight social indicators, as set out in Table 4.1 and discussed further in this section. The social dimensions of green hydrogen are not widely studied and therefore risks perpetuating inequalities in the current energy system (Virens, 2024). Social impacts should be considered, as they allow for better acceptance and understanding of technologies that may be subject to public objections (Evans et al., 2009). Gordon, Balta-Ozkan, & Nabavi (2024)'s conceptual framework for the social acceptance of hydrogen states that it is a function of cognitive processes, social capital, environmental attitude, risk perceptions, cost-benefit appraisal and affective responses. The most common social indicators found in the literature include employment created, skills development and transfer, and social acceptance.

The official and expanded unemployment rates in the Northern Cape were 26.9% and 42.9% respectively in the fourth quarter of 2023 (Stats SA, 2024), making **employment** a key indicator to consider when assessing sustainability. There is uncertainty regarding the sustainability of jobs that will be created by the green hydrogen economy. Initial estimates indicate that a full capacity of 40 GW in the province may be able to create 600,000 jobs; however, the masterplan indicates that an in-depth study is indeed required to confirm this assessment (NCEDA, 2023). The nature of the jobs created is worth understanding. Kalt et al. (2023) highlights that jobs for South Africans may be limited to short term construction work which is not sustainable. Furthermore, it is not sufficient for jobs to be created; they must have competitive salaries and wages. Such a scenario will occur if employment opportunities extend beyond construction, encompassing the entire supply chain, including sectors such as water management, electrolyser manufacturing, transport, storage facilities, and fuel cell production.(Kanakana-Katumba et al., 2023). This is supported by Gupta et al. (2023), who found that the manufacturing of machinery and equipment has the highest contribution to economic growth and full-time employment and therefore should be a policy priority. Therefore, employment needs to be permanent, fairly remunerated, and across value chains, for it to be considered sustainable.

Skills and knowledge transfers require consideration in a green hydrogen economy. This is particularly important as the green hydrogen economy may result in job losses in fossil fuel related industries thus necessitating the reskilling of this workforce to be able to work in the green hydrogen economy (Hamukoshi et al., 2022b). Furthermore, capacity building and the upskilling of the province's unskilled population may enable them to be economically active and participate in the development of a green hydrogen economy. The inadequacy of skills and education may be a barrier in the development and use of green hydrogen (Agyekum, 2024b). Although developed countries may wish to protect their intellectual property, there is a need to balance this with the sharing of intellectual property for the energy transition in Africa to not be burdened by this (Dagnachew et al., 2024). Indeed, for distributive justice to occur, the local community needs to be upskilled by providing bursaries and investment in educational infrastructure (NCEDA, 2023). Blohm & Dettner (2023) suggests that if investors do not implement adequate training, a share of their profit should be deployed to the establishment of training centres in the communities they operate. Therefore, these measures could contribute to the sustainability of green hydrogen production.

Social acceptance of green hydrogen has been widely researched in the field of social science and is considered a key indicator of sustainability including in Cremonese et al. (2023) and Gordon, Balta-Ozkan, & Nabavi (2024). Social acceptance plays a key role in the adoption of green hydrogen (Vallejos-Romero et al., 2023). Thus, building the social acceptance of green hydrogen is important. Häußermann et al. (2023) found that; firstly, the adoption of the technology hinges on confidence in scientific institutions, governmental bodies, media outlets, and organisations that ensure equitable distribution.; secondly sound participatory processes enhance acceptance, and lastly recurring participatory experiences can foster the trust. This is supported by Cremonese et al. (2023), who argued that social acceptance in renewable energy planning and development is limited in South Africa if the affected populations do not participate in these processes. Therefore, for green hydrogen to be socially acceptable and sustainable, its development must involve the participation of local communities, while providing them with sufficient information to foster trust.

The availability of energy is not just an economic consideration, but also a social one. For a green hydrogen economy to be sustainable, it needs to contribute to a reduction in **energy poverty**. Blohm & Dettner (2023) views energy poverty as a key consideration of their sustainability criteria and suggest that along with the investment in green hydrogen, construction of additional power generation capacity is required in areas with electrification rates that are less than 100%. This is the case in South Africa whereas at 2022, 93.6% of the population had access to electricity (Stats SA, 2023). However, access to electricity does not necessarily translate to availability, as observed during the period when the country experienced loadshedding. Therefore, green hydrogen should contribute to improving energy supply and security, as well as the electrification of the Northern Cape.

As previously discussed, job creation is a key factor in the assessment of sustainability. Additionally, **employee diversity** should be considered to ensure that the workforce in the green hydrogen economy is inclusive and representative of Northern Cape's population (Olabi et al., 2023). The social lifecycle assessment by Akhtar et al. (2023) included the consideration of women in the sectoral labour force of green hydrogen to ensure gender equality in line with the UNSDG8 and found South Africa to have a high social risk in this regard. Therefore, jobs created in the green hydrogen economy need to include women, youth, and previously disadvantaged groups to ensure sustainability.

In addition to creating jobs for diverse employees, the **wage fairness** of such jobs must be considered. This includes assessment of whether the remuneration paid constitutes a fair salary and if there is a material gender wage gap (Akhtar et al., 2023). Similarly, to employee diversity Akhtar et al. (2023) found South Africa to have a high risk of these social risks materialising, thus adversely affecting the sustainability of green hydrogen. Therefore, specific consideration of this indicator is necessary.

Stakeholder involvement requires the contribution of various stakeholders in the decision-making process related to green hydrogen projects for it to be sustainable. A high level of stakeholder involvement contributes to UNSDG 16 (Peace, Justice and Strong Institutions) (Olabi et al., 2023). This also ensures that the concerns of various stakeholders are considered thus making the process just.

Food security can be considered as a sustainability indicator because of the green hydrogen-water-food nexus as described by Borge-Diez et al. (2024). This is because water previously designated for agricultural purposes may be redirected to green hydrogen production, thus affecting agricultural yields and food security. Furthermore, food security may be affected if fertile lands are repurposed for renewable energy and green hydrogen production (Chigbu & Nweke-Eze, 2023). However, green hydrogen can be used in fertilisers, thus enhancing food security. Therefore, these factors should be considered.

4.2 Green Hydrogen Sustainability Indicators from Stakeholder Survey

As highlighted in Chapter 3, few studies have been undertaken in the South African context, specifically in the Northern Cape; therefore, certain indicators may be less relevant to the assessment of sustainability in the region. This raised a number of questions: Are these indicators an accurate reflection of green hydrogen-related issues in the Northern Cape context? Are additional indicators not found in the literature relevant for assessing the sustainability of a green hydrogen economy in the region? Do the various stakeholders involved in the development of the green hydrogen economy in the Northern Cape hold similar views on the importance of these indicators? Therefore, these questions necessitated surveys.

Table 4.2: Survey Results

Indicator	Symbol	1	2	3	4	5	N	WMS	Rank
Water Use	ENVIRO2	0	0	1	4	11	16	4.63	1
Impact on Biodiversity	ENVIRO9	0	0	0	8	8	16	4.50	2
Employment	SOCIO1	0	0	2	4	10	16	4.50	2
Energy Return on Energy Invested (EROEI) & Energy Efficiency	ECONO9	0	0	1	7	8	16	4.44	4
Skills Development & Skills Transfer	SOCIO2	0	0	2	5	9	16	4.44	4
Human Toxicity Potential	ENVIRO7	0	1	1	5	9	16	4.38	6
Marine Life Destruction & Water Pollution	ENVIRO4	0	0	3	5	8	16	4.31	7
Soil Pollution	ENVIRO11	0	0	2	8	6	16	4.25	8
Air Pollution, Carbon Emissions & Greenhouse Emissions	ENVIRO3	0	0	4	5	7	16	4.19	9
Social Acceptance	SOCIO3	0	0	4	5	7	16	4.19	9
Land Use	ENVIRO1	0	1	2	7	6	16	4.13	11
Local Procurement	ECONO6	0	0	4	6	6	16	4.13	11
Energy Supply Security	ECONO7	0	0	2	10	4	16	4.13	11
Economic Development	ECONO8	0	1	2	7	6	16	4.13	11
Wage Fairness	SOCIO6	0	0	3	8	5	16	4.13	11
Waste Generated	ENVIRO8	0	1	2	8	5	16	4.06	16
Resources, Minerals and Metals Use	ENVIRO5	1	0	2	8	5	16	4.00	17
Cost of Green Hydrogen	ECONO1	1	0	1	10	4	16	4.00	17
Economic Growth	ECONO2	0	1	3	7	5	16	4.00	17
Stakeholder Involvement	SOCIO7	0	2	3	6	5	16	3.88	20

Fossil Fuel Use	ENVIRO10	0	2	4	7	3	16	3.69	21
Generation of Foreign Currency	ECONO5	0	2	5	5	4	16	3.69	21
Generation of Tax Income	ECONO4	0	3	2	9	2	16	3.63	23
Energy Poverty	SOCIO4	1	3	2	5	5	16	3.63	23
Employee Diversity	SOCIO5	0	4	3	4	5	16	3.63	23
Food Security	SOCIO8	0	3	3	8	2	16	3.56	26
Noise Emissions	ENVIRO6	1	1	5	7	2	16	3.50	27
Import Dependency	ECONO3	1	2	3	8	2	16	3.50	27

1.Not important at all. 2. Slightly important. 3. Moderately important. 4. Very important. 5. Extremely important.

Source: Author

4.2.1 Overall Findings

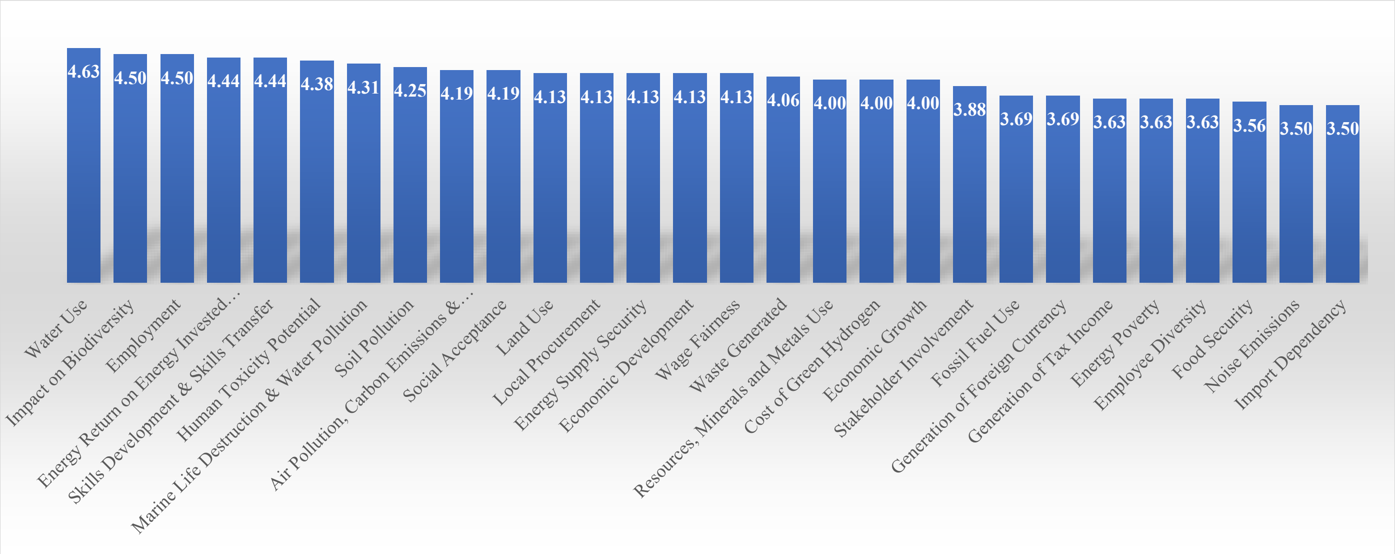


Figure 4.1: Visual representation of overall weighted mean score per indicator

Source: Author

The survey results supported the indicators found in the literature, with all identified sustainability indicators having a WMS of 3.5 or above indicating that at a minimum, all indicators are more than moderately important to stakeholders. This section discussed the overall WMS and rankings of sustainability indicators from the survey.

Environmental indicators were ranked the highest of the three categories, with a mean average score of 4.15, highlighting the importance of environmental considerations for stakeholders and substantiating why these are predominantly covered in the literature. The highest-ranking environmental indicators by the surveyed stakeholders included **Water Use** (1st), **Impact on Biodiversity** (Joint 2nd) and **Human Toxicity Potential** (6th). The top-ranking indicator may prove to be an obstacle for green hydrogen's sustainability in the Northern Cape as green hydrogen production process utilises more water than its alternatives with 40 - 90 kilograms of desalinated water potentially being required to produce a kilogram of hydrogen (IEA, 2023b).. However, owing to its low carbon emissions, green hydrogen is likely to be less harmful to humans which may support its adaptation. Stakeholders were also asked if there were any environmental indicators that were specifically not relevant to the Northern Cape. One participant noted that noise emissions are less important as projects will most likely be in remote areas but would, however, be extremely important if projects are situated close to the SKAO (Square Kilometre Array Observatory) satellite sites. This supports the relatively low overall ranking of this indicator (27th). Another participant noted that marine life is unlikely to be impacted as hydrogen plants would be onshore, and in the context of the Northern Cape, this will be mostly desert. However, this did not consider desalination projects, which will form part of the broader green hydrogen economy. Therefore, this appeared to be an isolated view, as this indicator is ranked 7th. Other participants did not identify any indicators that were either irrelevant to the Northern Cape or that had not been adequately covered in the literature review.

Economic indicators were ranked last among the three categories, with a mean average score of 3. 96. The highest ranked economic indicators were **EROEI** (Joint 4th), Energy **Supply Security, Economic Development** and **Local Procurement** (Joint 11th). The top-ranking economic indicator may prove to be an obstacle for green hydrogen's sustainability in the Northern Cape as green hydrogen has a lower EROEI than more traditional sources of energy such as renewables, uranium, coal and gas (Hong et al., 2023). The other top ranking economic indicators can be explained by the energy deficit experienced by the country along with the stagnant economic development evidenced by an average GDP growth rate of 0.78% between 2014 and 2023 (World Bank Group, 2024), which makes it important for the green hydrogen economy to help address these issues in the country and province. Surprisingly, the **Cost of Green Hydrogen** which is covered extensively in the literature and is seen as one of the drawbacks of green hydrogen projects reaching FID, is not in the top 10 rankings. This phenomenon could potentially be explained by Northern Cape's cost competitiveness compared to other regions, coupled with its export focus. No participants identified indicators that were either irrelevant to the Northern Cape or that have not been adequately covered in the literature review.

Social indicators were ranked second among the three categories with a mean average score of 3.99, indicating their overall higher importance in comparison to economic indicators and lower importance relative to environmental indicators. Despite the overall lower ranking of this category, specific indicators rank highly in this category, namely **Employment** (Joint 2nd) and **Skills Development and Transfer** (Joint 4th). These aspects are critical in the context of Northern Cape, given the high unemployment rate (particularly of the youth) as well as the unavailability of skilled labour. Therefore, a green hydrogen economy should address these social ills in order for it to be seen as sustainable. One of the lowest ranked indicators is social in nature, being **Food Security** (26th). This is supported by one of the participants' responses that food security is not relevant to the Northern Cape, as it is unlikely to produce food from hydrogen-based fertilisers, as it is significantly more expensive than standard processes. Other participants did not identify any indicators that were either irrelevant to the Northern Cape or that have not been adequately covered in the literature review.

4.2.2 Public vs Private Sector Participants Views

Although the survey indicated support for the indicators found in the literature, there were notable differences in the relative importance of indicators according to the public sector compared with the private sector, as shown in Figure 4.1. On average, private sector participants found the sustainability indicators to be very important (3.82), whereas the public sector was more emphatic in confirming the sustainability indicators to be extremely important (4.33).

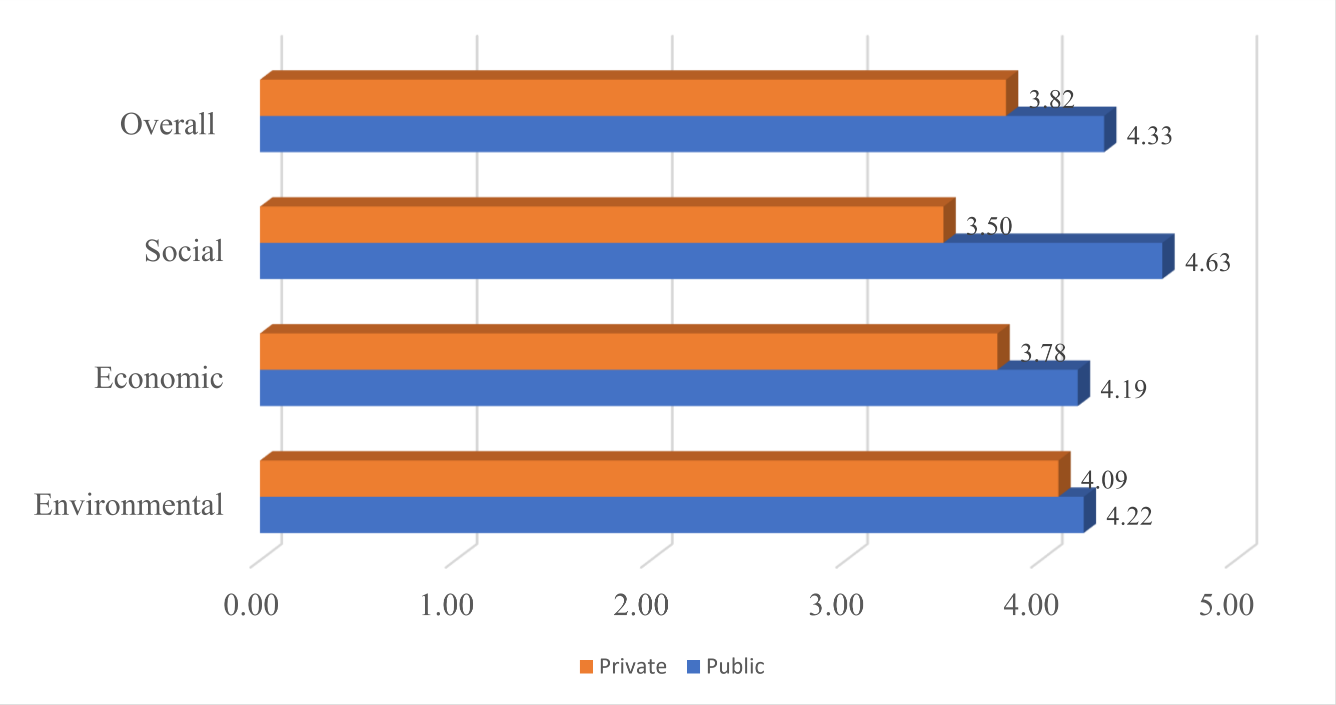


Figure 4.2: Weighted Mean Score Per Dimension: Public vs Private Sector

Source: Author

The private sector ranking trends showed that environmental indicators had the highest ranking, followed by economic and social indicators. Public sector participants, however, appeared to have different priorities to private sector participants. This group of participants found social indicators to be the most important, followed by environmental and economic. This indicated that these participants place great importance on social indicators which will ensure that the transition to a low-carbon future is just, particularly in the Northern Cape. The top-ranked indicators by public sector participants were **Employment** and **Skills Development and Transfer** which were unanimously found to be extremely important, highlighting the importance of human capital. Indeed, these two indicators are connected as skills development enhances the employability of the Northern Cape population, thus increasing the employment rates in the region, particularly for good quality jobs. Other highly ranked indicators in this group included **Economic Development**, **Energy Poverty,** and **Local Procurement (**WMS of 4.71). This indicates the importance of growing and developing the economy across the value chain, while maintaining a stable energy supply.

4.3 Conclusion

The findings in this chapter uncovered sustainability indicators of green hydrogen in the literature and confirmed their applicability to the Northern Cape by surveying stakeholders in the green hydrogen economy in the region. The results of this analysis provide a solid foundation for the recommendations to advance energy technology sustainability assessment of hydrogen economy, presented in Chapter 5.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This study aimed to describe the context of the green hydrogen economy and technology sustainability assessment and identify the key sustainability indicators of green hydrogen in the Northern Cape. This chapter reflects on the research questions addressed and offers recommendations to facilitate investment and policy decisions.

5.2 Connecting Theory to Practice

This study contributed to the field of energy technology assessment for sustainability, specifically for green hydrogen in South Africa, focusing on the Northern Cape Province. Furthermore, energy technology assessment for sustainability contributes to the field of development finance by enabling the alignment of capital with technologies such as green hydrogen. This can be done as energy technology assessment provides a framework for assessing the sustainability of various energy technologies thus facilitating the identification and prioritisation of investments based on transparent and objective sustainability indicators like the ones identified in this study. In essence, this study contributed to providing relevant sustainability indicators for hydrogen technology assessment that may enable evidence-based decision making in development finance resulting in finance being directed towards projects that consider such indicators to contribute to a sustainable future in line with the United Nations Sustainable Development Goals.

5.2.1 The Context of Green Hydrogen Economy and Technology Sustainability Assessment

The first research objective of this study was to describe the context of the green hydrogen economy and technology sustainability assessment which was conducted as part of the literature review in Chapter 2. The context green hydrogen economy in South Africa was found to be driven by the energy challenges facing the country coupled with the need to reduce carbon emissions and justly transition to a low carbon future in line with the framework developed by the Presidential Climate Commission. Despite green hydrogen's challenges including high costs, lack of infrastructure and sustainability uncertainties - it was seen as an integral part of this transition due to its application in hard-to-abate industries both locally and in export markets. South African government initiatives have been put in place to develop a green hydrogen economy culminating in the publication of South Africa's Hydrogen Society Roadmap and the Green Hydrogen Commercialisation Strategy for South Africa. Additionally, the Northern Cape's Green

Hydrogen Masterplan aims to create a conducive environment for investment in the green hydrogen economy and capitalise on the province’s abundant land, solar and wind resources.

Despite the promising green hydrogen context in South Africa, technology sustainability assessment, especially for green hydrogen, is found to be still an emerging field. Initial efforts were being made to assess the sustainability of green hydrogen technologies such as the pilot study launched by the United Nations Trade and Development in collaboration with the Department of Science and Innovation. However more holistic approaches to technology sustainability assessment that recognise the environmental, social and economic impacts of green hydrogen were found to be lacking. This was an important research gap that required filling as a sound technology sustainability assessment framework can facilitate policy and investment decisions to make a green hydrogen economy a reality. To contribute to this, this study identified key sustainability indicators for the green hydrogen economy in the Northern Cape that can be utilised in supporting technology sustainability assessment of hydrogen economy.

5.2.2 Key Sustainability Indicators of Green Hydrogen in the Northern Cape

The second research objective of this study was to identify the key sustainability indicators of green hydrogen in the Northern Cape. Through a systematic literature review and corroboration from green hydrogen stakeholder surveys, this study found that twenty-eight sustainability indicators were relevant to the Northern Cape: eleven were environmental indicators, nine were economic indicators and eight were social indicators.

The study not only established sustainability indicators but also ranked the relative importance of these indicators according to the surveyed stakeholders. Indeed, water use, impact on biodiversity, employment, energy return on invested energy, and skills development and skills transfer were found to be the top five green hydrogen sustainability indicators in the Northern Cape.

Furthermore, the study revealed divergent views on the relative importance of indicators held by public and private sector stakeholders. Private sector stakeholders were found to place greater importance on environmental indicators, such as water use, human toxicity potential, impact on biodiversity, and soil pollution. In contrast, public sector stakeholders placed greater importance on social indicators, such as employment, skills development and skills transfer, and energy poverty. This highlighted the contested nature of a just transition, as different stakeholders placed value on different indicators, necessitating a delicate balancing act of transitioning to an environmentally friendly society while ensuring that a positive social impact is achieved.

The results of this study can enable green hydrogen investors in the Northern Cape to know which sustainability indicators to consider before undertaking an investment in these projects while also providing insight to researchers in undertaking assessments for hydrogen economy, and policymakers on the sustainability indicators to consider when drafting policies.

5.3 Limitations of Study

This study had potential limitations. The first was the limited sample size of only 16 stakeholders surveyed. This was relatively small and may not be fully representative of all perspectives in the Northern Cape's green hydrogen economy, thus the findings may not be generalised to the full population. The purpose of sampling in this study was not for generalisation purposes but to explore the views of stakeholders in the province however future research should consider the enlargement of the sample size so as to ensure that the findings can be generalised to Northern Cape's green hydrogen economy.

The second limitation was the reliance on grey literature for the purposes of understanding the context of green hydrogen economy in South Africa. This was due to the lack of country specific peer reviewed publications because of the infancy of the field in the country resulting in most literature being from government reports, policy documents and research reports from organisations such as the International Energy Agency. Therefore, as the field evolves and more South African based literature becomes available, this can be incorporated into future research.

The third limitation was the potential bias in stakeholder selection due to non-probabilistic purposeful sampling being utilised to select stakeholders to survey. Although measures were taken through stakeholder mapping that the stakeholders are representative of the green hydrogen economy, the selection may not capture all relevant stakeholders such as local residents in the Northern Cape who neither have access to the internet nor participate in green hydrogen related events.

The final limitation was the limited exploration of sustainability indicator interactions. This study did not explore how the identified indicators interact or conflict with each other in practice as well as the trade-offs between the different indicators that policymakers and investors may face. The study focused on the ranking of the indicators individually and future research may consider the interactions.

While the above limitations did not invalidate the study's findings, they did suggest areas where further research and more comprehensive approaches could enhance the understanding of green hydrogen sustainability in the Northern Cape.

5.4 Recommendations

Based on the findings of this study we recommended that firstly an energy technology sustainability assessment for green hydrogen economy should be undertaken, utilising the sustainability indicators established in this study. Secondly, given the diverging views on the relative importance of sustainability indicators between stakeholders as found in this study, the assessment should be conducted in collaboration between various stakeholders to ensure all views were considered, as suggested in Musango & Ouma-Mugabe's (2024) generic framework for energy technology sustainability assessment. Thirdly, the energy technology assessment for sustainability framework can leverage off this study by incorporating the sustainability indicators found herein thus ensuring that the impact of the green hydrogen economy on these indicators is considered. This consideration can be utilised by researchers, policymakers and investors alike in undertaking assessments, and informing decision making thus ensuring capital is mobilised and aligned to sustainable energy technologies, of which green hydrogen is one of them.

5.5 Avenues for Future Research

This study applied only the first two phases of Musango & Ouma-Mugabe (2024)'s 3 phased framework for action-oriented energy technology assessment for sustainability, with specific reference to the Northern Cape. Future research could apply this to other regions in Africa that have the potential to develop a green hydrogen economy. Additionally, future research can build on the findings of this study and undertake Phase 3 of the framework by assessing the sustainability of green hydrogen in the Northern Cape, including the interaction and trade-offs between these indicators. Finally, this study can be broadened by increasing the sample size of stakeholders to identify more trends, similarities, and differences in stakeholder views on sustainability indicators.

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APPENDICES

Appendix A: Sampled Documents

Authors	Title	Year	Source Title	Reference
Dagnachew A.G.; Yalew S.G.; Tesfamichael M.; Okereke C.; Abraham E.	A green hydrogen revolution in Africa remains elusive under current geopolitical realities	2024	Climate Policy	(Dagnachew et al., 2024)
Imasiku K.; Farirai F.; Olwoch J.; Agbo S.N.	A policy review of green hydrogen economy in Southern Africa	2021	Sustainability (Switzerland)	(Imasiku et al., 2021)
Kweinor Tetteh E.; Sijadu N.G.; Rathilal S.	An overview of non-carbonaceous and renewable-powered technologies for green hydrogen production in South Africa: Keywords occurrence analysis	2024	Energy Strategy Reviews	(Kweinor Tetteh et al., 2024)
Hamukoshi S.S.; Mama N.; Shimanda P.P.; Shafudah N.H.	An overview of the socio-economic impacts of the green hydrogen value chain in Southern Africa	2022	Journal of Energy in Southern Africa	(Hamukoshi et al., 2022b)
Ellaythy I.; Osman Y.; Elmotkassi T.; Al Shammre A.S.; Alyousef B.K.	Assessment of Economic and Environmental Impacts of using Green Hydrogen Gas for Generating Electricity in the KSA	2024	WSEAS Transactions on Environment and Development	(Ellaythy et al., 2024)
Kalt T.; Simon J.; Tunn J.; Hennig J.	Between green extractivism and energy justice: competing strategies in South Africa’s hydrogen transition in the context of climate crisis; [Entre extractivisme vert et justice énergétique : stratégies concurrentes pour la transition hydrogène de l’Afrique du Sud dans le contexte de la crise climatique]; [Entre o extrativismo verde e a justiça energética: estratégias concorrentes na transição para o hidrogénio na África do Sul no contexto da crise climática]	2023	Review of African Political Economy	(Kalt et al., 2023)
Apata O.	Charting the Course for Sustainable Energy Development: The State of Energy Storage in South Africa's Decarbonization Efforts	2024	2024 IEEE Conference on Technologies for Sustainability, SusTech 2024	(Apata, 2024)
AbouSeada N.; Hatem T.M.	Climate action: Prospects of green hydrogen in Africa	2022	Energy Reports	(AbouSeada & Hatem, 2022)
Kanakana-Katumba M.G.; Maladzhi R.W.; Adeodu A.O.	Comparative Study of Green Energies Exploration in South Africa	2023	2023 IEEE 11th International Conference on Smart Energy Grid Engineering, SEGE 2023	(Kanakana-Katumba et al., 2023)

Gordon J.A.; Balta-Ozkan N.; Haq A.; Nabavi S.A.	Coupling green hydrogen production to community benefits: A pathway to social acceptance?	2024	Energy Research and Social Science	(Gordon, Balta-Ozkan, Haq, et al., 2024)
Das S.	Data Analysis of Factors Contributing to the Adoption of Green Hydrogen	2023	Journal of Environment and Development	(Das, 2023)
Park J.; Kang S.; Kim S.; Kim H.; Cho H.-S.; Lee J.H.	Enhancing the economic viability and reliability of renewables based electricity supply through Power-to-Gas-to-Power with green hydrogen	2024	Energy Conversion and Management	(Park et al., 2024)
Shen H.; Crespo del Granado P.; Jorge R.S.; Löffler K.	Environmental and climate impacts of a large-scale deployment of green hydrogen in Europe	2024	Energy and Climate Change	(Shen et al., 2024)
Hong S.; Kim E.; Jeong S.	Evaluating the sustainability of the hydrogen economy using multi-criteria decision-making analysis in Korea	2023	Renewable Energy	(Hong et al., 2023)
Hussein H.I.; Heffron R.J.; Phillips A.; Jarin J.-B.; Basil C.V.	Future-proofing for green hydrogen in the Global South: a procedural justice perspective	2024	Journal of Energy and Natural Resources Law	(Hussein et al., 2024)
Virens A.	Green hydrogen futures: Tensions of energy and justice within sociotechnical imaginaries	2024	Energy Research and Social Science	(Virens, 2024)
Chigbu U.E.; Nweke-Eze C.	Green Hydrogen Production and Its Land Tenure Consequences in Africa: An Interpretive Review	2023	Land	(Chigbu & Nweke-Eze, 2023)
Blohm M.; Dettner F.	Green hydrogen production: Integrating environmental and social criteria to ensure sustainability	2023	Smart Energy	(Blohm & Dettner, 2023)
Olabi A.G.; Abdelkareem M.A.; Mahmoud M.S.; Elsaid K.; Obaideen K.; Rezk H.; Wilberforce T.; Eisa T.; Chae K.-J.; Sayed E.T.	Green hydrogen: Pathways, roadmap, and role in achieving sustainable development goals	2023	Process Safety and Environmental Protection	(Olabi et al., 2023)
Rey J.; Segura F.; Andújar J.M.	Green Hydrogen: Resources Consumption, Technological Maturity, and Regulatory Framework	2023	Energies	(Rey et al., 2023)
Agyekum E.B.	Is Africa ready for green hydrogen energy takeoff? – A multi-criteria analysis approach to the opportunities and barriers of hydrogen production on the continent	2024	International Journal of Hydrogen Energy	(Agyekum, 2024b)
Gupta R.; Guibentif T.M.M.; Friedl M.; Parra D.; Patel M.K.	Macroeconomic analysis of a new green hydrogen industry using Input-Output analysis: The case of Switzerland	2023	Energy Policy	(Gupta et al., 2023)
Das S.; De S.; Dutta R.; De S.	Multi-criteria decision-making for techno-economic and environmentally sustainable decentralized hybrid power and green hydrogen cogeneration system	2024	Renewable and Sustainable Energy Reviews	(Das et al., 2024)

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Appendix B: Survey Questionnaire

Section 1: Demographic information

1. Participant full names
2. What is your email address?
3. What is your gender?
4. What is your age?
5. Who is your employer?
6. What is your current role in your organisation?

Section 2: Interview/Survey question

I have undertaken a systematic literature review on the sustainability indicators of a green hydrogen economy and identified 12 environmental indicators, 8 economic indicators and 8 social indicators. I am now undertaking this stakeholder survey to determine if these indicators are relevant to stakeholders in the Northern Cape's potential Green Hydrogen economy and if other indicators are missing.

1. How important do you consider the following sustainability indicators in the development of a green hydrogen economy in the Northern Cape? Please rate each indicator on a scale of 1 to 5, where 1 means "Not important at all", 2 means “Slightly important”, 3 means “Moderately important”, 4 means “Very important” and 5 means "Extremely important".

		Scale				
Indicator	**Description**	**1**	**2**	**3**	**4**	**5**
ENVIRONMENTAL INDICATORS						
Land Use	Measures the amount of land required for green hydrogen production facilities, including electrolyzers, renewable energy sources (solar panels, wind turbines), and transportation infrastructure.					
Water Use	Measures the water consumption for electrolysis, cooling systems, and potential cleaning processes.					
Air Pollution, Carbon Emissions & Greenhouse Emissions	Measures the amount of air pollutants, carbon dioxide, and other greenhouse gases released due to green hydrogen production and consumption.					
Marine Life Destruction & Water Pollution	Represents the potential impact of green hydrogen production facilities on marine ecosystems and water quality. This includes potential spills, discharges, and disruptions to marine life.					
Resources, Minerals and Metals Use	Measures quantities of resources (for example, platinum group metals) needed for electrolyzers, renewable energy infrastructure, and associated equipment.					
Energy Return on Energy Invested (EROEI) & Energy Efficiency	Measures the efficiency of green hydrogen production. EROEI compares the energy output (green hydrogen) to the energy input (renewable electricity) used in the process.					
Noise Emissions	Measures the noise pollution generated by electrolyzers, renewable energy sources, and transportation of equipment.					
Human Toxicity Potential	Measures the potential risks of green hydrogen production on human health, including exposure to toxic materials used in equipment or potential leaks.					

Waste Generated	Measures volumes of waste generated during green hydrogen production, such as hazardous materials, used equipment, and water treatment residuals.					
Impact on Biodiversity	Measures potential negative impacts on plant and animal life caused by green hydrogen production facilities and their land use.					
Global Warming Potential	Measures the overall impact of green hydrogen production on global warming by considering all greenhouse gas emissions throughout the lifecycle.					
Soil Pollution	Evaluates the potential for soil contamination from spills, leaks, or improper waste disposal during green hydrogen production.					
ECONOMIC INDICATORS						
Cost of Green Hydrogen	Measures the cost of green hydrogen to the customer based on the Levelised Cost of Energy (LCOE).					
Economic Growth	Measures the impact on economic activity as measured by the GDP per capita.					
Import Dependency	Measures the reliance on imported resources for green hydrogen production and the potential for domestic manufacturing.					
Generation of Tax Income	Measures the potential tax revenue generated from green hydrogen production facilities and associated industries.					
Generation of Foreign Currency	Measures the potential foreign currency revenue generated from green hydrogen exports.					
Local Procurement	Measures the extent to which green hydrogen production utilises local resources, labour, and services to promote local economic development.					
Energy Supply Security	Measures the potential of green hydrogen to diversify energy sources and reduce reliance on imported fossil fuels.					
Economic Development	Evaluates the broader economic benefits of green hydrogen production, such as stimulating innovation and creating new industries.					

Infrastructure Developed	Evaluates the type and scale of infrastructure (e.g., pipelines, storage facilities) built to support green hydrogen production and distribution.					
SOCIAL INDICATORS						
Employment	Measures the number of potential jobs created in green hydrogen production, operation, maintenance, and associated industries.					
Skills Development & Skills Transfer	Evaluates the new skills and training programs gained by the local community.					
Social Acceptance	Evaluates public opinion and acceptance of green hydrogen production facilities in local communities.					
Public Perception of Safety	Evaluates public concerns about the potential risks associated with green hydrogen production, storage and consumption.					
Energy Poverty	Evaluates the potential of green hydrogen to contribute to alleviating energy poverty by providing access to clean energy for disadvantaged communities.					
Employee Diversity	Measures the diversity and inclusivity of the workforce involved.					
Wage Fairness	Evaluates whether wages paid to workers in the green hydrogen industry are equitable and comparable to similar roles in other industries.					
Stakeholder Involvement	Measures the extent to which various stakeholders (e.g., local communities, environmental groups, government agencies) are involved in the decision-making process related to green hydrogen projects.					
Food Security	Evaluates the potential impact of green hydrogen production on food security, particularly in regions where agricultural activities may be affected by land use changes or resource competition.					

2. Are there any environmental, economic or social sustainability indicators that you believe were not adequately covered in this survey? Please specify below:

3. Were there any environmental, economic or social sustainability indicators in the list that are not relevant to the Northern Cape? Please specify and explain: