The relevance of industrial development zones as prototyping hubs for the diffusion and scale-up of green hydrogen powerfuels for South Africa: A case study of Atlantis in Western Cape

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Urban Studies in Sustainable Energy Efficient Cities.

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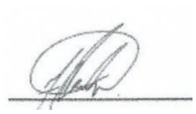
Declaration

I, Fadheelah Madhi declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Urban Studies in the field of Sustainable Energy Efficient Cities, to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.



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Date: 29 November 2023

Abstract

In South Africa, provinces such as the Western Cape (WC) enjoy high levels of renewable energy (RE) resources such as solar and wind energy while also experiencing critical transmission and storage constraints. On the other hand, industrial development zones (IDZs) such as Atlantis in the WC, offer opportunities for adaptable infrastructure in support of green hydrogen (GH) technologies that can convert surplus RE to GH which is rapidly evolving as a globally flexible powerfuel. Through a qualitative study approach, the study assessed the relevance of IDZs as prototyping hubs for addressing the challenges facing the prototyping and scale-up of GH from RE resources which are commonly associated with intermittency.

Primary data were collected through interviews with senior engineers (electrical, mechanical, and industrial) in RE and GH while secondary data were extracted from relevant studies and industry reports as well as policy and regulatory frameworks covering RE, GH and IDZs. As one of the initial findings, in spite of rapid evolution in RE-technologies and policies in South Africa and globally, key barriers still exist in the adoption and diffusion of GH-technologies. Five key barriers identified are infrastructure, socio-economic, economic, water scarcity for GH from electrolysis, policy, and regulatory constraints.

Secondary data further indicates that SA is in the roll-out stage of two key GH initiatives (Green Hydrogen Valley - GHV and Sasol-Toyota GH joint venture) aimed at tackling the identified barriers. However, further analyses indicates that such prototyping projects would still leave major gaps that need to be closed in order to expedite the scale-up of GH nationally. The study then interviewed one Atlantis IDZ official on the extent to which IDZs could facilitate in closing the adoption and scale-up gaps for GH in South Africa.

As a hub specifically created for the testing, prototyping and production of green technologies in order to facilitate their scale-up and adoption, the study finds that Atlantis IDZ is uniquely positioned for mitigating the barrier-gaps identified. The IDZ is equipped with secure streams of capital investments which could be leveraged for GH-technologies as well as for addressing related constraints such as water scarcity through desalination technologies. Atlantis also holds unique learning opportunities, operates under entrepreneurship-friendly special policies, and enjoys access to infrastructure relevant for the adoption and scale-up of GH. Based on these findings, the study concludes that IDZs are not only relevant for the national adoption of GH but also critical for positioning South Africa as a leading GH economy globally.

Key Words: *Atlantis Industrial Development Zone, energy resource intermittency, green hydrogen, renewable energy resource, solar PV, technology diffusion and scale-up barriers, wind energy*

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Table of Contents

List of Tables

List of Figures

List of Abbreviations and Acronyms

Abbreviation	Description
BEV	Battery Electric Vehicle
DBSA	Development Bank of South Africa
EIA	Environmental Impact Assessment
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GH	Green Hydrogen
GHV	Green Hydrogen Valley
GRI	Gestamp Renewable Industries
GW	Gigawatt
H2	Hydrogen
HSRM	South African Hydrogen Society Roadmap
ICEV	Internal combustion Engine Vehicle
IDC	Industrial Development Corporation
IDZ	Industrial Development Zone
IPAP	Industrial Policy Action Plan
IPP	Independent Power Producers
IRP	Integrated Resource Plan
LNG	Liquified Natural Gas
NERSA	National Energy Regulator South Africa

PGM	Platinum Group Metals
PVI	Platinum Valley Initiative
R&D	Research and Development
RE	Renewable Energy
REDZ	Renewable Energy Development Zone
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
SEZ	Special Economic Zone
TSAM	Toyota South African Motors
WC	Western Cape

1. Introduction and Overall Context

Energy is at the heart of all economic development initiatives and constitutes the key driver of all socioeconomic activities, including the production and supply of goods and services globally. Currently, South Africa generates "69% of its electricity supply from coal" (South Africa Energy Sector Report, 2019,15). The effects of this coal dependence include many negative consequences to the environment, such as increasing levels of carbon emissions, with South Africa, ranked as the twelfth largest carbon emitter in the world (Check, 2021). Following the energy crisis in 2008, a need for new renewable energy (RE) alternatives was articulated to aid in meeting the demand for energy while also reducing CO_2 emissions. As a result, South Africa commenced its transition to solar and wind power generation in 2011 (Jain and Jain, 2017), which currently stands at 16.1% of the country's energy mix as of 2020 (Enerdata, 2021). However, these RE sources face challenges of intermittency and storage limitations which constraint their potential towards facilitating transitioning towards a green and clean economy for South Africa.

RE sources such as wind and solar alone therefore are not enough regarding the long-term solution for energy security and mitigation of climate change. This calls for an increase in the diversity in the country's energy mix by introducing new technologies such as green hydrogen. With specific reference to green hydrogen as one of the energy-mix options, the study aimed at understanding the potential of the technology as well as its diffusion pathways in the South African economy.

1.1. Background to the Study

1.1.1. GH in Combatting Intermittency Challenges

A complete switch to renewable energy is impossible without a solution to match intermittent generation from renewable resources with demand. As one of the key insights from Chapter 2, RE sources such as wind and solar face challenges of intermittency and storage limitations. Thus, for successful energy transition to RE, the issue of intermittency needs to be addressed. RE generated by wind and solar farms cannot consistently supply electricity at all hours of the day. Solar power can only be generated during daylight hours and wind power only when the wind blows. This raises various concerns such as lack of predictability, blackouts, and potential overloading if too much power is generated relative to grid capacity. Due to these factors, an average of 20-30% of solar energy and 30-50% of wind energy is wasted (Interview conducted in February 2022).

Green hydrogen can address this challenge primarily because it is storable. When combined with wind or solar technology, green hydrogen can fill-up the generation gaps and thus facilitate for an uninterrupted supply of clean energy. While a standard battery system can store up to roughly 10MWh of energy without modular scale-up, a standard GH system can store up to 1TWh of energy (Lin, 2020,3).

1.1.2. Colour Labels for Hydrogen Types

Industry players differentiate between the diverse range of technologies used to produce hydrogen gas through colour labels and designations where the ‘colour’ label for hydrogen depends on how it is generated (Dodgshun, 2020). The four main colour-labels in use are illustrated in Figure 1.1.

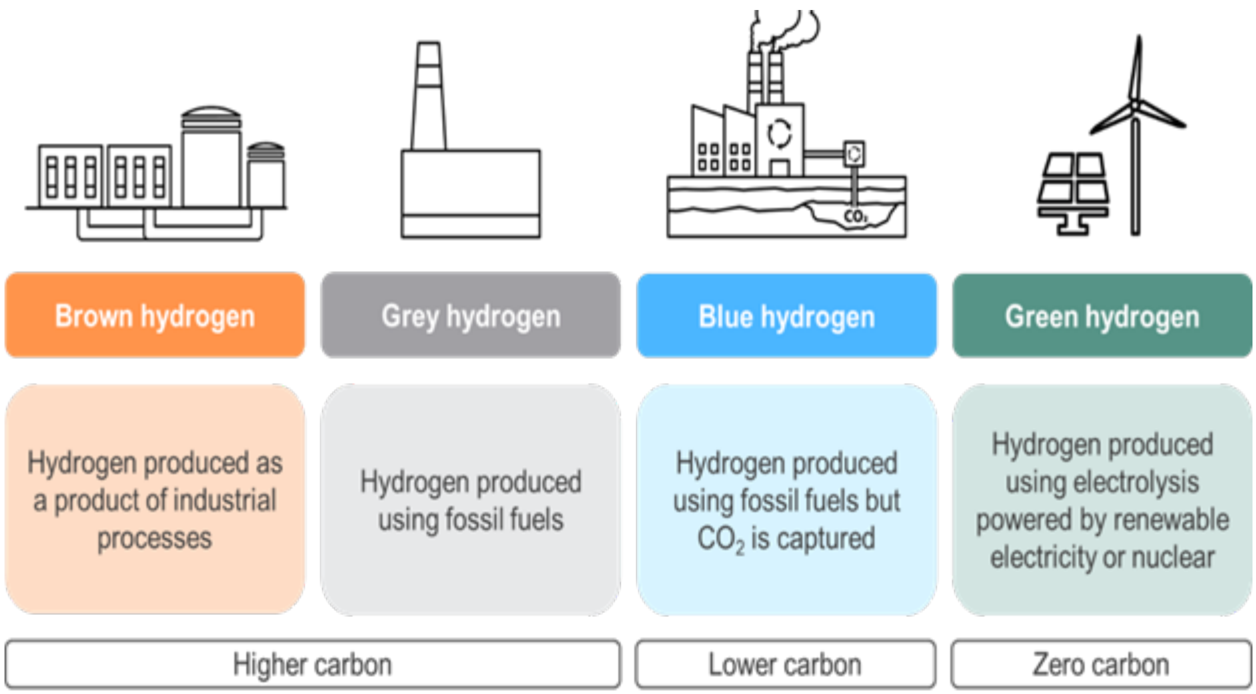

Figure 1.1: Different Colours of Hydrogen, Source: Wilton International (2021, 4)

Brown hydrogen is produced through an industrial process based on the gasification of coal. It is therefore deemed to be the most polluting in terms of CO2-emissions (Purtill, 2021). The second type is grey hydrogen which relies on natural gas, primarily steam methane, for production (Leachman, 2015). The third label is blue hydrogen which is produced in a similar manner to grey hydrogen but with CO2-emissions captured through carbon capture and storage (CCS) technologies. The use of CCS “reduces the emissions created from producing hydrogen and minimizes the environmental impact” (Farmer, 2021,3). The fourth label is green hydrogen which is created through electrolysis of water where an “electric current is used to split water molecules into hydrogen and oxygen. If the energy used in the electrolysis processes comes from a renewable energy source such as wind or solar power, the hydrogen is considered green" (Deign, 2020,2). The production of green hydrogen is deemed to carbon-free (free of CO2-emissions) and has been identified as a clean energy source that could potentially aid in facilitating a net-zero emissions world (Purtill, 2021).

Less common forms of hydrogen also exist, these include pink/purple hydrogen, turquoise hydrogen, and recently categorised white hydrogen. Pink/purple hydrogen, often grouped as one category, is hydrogen produced form nuclear power (National Grid Group, 2022, 3). Purple hydrogen is made by using nuclear power and heat through combined chemo thermal electrolysis splitting of water (H2Bulletin, 2023, 2), while pink hydrogen is generated through electrolysis of water by using electricity from a nuclear power plant (H2Bulletin, 2023, 2). Both pink and purple hydrogen produce less emissions than grey and blue hydrogen (Hydrogen Society Roadmap for South Africa, 2021, 14)

Turquoise hydrogen is hydrogen produced from "thermal splitting of methane, which produces solid carbon rather than carbon dioxide. The heat for the high-temperature reactor is produced from renewable or carbon-neutral energy sources" (Hydrogen Society Roadmap for South Africa, 2021,14). In the future, turquoise hydrogen may be valued as a low-emission hydrogen, dependent on the thermal process being powered with renewable energy and the carbon being permanently stored or used (National Grid Group, 2023, 4).

Finally, white hydrogen, also referred to as natural hydrogen, is hydrogen produced by a 'natural geochemical process deep inside the Earth's crust, making it a sustainable and inexhaustible source" (Solar Impulse Foundation, 2020,1). White hydrogen is extracted by fracking. "The process involves drilling through geological layers and injecting a mixture of water, sand, and chemicals under high pressure to release the gas from the rocks. However, exploitation of the fuel still poses challenges for the industry" (Balkan Green Energy News, 2023,2). White hydrogen is deemed the most cost-effective method for generating carbon-neutral hydrogen, it competes favorably with traditional fossil fuels in terms of affordability (Solar Impulse Foundation, 2020,2).

1.1.3. Advantages and Disadvantages of Green Hydrogen

Like other forms of hydrogen, green hydrogen entails a variety of advantages and disadvantages. Four main advantages of green hydrogen are commonly discussed. The first one links to sustainability in that green hydrogen does not emit any harmful gasses during both production and use in diverse applications such as combustion (Purtill, 2021). Secondly, unlike battery-storage, green hydrogen can be stored in large quantities over extended periods of time (Cho, 2021). This allows hydrogen to be used for diverse applications and at various times other than directly after production. Thirdly, due to the expansive flexibility of hydrogen molecules, green hydrogen is multifaceted and versatile thus creating opportunities for powering the grid in multiple ways such as through conversion in a fuel cell or by direct combustion in a gas turbine (Lin, 2020). Additionally, Green hydrogen can be transformed into electricity or synthetic gas and used for domestic, commercial, industrial or mobility purposes. Finally, green hydrogen can be mixed with natural gas and travel through the same gas pipelines and infrastructure, thus making it easily transportable. Furthermore, green hydrogen can be stabilized as ammonia for worldwide distribution via ships or trucks (Deign, 2020).

Two major disadvantages of green hydrogen are commonly cited. The first one relates to its high cost of production. This is mainly because electrolysis technology is still at a very low level of diffusion and thus high in cost. This is primarily due to currently low demand for the technology. However, as green hydrogen continues to gain traction globally, it is predicted that the cost of the technology will become more affordable as the associated costs decrease (International Renewable Energy Agency - IRENA, 2020). Furthermore, in certain parts of the world, renewable energy is currently more expensive to generate than traditional forms of energy (ibid). Once again, as the demand for carbon-free and sustainable energy increases, the cost of renewables is predicted to decrease globally. The second common disadvantage of green hydrogen is its associated safety concerns. Hydrogen is a highly volatile and flammable chemical element and thus extra caution needs to be taken to prevent any leakage which escalates the risk of devastating explosions (Frawley, 2021).

1.1.4. Industrial Development Zones and the Case of Atlantis

Special Economic Zones (SEZ) are "geographically designated areas of a country set aside for specifically targeted economic activities, supported through special arrangements such as legislation and governance systems that are often different from those that apply to the rest of the economy" (Department of Trade, Industry, and Competition, 2021, 2). SEZ commonly fall into four distinct sectors as follows:

- Industrial Development Zones: purpose-built industrial estates.
- Free Port: duty-free areas adjacent to a port of entry.
- Free Trade Zones: duty-free areas offering storage and distribution facilities.
- Sector Development Zones: a zone focused on the development of a specific sector or industry.

Various benefits and incentives of operating within a SEZ contribute to growth, revenue generation, creation of jobs, international competitiveness, and attraction of foreign direct investment. These incentives include a preferential corporate tax at 15% compared to the standard 28% (SARS,2022), building allowance, tax relief subject to requirements under Income Tax Act of 1962, customs-controlled area, and 12I tax incentive to support both greenfield and brownfield investments (Department of Trade, Industry, and Competition, 2021).

Currently there are five operational Industrial Development Zones in South Africa: Atlantis, Nkomazi, Coega, Richards Bay and East London (Ibid). Atlantis was in-part developed as part of the City of Cape Town's initiative to establish a "greentech manufacturing hub" (Department of Trade, industry, and Competition, 2021, 4) and is situated 40km's from Cape town. Greentech refers to green technologies that decrease or reverse the impact of the population on the planet (Green Cape, 2018, 11). The further development of Atlantis was done in response to the Department of Energy's Renewable Energy Independent Power Producer Programme (REIPPPP) and capitalizes on the province's currently booming renewable energy and green technology sector. Industries for manufacturing renewable energy technologies, such as wind turbines and solar panels are currently operational within Atlantis (ibid).

1.2. Problem Statement and Rationale

As the global pursuit of sustainable energy intensifies, the critical challenges surrounding the diffusion pathways of green hydrogen have become paramount. Recognizing the significance of green hydrogen as a clean and renewable energy source, there are still many obstacles hindering its widespread adoption. Moreover, Industrial Development Zones (IDZs) like Atlantis, endowed with substantial resources, have not witnessed a substantial upscaling in the adoption of green hydrogen.

High levels of renewable energy potential around Atlantis, coupled with existing infrastructure within the SEZ, the ability to build and adapt new infrastructure and necessary systems, as well as the conducive policy environment would suggest Atlantis to be a suitable prototyping hub for the diffusion and adoption of green hydrogen technology in South Africa. It is imperative to scrutinize the reasons behind this lack of progress and to ascertain the potential of these IDZs in effectively adopting and expediting the deployment of green hydrogen and associated technologies.

1.3. Research Aim and Objectives

Guided by the context and background as outlined in previous sections, the study aimed to assess the relevance of Industrial Development Zones as prototyping hubs for the diffusion and scale-up of green hydrogen and the extent to which these zones can be considered for related prototyping in South Africa. The study was therefore based on the following research objectives:

- Identifying challenges related to the diffusion and adoption of green hydrogen in South Africa.
- Reviewing the status and planned future pathways of green hydrogen adoption and diffusion in South Africa.
- Examine the suitability of Atlantis Industrial Development Zone as a case study and evaluate the broader applicability of Industrial Development Zones as prototyping hubs for promoting a green hydrogen economy in South Africa.
- Deriving responsive findings, conclusions, and recommendations.

1.4. Rationale of the Study

Atlantis IDZ was developed with the purpose of testing and implementing existing and emerging green technologies. As such, the Atlantis IDZ is home to numerous renewable energy technology businesses primarily in wind and solar. Such businesses continue to increase as a steady stream of investment opportunities expand within Atlantis IDZ.

This triggered the study towards an understanding of the extent to which green hydrogen could be adopted in such zones in South Africa. This study explores the critical issues of intermittency and surplus waste as well as the potential of GH from RE sources such as wind and solar through a focus on policy frameworks, socio-economic, infrastructure, and financial factors in relation to the adoption of GH and RE within the zones which would in turn facilitate adoption and scale-up of GH in South Africa.

1.5. Primary Research Question

Arising from the rationale and objectives of the study, the overall research question of the study was conceptualized as follows:

With Atlantis, in the Western Cape, as a case study, what is the relevance of Industrial Development Zones as prototyping hubs for a green hydrogen economy in South Africa?

1.6. Sub-questions of the study

The main research question was addressed through the consolidation of sub-findings based on the following sub-questions:

- What are the critical challenges in the diffusion pathways?
- What is the status and planned future pathways of green hydrogen powerfuel adoption and diffusion in the market in South Africa?
- What is the relevance of Industrial Development Zones as prototyping hubs in relation to the critical challenges in the diffusion pathways?

1.7. Definition of Key Terms of Study

Adoption refers to the uptake and use of GH in South Africa. It refers to both investments being made in GH in terms of infrastructure, socio-economic, economic, research, and policy and regulatory framework, as well as the actual use of the powerfuel.

Baseload Energy refers to minimum amount of energy produced over a certain period of time at a consistent rate (Merriam-Webster, 2023).

Diffusion of GH refers to the way in which GH is being used, spread, and adopted across different industries/sectors within the country, as well as to the advancements and emergence of the powerfuel.

Green Hydrogen refers to hydrogen produced from RE sources. GH produced is used as a storage medium for excess and waste energy from these sources. GH can be used at any time and has a larger storage capacity than existing storage systems. GH is transportable and can be used for export purposes (Deign, 2020, 3).

Green Hydrogen Economy refers to an economy that relies on GH as its primary clean energy source. It consists of a GH infrastructure and has the ability to export or import GH. A GH economy is considered a net-zero carbon economy Green Hydrogen Economy (Oliveira et al., 2021,6).

Industrial Development Zones (IDZ) refer to specific industrial estates within South Africa that have direct access to international ports or airports. These zones have been created with the purpose of establishing new investment through export orientated and similar services (Department of Trade, industry, and Competition, 2021, 1). This report specifically focuses on Atlantis IDZ as it focuses on green technology and investments.

Intermittency refers to the state of solar and wind resources. These sources are unable to produce continuous energy as they are depended on sunlight and wind levels. Thus, they do not continuously generate energy that can be used or stored.

Net-Zero Carbon Economy refers to the amount of greenhouse gas, specifically CO_2 being produced in a country/region/economy. To reach a net-zero carbon economy one must be compensating for the amount of CO_2 produced in relation to what is being removed from a region's atmosphere (University of Oxford, 2023, 2).

Powerfuel in the context of this report refers to a gas that is created using renewable energy. Powerfuels are considered sustainable, non-harmful to the environment, and can be used as both energy carriers and feedstock. GH is considered a powerfuel as it uses RE sources to produce a clean, net-zero gas that can be converted into energy. Powerfuels are considered "climate-friendly solutions to application with no viable alternatives, they can reduce the cost of energy by utilizing existing infrastructure and they provide long term storage options for RE" (Global Alliance Powerfuels, undated, 1-3). Additionally, powerfuels can be transported and traded globally, and could "defossilise existing consumer end-use equipment as a green drop-in alternative to fossil fuels" (Global Alliance Powerfuels, undated, 3). Figure 1.2 below indicates the different powerfuel processes, end products, and example application.

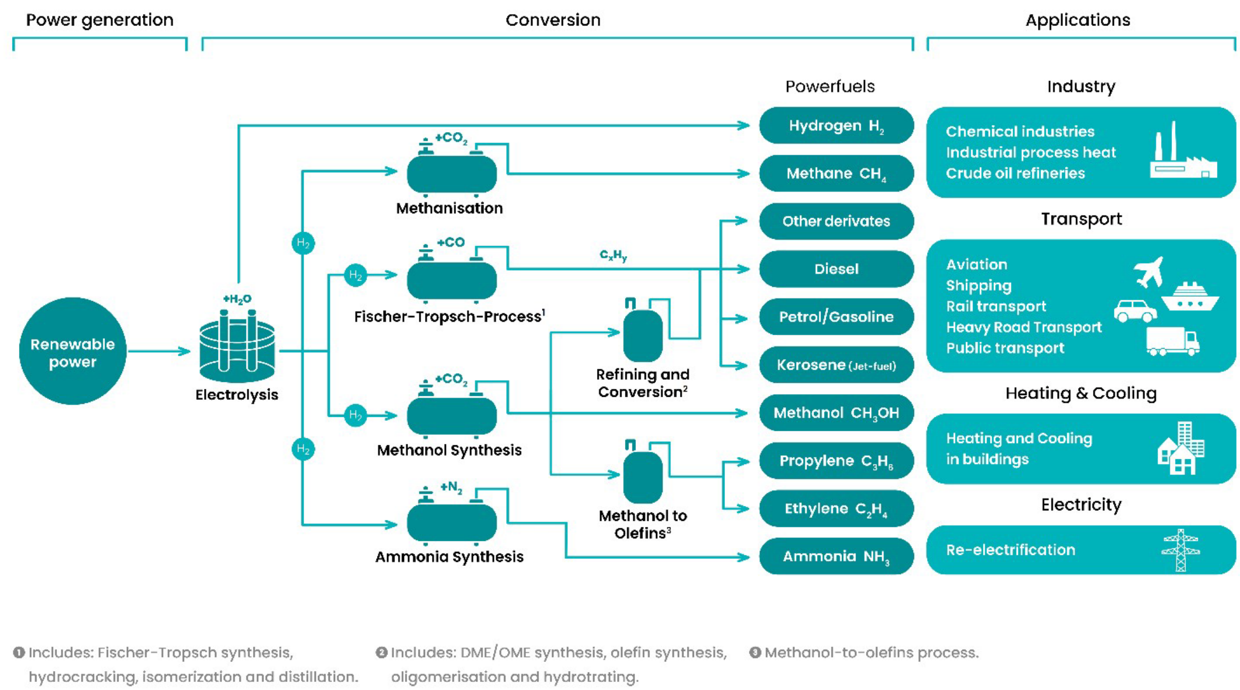

Figure 1.2: Different possible powerfuel processes, end products, and example applications., Source: Global Alliance Powerfuels, Undated. Pg 2.

Renewable Energy refers to renewable sources, specifically wind and solar energy (United Nations, 2023, 1). These sources are considered for the production of GH.

Special Economic Zones refer to designated geographical areas within South Africa that are specially set aside for different forms of targeted economic activities. These zones are established with the aim of promoting economic growth and exports by offering special incentives to attract national and foreign investment and technological advancements (Department of Trade, industry, and Competition, 2021, 1).

1.8. Working Hypothesis

The study envisaged the following findings:

- There already exists systematic and rapidly evolving diffusion pathways which would ensure that GH is widely adopted as a clean powerfuel in South Africa as well as for export.
- The evolving pathways systematically identifies and responds to diffusion challenges facing the adoption and diffusion of GH which include limited transport capacity and infrastructure-related challenges, increased stress on water because of electrolysis-process being water-intensive, the

current high cost of adopting GH as it is still an emerging technology which can be expected to take a while to mature, and policy and regulatory barriers.

- Industrial Development Zones such as Atlantis present South Africa with significant prototyping and proofing grounds for green hydrogen powerfuel thus opening the door for an improved understanding of national diffusion and scale-up requirements in the next ten years to a point where the powerfuel becomes a significant contributor to the country's overall energy mix as well as overall growth of the economy.

1.9. Delimitation, Limitations, and Assumptions

This study was limited to Atlantis IDZ as a case study in order to identify the relevance of Atlantis IDZ as a prototyping hub for the adoption and diffusion of GH in relation to the critical challenges established. It investigated the potential of GH adoption based on solar and wind resources. The choice of limiting the study to these resources was influenced by both the solar and wind potential in South Africa as well as the rapid adoption of generation technologies based on both resources.

Even though the study considered financial implications surrounding the adoption of GH; it did not investigate the costing of infrastructure and systems such as electrolyzers needed for the generation of GH. It also did not consider the cost in relation to existing battery storage systems, nor did it consider the long-term financial implications. Rather, the study was conducted based on the assumption that with the predicted widespread adoption of green hydrogen, related powerfuels will become cost-effective in South Africa within a decade or so. The study, therefore, did not consider the cost of adopting green hydrogen within South Africa. Instead, the study focused on the specific role which IDZ could play in facilitating the adoption of GH given the extensive RE resource potential in South Africa.

Additionally, this study did not consider, in depth, how the GH produced in South Africa based on foreign investments is likely to be apportioned among local use versus exports to other countries, especially those of the North. The study, however, considers how (in what industries) green hydrogen could be used within South Africa in order to contribute towards a net-zero carbon emission economy.

Moreover, the exploration of GH applications within extensive electricity networks falls beyond the purview of this study and, consequently, was not subject to detailed examination or research. The study primarily focuses on offering a cursory overview of GH's potential applications across diverse sectors such as building, transport, energy, industrial heat, and feedstock.

Further, this study did not assess levels of surplus energy around Atlantis IDZ that can be harnessed for GH adoption. Such scope would require a separate investigation, as noted under recommendations in Chapter 7. However, there is adequate secondary data indicating that potential RE resource levels is high especially for solar and wind.

1.10. Outline of the Report

Guided by the study objectives on the relevance of Atlantis IDZ as a prototyping hub for the diffusion and adoption of GH in South Africa, the report is structured into seven chapters as follows:

Chapter One is the introductory chapter which presents the background and motivation of the research. It further presents the primary research question and sub-questions alongside the key objectives of the study, working hypothesis, delimitation, limitations, and assumptions of the study, as well as definitions of key terms.

Chapter Two presents an appraisal of studies on the core theoretical themes of the study. The themes include availability and potential of RE resources in South Africa, battery storage systems, GH, and its potential uses. Further, it considers key challenges regarding infrastructure, socio-economic, financial, and water-related challenges. Finally, it considers RE policy and regulatory frameworks that are analyzed in subsequent chapters of the study. The chapter therefore establishes the link between RE and GH and the various related theoretical themes to provide key insights that guided the rest of the study. This chapter starts with a review of studies aimed at an improved understanding of RE resources, how they work and how key components of related systems such as battery storage works.

The chapter then establishes GH as an energy medium as well as a storage system. Due to GH being highly water intensive, readings on the extent of the water crisis in South Africa are also appraised. The chapter then appraises readings on the different uses of GH to allow for an understanding of how it can facilitate a zero-carbon economy. Readings on the global context are then appraised to establish SA's unique position as a front-runner in both RE and GH. Finally, readings on the current landscape of GH in SA, as well as related challenges are appraised.

Chapter Three presents the overall research approach and method used to collect both primary and secondary data. Primary data were gathered through semi-structured interviews with sector professionals while secondary data were collected from several academic articles, industry and online reports, official government documents, and reports from the rapidly growing series of relevant webinars and seminars on GH in South Africa and globally.

Chapter Four presents data and analyses towards sub-findings on the first sub-question, which focuses on the challenges and barriers of adopting GH in South Africa. Key focus was placed on infrastructure, socioeconomic, financial, resource availability (such as water), policy and regulatory framework challenges in relation to GH and RE. Potential solutions to some of these barriers were also appraised.

Chapter Five presents data and analyses towards sub-findings on the second sub-question, which focuses on the status and planned future pathways of GH adoption and diffusion in SA. It establishes the status of RE sources relevant to produce GH, increasing role of GH towards combatting issues of intermittency and waste, as well as the key relevant policies and regulatory framework enabling the adoption and diffusion of GH in South Africa.

Chapter Six presents data and analyses towards sub-findings on the third sub-question which focuses on the relevance of industrial development zones as prototyping hubs in relation to the critical challenges in the diffusion pathways of GH in South Africa. The chapter specifically assesses the extent to which Atlantis IDZ is equipped to combat the challenges identified in Chapter 4. In doing so it substantiates on how Atlantis could be a suitable prototyping hub for GH in South Africa.

Chapter Seven presents a consolidation of the sub-findings into the overall research findings and conclusions as the overall response to the main research question. This is followed by recommendations for further research.

2. Literature Review

2.1. Introduction

This chapter presents and appraisal of studies on core themes relevant throughout this study. These themes range from the availability of RE sources in South Africa to the current landscape of GH in the country. The chapter starts with a review of studies aimed at an improved understanding of RE-resources, and how key components of related systems such as battery storage work. The chapter then reviews readings on GH as an energy medium as well as a storage system. Due to GH being highly water intensive, readings on the extent of the water crisis in South Africa are also appraised. This is followed by appraisal of readings on the different uses of GH to allow for an understanding of how it can facilitate a zero-carbon economy. Readings on SA's unique position as a front-runner in both RE and GH globally are then appraised. Finally, readings on the current landscape of GH in SA, as well as related challenges are reviewed followed by consolidation of key insights and a conceptual framework of the study.

2.2. Resources in South Africa

Green hydrogen production depends on energy produced from renewable resources such as wind and solar. As such, the status of RE resources must be established to understand the generation capacity of GH in South Africa. Compared to the rest of the world, the country has one of the highest solar and wind resources. On average, the country experiences between 4.3-6.3 daily peak hours of sunlight as one of the key resources used in solar systems throughout the year. As illustrated in Figure 2.1 solar radiation levels range between 4.0 and 6.9kWh/m2 per year (Sola, 2023, 3). In addition, Figure 2.1 indicates that the Northern and Western Cape provinces in South Africa experience the highest levels of intensity of radiation in the country, this is further indicated in Figure 2.2.

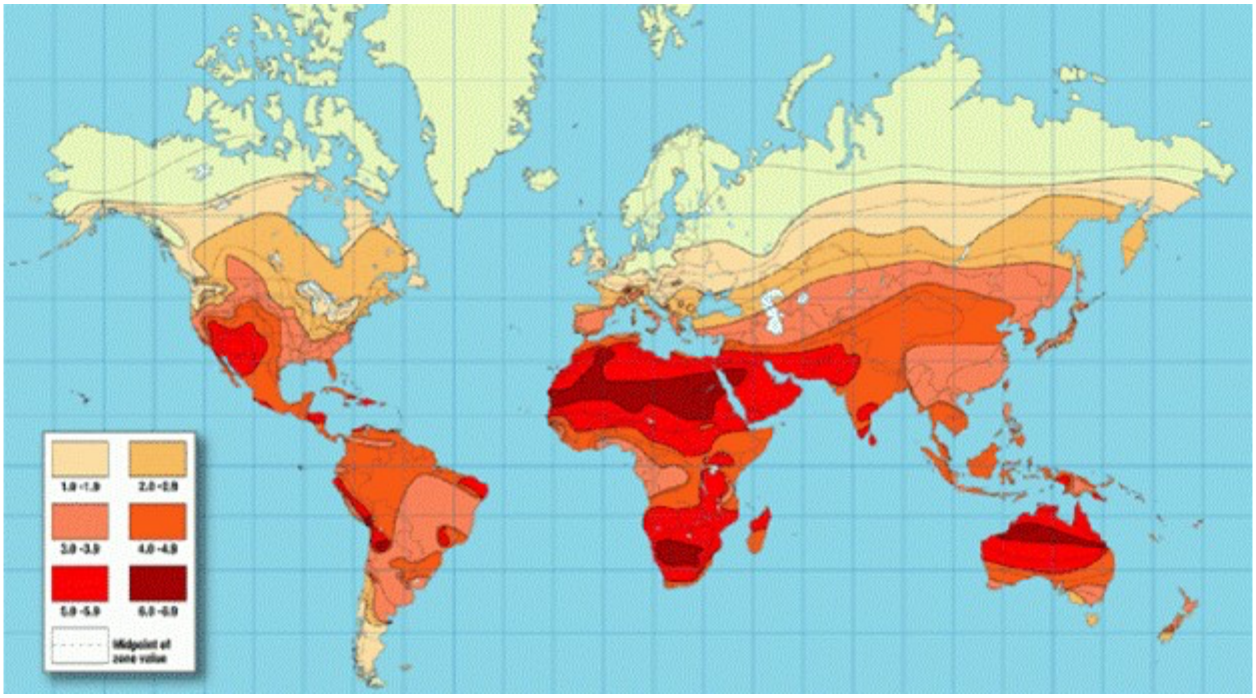

Figure 2.1: Average Annual Solar radiation intensity levels globally. Source: SOLA (2022,3)

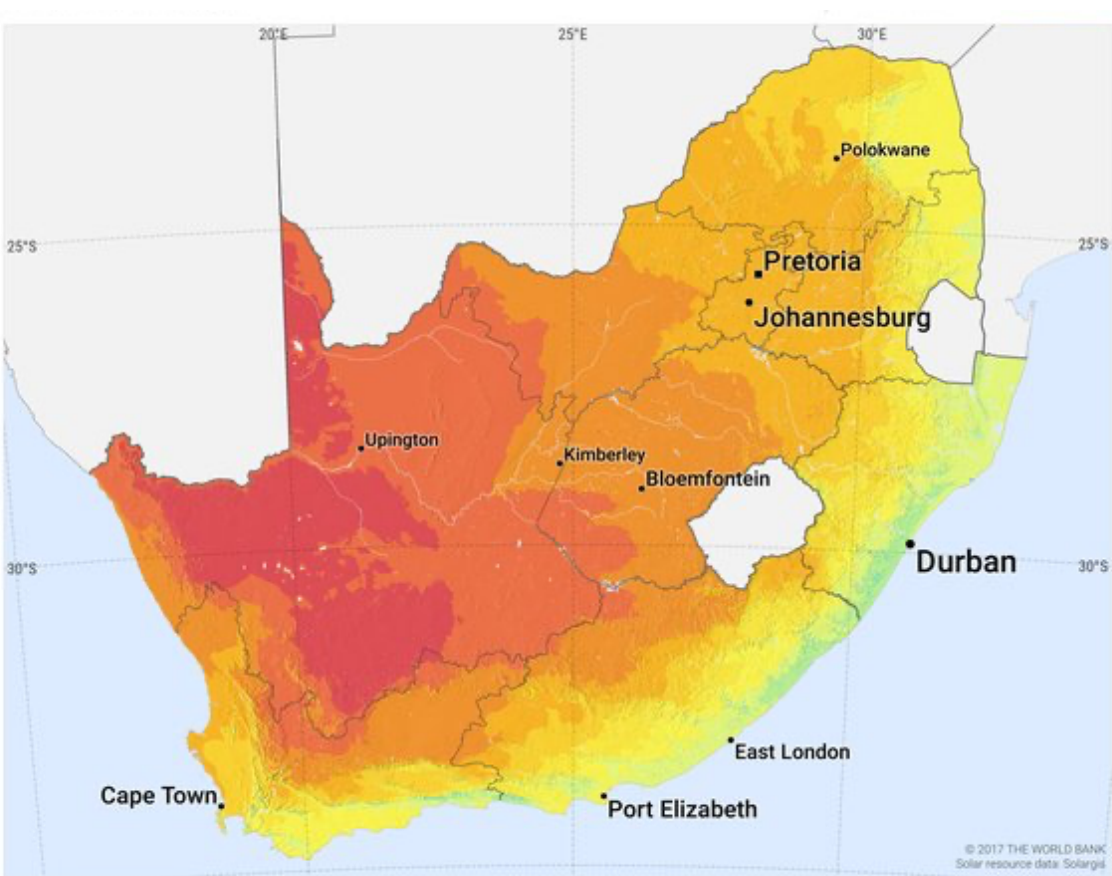

Figure 2.2: Map indicating solar radiation levels in South Africa (SolarGIS,2023).

Similarly, South Africa is also highly endowed with wind resources, especially along its extensive coastal regions. South Africa experiences wind speeds ranging from 2 to 10 meters per second, with 10 meters per second being the maximum wind speed observed (WASA, 2020, 7). As demonstrated in Figure 2.3, provinces with the highest windspeeds include the Western Cape with speeds between 4 -10ms^{-1} and the Eastern Cape with levels between 7 - 10ms^{-1}.

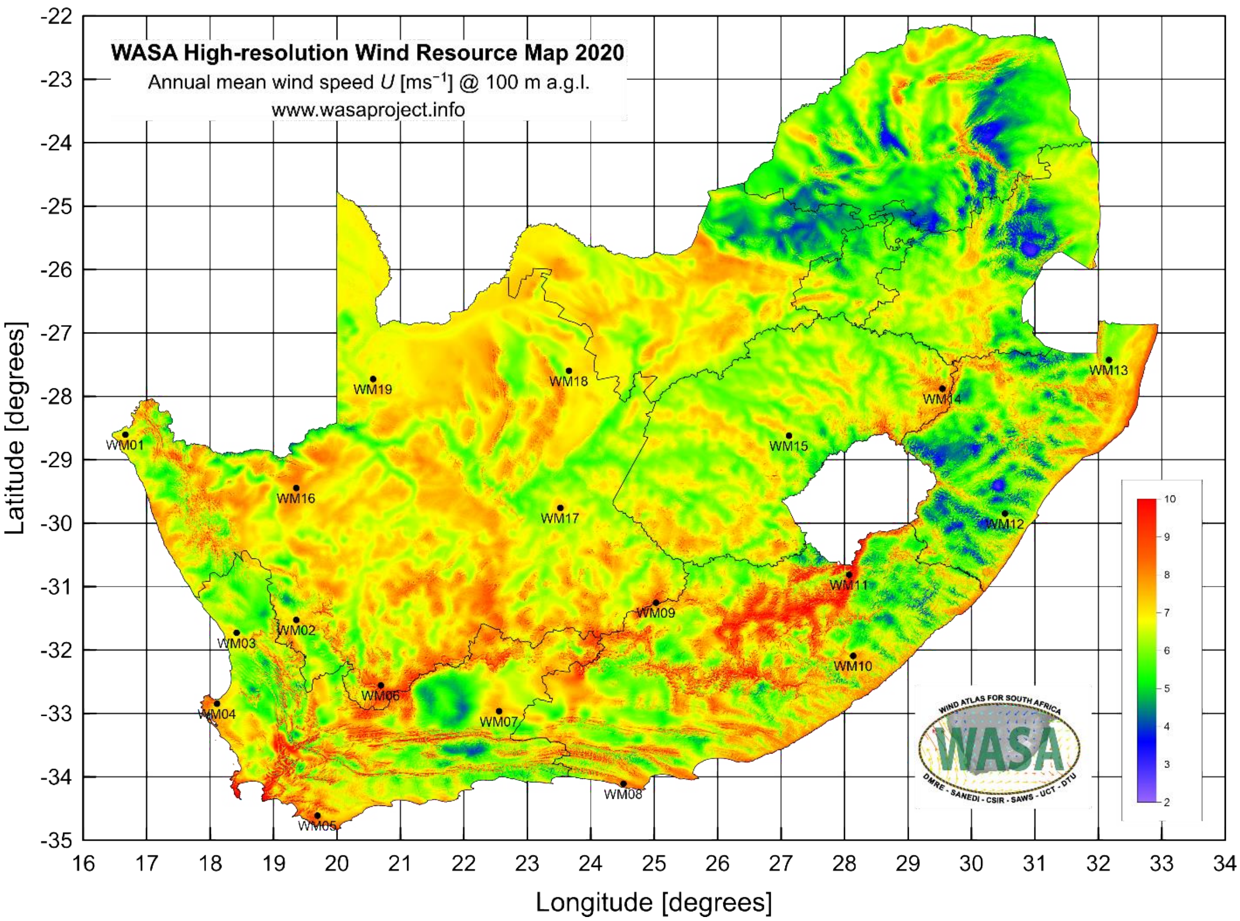

Figure 2.3: Wind Resource Map for South Africa. Source: Wind Atlas for South Africa, (2020, 9)

South Africa's competitive advantage in the realm of natural resources, specifically wind and solar, not only renders it advantageous for GH production but also imparts a distinct economic viability to the process. The considerable reserves of these renewable resources position South Africa as a preeminent hub for GH production, with cost considerations further underscoring its status as one of the most economically viable locales for such endeavors, as illustrated in Figure 2.4.

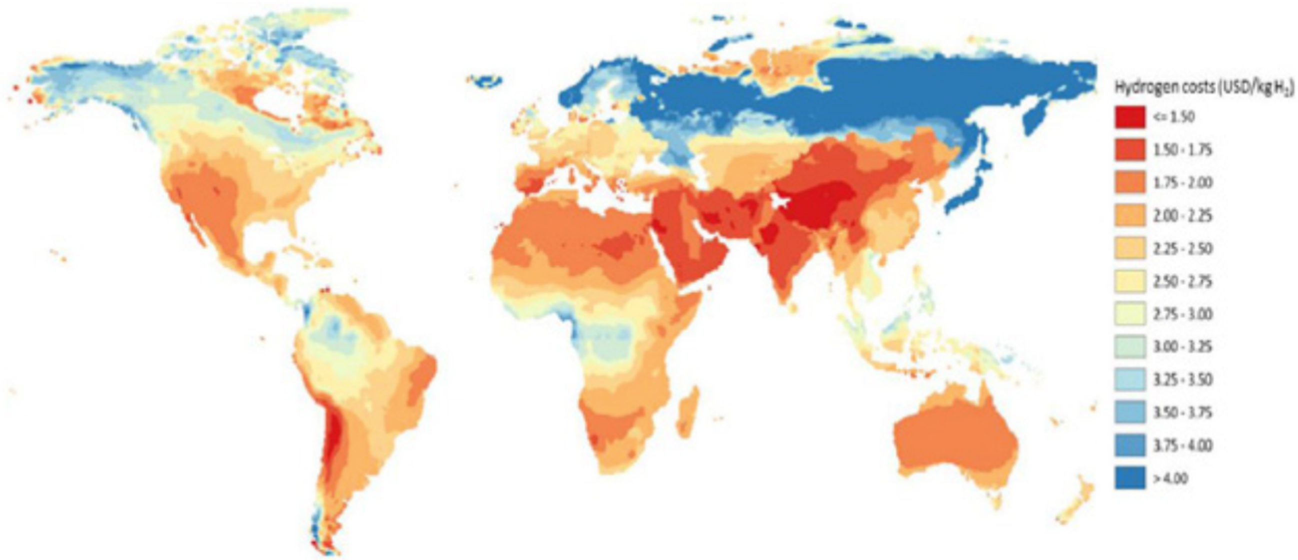

Figure 2.4: IEA 2021,16 Global Hydrogen Review.

2.2.1. Limitations of Renewable Energy Sources

The intermittent nature of most RE resources is a hindrance to increasing adoption of related technologies into the energy mix of modern economies globally. In particular, erratic availability of wind and solar resources (variations in wind speed and solar irradiance), pose critical reliability and stability challenges for the power system. In addition, both solar and wind resources face storage challenges in that they cannot be captured and stored directly in their naturally available form without a conversion process (Asiaban et al., 2021, 3).

Unlike fossil fuels, solar energy production is less predictable. It can fluctuate seasonally and even hour to hour as local weather changes. In addition, solar energy is only available during daytime hours when sunshine/solar radiation can be available for solar panels which convert the resource to electricity. This means that there are several hours each day when the system would not be generating any energy at all. This calls for storage technologies and systems (usually battery technology) to transform and store the energy produced during peak sunlight hours so that it can be accessed later when solar radiation is unavailable (FCHEA, 2022, 3)

2.2.2. RE Resource in Relation to GH

The interplay between wind and solar energy holds immense potential for advancing green hydrogen production. Combining these renewable sources offers several key advantages. First, they provide a complementary and balanced energy supply, as wind power often peaks during the night, while solar energy reaches its maximum generation during the day. This complementarity ensures a consistent energy input for hydrogen production, enhancing the system's reliability and mitigating intermittency issues commonly associated with individual renewable sources. Furthermore, the synergy between wind and solar technologies allows for a diversified energy mix, reducing the reliance on a single source, and increasing the overall efficiency of the hydrogen production process. By harnessing the joint power of wind and solar energy, we can maximize the utilization of abundant renewable resources, reduce greenhouse gas emissions, and advance the development of a sustainable and carbon-neutral energy sector.

Besides its excellent solar and wind resource, South Africa is positioned as a front-runner for GH technology due to its rich mineral resources for various RE technologies such as electrolyzers, batteries and fuel cells. The country also has multiple planned and existing solar and wind energy power plants with a high potential for green hydrogen production. Additional competitive advantage factors in the production of green powerfuels in South Africa include the following:

- High levels of solar and wind resources translate to large volumes of GH to satisfy local energy demand (thus bridging the gap between energy demand and supply) and for export purposes (International Energy Agency, 2019, 5).
- Abundant low-cost land primarily because most of the solar resource happens to be in areas unsuitable for other land-uses such as agriculture of forestry (GreaterGood SA, 2021, 4-6).
- 50 years of experience in the commercial production of synthetic fuels using the Fischer-Tropsch process, largely used by SASOL in South Africa (Quest, 2011, 11-13).
- Good shipping access to the rapidly growing international markets of the European Union and the Far East, including China and Japan all of which have a growing interest and active investment in GH and GH technology (Toyama, 2022, 1-3).

2.3. Green Hydrogen as a Storage System

GH is created using renewable energy, mainly wind or solar technology, and can be stored and reconverted to electricity when needed. Green hydrogen itself is not considered an energy source but more as a convenient medium of storing and transferring energy generated from renewable sources with electrolysis as the key conversion technology. GH can then be used immediately or stored to serve as a fuel at a later stage (Cho, 2021,19).

Presently, the 'round-trip efficiency,' defined as the percentage of electricity converted into storage and later retrievable for use (EIA, 2015, 25), of green hydrogen stands at approximately 50%. This figure lags behind the round-trip efficiencies of alternative storage systems, as evidenced by Edelstein (2021, 22). Battery storage, for instance, demonstrates a round-trip efficiency ranging from 80% to 85% (EIA, 2023, 2), while compressed air storage maintains an efficiency of approximately 70% (Meyer, 2018, 3). Pumped storage, as per Blaker et al. (2021, 11), boasts a round-trip efficiency of 80%. Despite the low efficiency of GH, the interest in hydrogen energy storage is growing due to its much higher storage capacity compared to batteries, pumped-hydro or compressed air storage (Lin, 2020,18). This is illustrated in Figure 2.5.

Low quantities of hydrogen can be stored in "pressurized vessels or solid metal hydrides" (Lin, 2020, 3). Additionally, nanotubes can store hydrogen with high levels of density. Large amounts of hydrogen can be stored in existing underground salt caverns of up to "500,000 cubic meters at 2,900 psi (Lin, 2020, 4)". This roughly translates to 100 GWh of stored electricity (Lin, 2020, 8). In this way, longer periods of surplus wind or solar PV energy production can be leveled out. Additionally, GH can be delivered through existing gas pipelines and stored in existing storage infrastructure with minimal modifications.

Despite GH currently being an inefficient storage system in comparison to alternative technologies such as batteries, it continues to attract increasing interest due to its much higher energy-storage capacity as well as the enormously diverse use options it facilitates. This is important when considering the introduction of GH technology in South Africa where the country's energy challenge requires storage of surplus energy from renewable energy technologies for longer periods and thus renders RE-resources and technologies fit for baseload requirements of the economy.

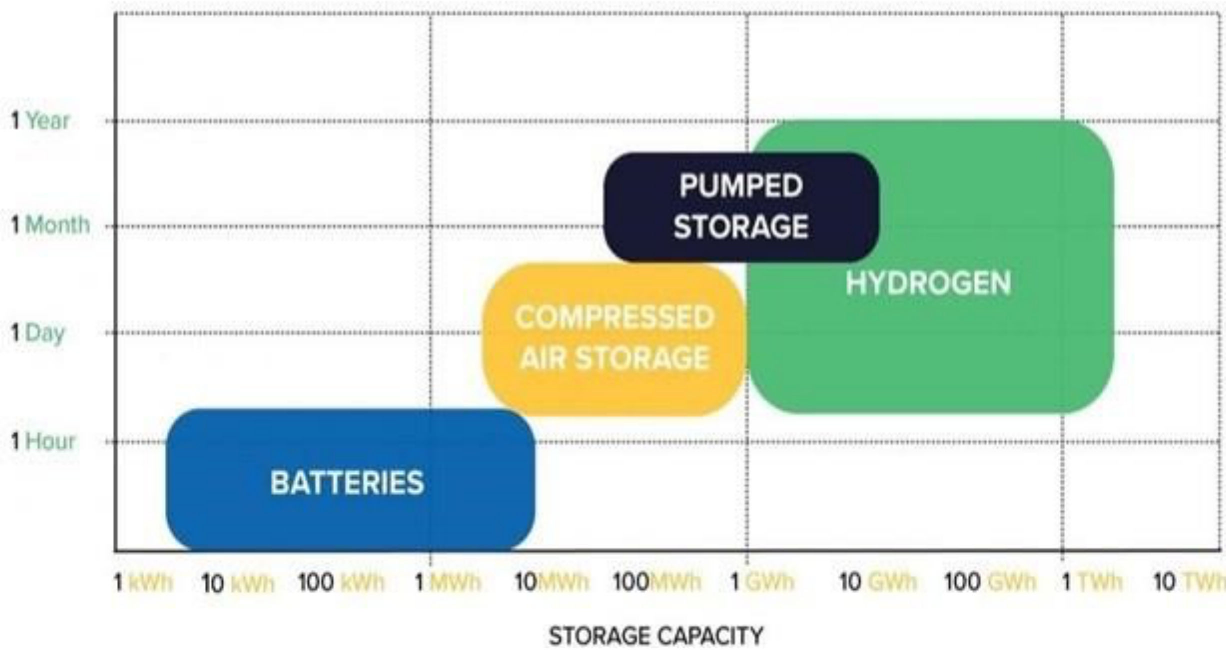

Figure 2.5: Storage capacity of green hydrogen in relation to alternative storage technologies. Source: (Lin, 2020, 3)

Based on insights from this appraisal, it is envisaged that GH will be adopted as a superior storage system compared to prevailing alternatives such as batteries, compressed air storage and pumped storage. In addition to energy storage, GH technology can be used to transfer electricity at any point in time unlike its competitors. Whereas the cost of GH is currently prohibitive, it is expected to gain traction and be adopted at a large enough scale to render it cost-effective in comparison to competing alternatives. This suggests a strong case for the adoption of GH, especially for countries such as South Africa which face energy challenges while enjoying immense endowment of RE-resources.

2.4. Use of Green Hydrogen

GH has multiple applications across different sectors such as industrial, residential, and commercial sectors, where it can be used in various ways across 4 main industries as illustrated in Figure 2.6. Additionally, GH can be re-converted back to electricity through diverse technologies such as fuel cells. Alternatively, it can be burned in combined "cycle gas power plants to produce heat with efficiencies up to 60%" (Energy Storage Association, 2021, 5). GH can be used directly at the point of production, or it can be transported elsewhere through pipelines, trucks, or shipping. Usually, it is converted into ammonia to allow for safer handling and transportation over long distances thus increasing access to powerfuel industries globally.

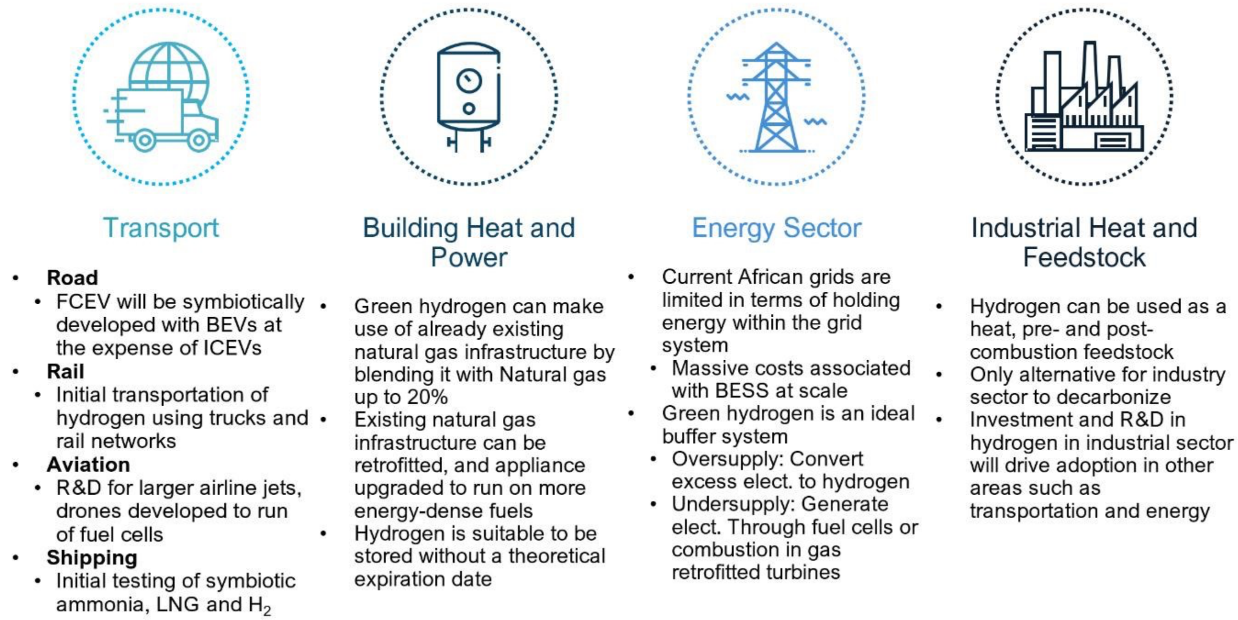

Figure 2.6: Application and uses of GH across 4 key industries. Source: ESI Africa, 2022, 3

As illustrated in Figure 2.7, other potential applications of GH include powering of container ships using liquid ammonia derived from GH, as well as in industrial processes (as a heat source) such as combustion in furnaces for production of green steel (Cho, 2021,11). Moreover, green hydrogen can be used to power electricity turbines that can generate electricity at times of peak demand to stabilize the grid. It can also be used as a substitute for natural gas in residential and commercial buildings as well as feedstock for diverse industrial processes (Amelang, 2020,9).

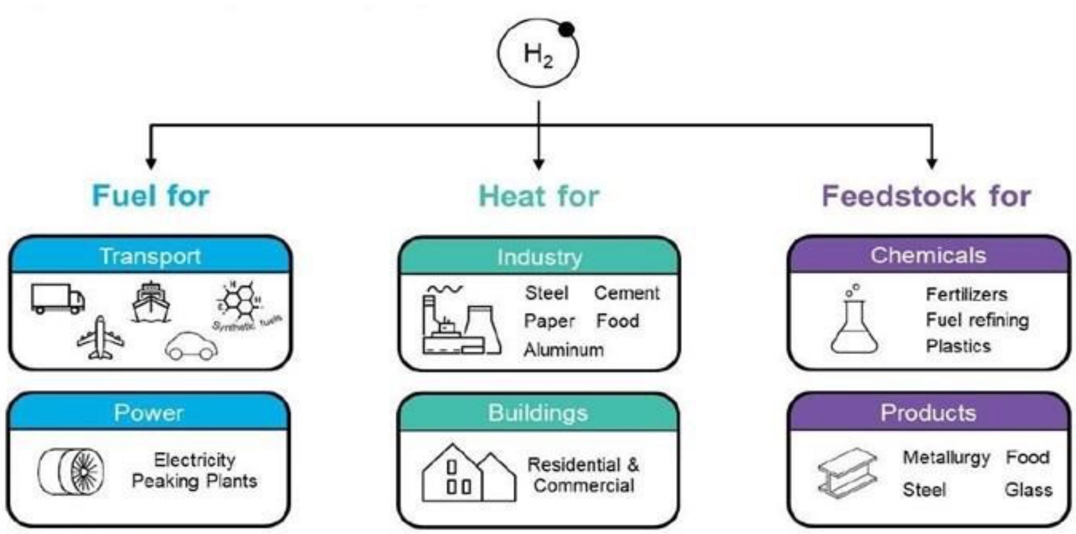

Figure 2.7: Applications of green hydrogen. Source: Clean Energy Wire, (2021, 8)

2.5. Overview on Transformation to GH-Economies Globally

GH has gained traction over the last few years as the future green fuel of choice, and several countries around the world have started transforming themselves into GH economies. As a key example, in 2017 Neom (a smart city currently under development on the Red Sea and comprising of various zones such as industrial and logistics) unveiled its plan to build a zero-carbon city by implementing a green hydrogen plant valued at $5 billion (Rashad, 2021).

Currently said to be the world's biggest hydrogen plant, the project will produce 1.2 million tons of green ammonia per year, which will "use hydrogen produced from electrolyzers powered by more than 4 GW of solar and wind energy" (Rashad, 2021, 4). Hydrogen production from the plant is expected to start in 2025. In addition to using GH within Neom, further plans are in place to export GH to different countries such as Germany (Ratcliffe, 2021). Already considered a front-runner in hydrogen technology development, Germany has invested a further $110 million in GH research and development towards facilitating the use of GH in various applications (including transport) to ensure decarbonization of its economy (Deign, 2019).

On the path to a GH economy, other countries such as Australia, Canada, the U.S, and the U.K aim to produce GH for self-use and export purposes. Australia has entered a partnership with Siemens to develop a 5GW hybrid solar-wind power plant aimed at producing GH for export purposes and to replace fossil fuels (Deign, 2019). Canada began its transformation into a GH economy as both a producer of the powerfuel as well as a manufacturer of fuel cells powered by hydrogen. Being advantageously positioned within the fuel-cell sector, Canada aims to be a front-runner in the sector and has partnered with global leaders such as Ballard Power Systems and Hydrogenics (Ballard, 2021).

From its enormous endowment with wind resources, the U.K. has begun assessing feasibility of GH as a "way of reducing gas imports and to help decarbonize the heating sector" (Ballard, 2021, 3). In September 2019, the U.K government unveiled a "$15 billion plan to use 5GW of offshore wind for the production of green hydrogen by 2030" (UK Hydrogen Strategy, 2021, 4). In the U.S, California is racing to become a world-leading GH market. California's transition to a GH economy is driven by goals to decarbonize the state, which also entails the phasing out of all diesel and natural-gas-powered buses by 2040. California, therefore, considers GH as a key to reaching its decarbonization targets (Deign, 2019).

Other countries such as Japan, China, France, Norway, and South Korea aim at producing GH primarily for use in the transport sector. Japan is currently leading the way in GH fuel-cell vehicle development with

Toyota and Honda as the key players. The use of GH is also encouraged through a policy aimed at stimulating "green hydrogen as an alternative to liquefied natural gas" (Tuch, 2021, 2). In September 2019, Japan announced an action plan to set up "10 000 refueling stations over the next decade" (Tuch, 2021, 2).

Alongside electric vehicles, China considers GH as an important factor in decarbonizing its transportation sector. It therefore aims to have 5 000 fuel-cell vehicles by 2025 (Argus, 2021, 1-2). China also aims to incentivize the use of GH by implementing tax exemptions for hydrogen vehicles (Deign, 2019). Furthermore, cities, such as the capital of Hubei Province in central China, are being styled as hydrogen cities with the inclusion of up to 100 fueling stations to service fuel-cell vehicles (ibid).

In 2018, France unveiled plans to invest $117 million into GH technology (Mathis, 2021). Auvergne RhôneAlpes, a region located in Southeast-central France, committed over $238 million towards 1 000 hydrogen vehicles and 15 electrolyzers, and in September 2019, the country started deploying its first hydrogen powered bus (Fuel Cells Works, 2021).

Norway has vast potential to create GH from hydropower and is "pioneering in the use of fuel cells" (Fuel Cells Works, 2021, 2). It is currently home to various hydrogen filling stations and is set to have 15 new stations in southern Norway by the end of 2023 (Tisheva, 2021). In 2019, Norway reported its first hydrogen filling station accident in which two people were injured but, Nel hydrogen, the filling station operator, reassured the public that the accident was a rare occurrence (Deign, 2019). Additional reports of hydrogen-related incidents were reported in South Korea, where in May 2019, a hydrogen storage tank exploded at a state-owned research facility, killing two people, and injuring an additional six (Chung and Jin, 2019). Despite the accident, South Korea remains on track to roll out plans of getting 850 000 fuel-cell vehicles coupled with a budget of $1.8 billion for vehicle and refueling station subsidies by 2030 (Deign, 2019).

Leading countries around the world continue to increase investments in the development and diffusion of GH technology across various sectors, including transport, exports, and in the cases of Neom and Germany, across multiple sectors, as a way of decarbonizing economies through phasing out fossil fuels.

2.6. Green Hydrogen in South Africa

Due to the extensive wind and solar resources available, South Africa enjoys a competitive edge in the production and export of GH (Slater, 2021, 13). PwC (2021) analyzed South Africa's hydrogen potential in relation to global decarbonization and contribution to South Africa's net-zero emission goal by 2050. As the use of renewable energy is predicted to increase to 85% of total electricity production by 2050, the production of energy will become "geographically constrained, thus increasing the need for cross border transportation and storage of green energy" (Slater, 2021,13). GH is emerging as the ideal solution to this challenge.

PwC (2021) also notes that investing in GH is necessary for diversifying the South African economy. Given its unique production capabilities, South Africa has the opportunity to become a booming hydrogen economy. Whereas South Africa has been a "net importer of energy, with the production of green hydrogen, the country can claim its position as a net exporter of clean energy" (PwC, 2021, 4) and, in doing so, ensure the overall transformation of the economy.

In taking steps towards a GH economy, several projects have been initiated in the country. For example, Sasol and Toyota South Africa Motors (TSAM) announced a joint venture in which they will pursue the "development of a proof-of-concept demonstration for a green hydrogen mobility ecosystem" (ESI Africa, 2021,9). Additional projects include a hydrogen valley within South Africa where Anglo American has initiated collaboration on a feasibility study for South Africa's 'hydrogen valley' (Creamer, 2021,7).

This is expected to be among the projects that will be implemented in partnership with the private sector to support the Platinum Valley Initiative (PVI) aimed at supporting "small, medium-sized, and microenterprises to take advantage of opportunities in the green economy in support of a just transition" (Creamer, 2021,11). The collaboration follows the 2020 launch of the South African Hydrogen Society Roadmap, which aims at "integrating hydrogen into the economy by capitalizing on the country's PGM resources and renewable energy potential to revitalize and decarbonize key industrial sectors" (Creamer, 2021,12). .

South Africa can therefore address future challenges of geographically constrained energy production and current challenges of storing surplus energy produced from its RE-resources, as well as addressing the need for additional electricity supply by leveraging its unique position for developing and diffusing GH technologies. Integration of GH into South Africa's economy will be primarily incentivized through the

South African Hydrogen Society Roadmap introduced in 2020. Finally, various prototype projects involving GH (such as the joint venture between Sasol and TSAM and the proposed hydrogen valley) are already at advanced implementation stages.

2.7. Challenges Facing Green Hydrogen

Whereas the adoption of GH globally has recently started gaining traction, it still faces various technical, viability, socio-economic, and political challenges globally as well as in South Africa. The key challenges faced globally include the cost of electrolyzers which are critical for GH production. This is in part due to the limited production of the required materials. However, it is envisaged that as the demand for GH increases over the next 5-10 years, the cost of electrolyzers will dramatically decline in a manner similar to what has already happened with RE-technologies (Christopher, 2021, 12).

Furthermore, the high flammability of hydrogen reinforces concerns regarding safety in its transportation and storage (Eljack and Kazi, 2021). Finally, the challenge of water for electrolysis is faced on a global scale (Ackermann and Werner, 2021). Water is already considered a problem for thermal/steam-based generation, especially in areas where water scarcity is starting to intensify due to climate change.

Challenges specific to South Africa mainly relate to regulation and policy. Although South Africa has introduced the South African Hydrogen Strategy and Roadmap, it is yet to be finalized for roll-out (Creamer, 2021). Furthermore, energy policy regulations restrict utility-scale independent power project developers for renewable energy access to Eskom-grid even though access for wheeling is gaining traction. This limits the opportunity for such IPPs (independent power producers) to contribute to GH goals in the short-to medium term (Slater, 2021). Moreover, where independent generators produce renewable energy for their own use (self-generation), they are faced with a 100 MW threshold (Planting, 2021). This signifies the need for realigning energy policies and regulations with GH aspirations of the economy.

Additional challenges faced in South Africa include inadequate knowledge and skills needed to ensure safe production, storage, transport, and usage of GH. As a result, increasing demand for engineers to install, monitor, operate, and maintain fuel cells and hydrogen systems which cannot be currently met. Finally, there are severe constraints in attracting investments for capital-intensive projects to build large scale plants and thus facilitate lower cost of GH. There is therefore a need for national strategies towards ensuring harmonization of infrastructure investment with commercial needs and market readiness for GH (Lawlor, 2021).

2.8. Conclusions and Conceptual Framework of the Study

South Africa is one of the leading countries in the world in terms of the availability of RE sources. The vast availability of these sources poses a unique opportunity for South Africa to be a leading GH economy due to its larger GH production potential. GH Itself is not considered a source of energy but rather a storage medium in contrast to existing storage mediums such as battery systems, GH is unique in that it has a larger storage capacity and can be stored for longer periods of time and converted back into energy when needed. GH, unlike other storage systems can also be transported and thus can be exported to other countries. The variability of GH allows it to be used across various sectors including four key industries: transport, building heat and power, energy, and industrial and feedstock. This vast potential of application makes GH extremely valuable.

Over the last few years GH has gained traction globally, with major countries around the world investing in the powerfuel and transforming themselves into GH economies as a way of decarbonizing their economies and transitioning towards net-zero carbon status. These countries include the EU, Japan, China, Australia, Canada, and the U.S. The same trend has been found in South Africa with various GH pilot projects and feasibility studies being conducted, as well as the introduction of new policies and regulatory frameworks to assist in the transition to a GH economy.

Despite this vast traction in GH, various challenges still exist that must be overcome to ensure a smooth and successful long-term transition into a GH economy. These challenges are faced globally and include barriers such as cost, safety, infrastructure, technical skill, and policy and regulation. The existing and increasing investment into GH includes investigating solutions to overcome these challenges.

Based on the current state of economies around the world and the rising concern around climate change, the increase in GH remains steady and is only predicted to increase over time. The global adoption and increased interest in GH technology as a way of overcoming various issues and enabling countries to reach net-zero carbon status ensures the continuous adoption of the powerfuel. Moreover, the global investment in GH has resulted in various infrastructure to support the adoption of GH as well as the emergence of policy and regulation to ensure the adoption and diffusion of GH in the long term and the transition to a GH economy.

The conceptual framework diagram (Figure 2.8) presented herein serves as a visual representation of the multifaceted considerations central to understanding and fostering the diffusion and adoption of GH in the South African context. The inputs into this framework encompass a comprehensive analysis of critical challenges associated with the uptake of GH, an assessment of the current status and future trajectories planned for GH in South Africa, and an evaluation of the suitability of IDZs as potential prototyping hubs for advancing the cause of GH in the region. Through this structured framework, we aim to synthesize and interconnect these key elements, providing a holistic view that aids in unraveling the complexities and intricacies surrounding the integration of GH within South Africa's energy landscape.

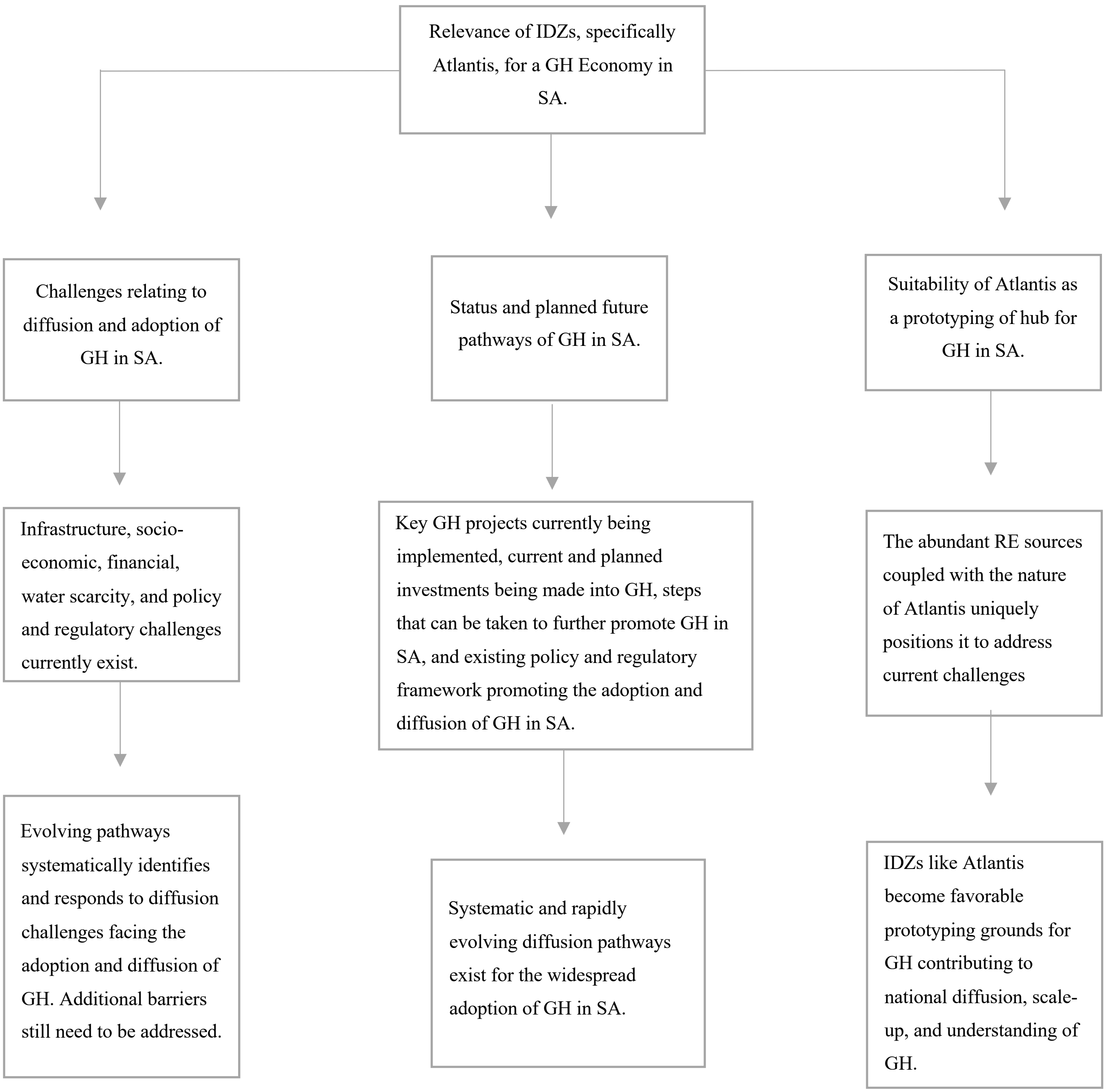

Figure 2.8: Conceptual Framework Diagram

3. Research Methods

3.1. Research Approach

Research method is the overall strategy of enquiry applied in the study in response to the objectives, research question, and conceptual framework. The strategy is then applied to guide research design in terms of conceptualizing data required, data collection, and analyses tools as well as approach to derivation of findings (Myers and Avison, 2005). Qualitative and quantitative research are the two common approaches used in research strategy and design. Qualitative approach is primarily based on interpretivist method and tools while quantitative approach applies a statistical method.

In qualitative studies, the researcher serves as the primary instrument of data collection and analyses based on various tools of capturing data. This study applied a qualitative approach where multiple claims to knowledge, enquiry strategies, data collection and analyses tools were employed. Qualitative data used in the study includes primary data based on interviews with interview schedules as the main data collection tool and secondary data extracted from existing studies, reports, and policy as well as regulatory documents. Table 3.1 presents a summary of data required, data collection and analyses tools for the derivation of sub-findings on the sub-questions which is consolidated into overall findings in relation to the overall research question.

Primary data consists of participant responses to semi-structured interviews with experts in energy, economic development, and the Atlantis Industrial Development Zone. Energy experts interviewed work within the energy sector as well as specifically within the renewable energy department within Atlantis IDZ. Based on this approach, participants were purposefully selected based on their roles within their respective sectors as well as facilitation through personal networks of the researcher within the energy sector.

Based on the sub-questions, the interviews focused on RE-resources specifically focusing on wind and solar as well as related intermittency challenges and how GH plays a role in combating this issue. Additional interview questions addressed current and future landscape of GH in SA as well as views on key projects such as the Green Hydrogen Valley, key challenges associated with GH in terms of infrastructure, socioeconomic factors, financial and water related challenges. The interviews also solicited responses on the relevance of IDZs towards tackling these challenges. Secondary data were extracted from a variety of local and international sources such as academic articles, media and online content, official government policies and reports, seminar, and webinar presentations as well as books and book-chapters covering the diffusion and adoption of GH in South Africa.

3.2. Data Requirements, Collection Tools, Analyses and Derivation of Findings

Table 3.1: Overview on data collection and analyses tools

Research and sub-questions	Data required: Collection, tools, and process	Data analyses and derivation of findings
Sub-question 1: What are the critical challenges in the diffusion pathways of GH in South Africa?	**Primary data needed:** The following data parameters were considered: • Technical challenges, in terms of required versus existing skills for adoption and diffusion pathways of GH in South Africa. • Infrastructure related challenges in the adoption of GH in SA. • Economic challenges in diffusion pathways of GH in South Africa. • SAs water crisis as a challenge in diffusion and adoption of GH in SA. • Policy and regulatory challenges in diffusion of GH in South Africa. **Primary data tools:** Interviews were conducted with leading energy experts in South Africa who have worked in the energy space for over 20 years. Each interview was conducted using MS Teams. Participant 1 was interviewed over 3 sessions, while participant 2 and 3 were interviewed over 2 sessions. Each session lasted between 45 minutes to 1 hour. Each interview was recorded using the recording function in MS teams. Each interview was converted into a transcript to avoid the loss of any information as MS Teams recording expired after one month. **Secondary data needed:** Data parameters for secondary data were similar to those applied for primary data. Secondary data aimed to fill any gaps in primary data collected versus data needed under each parameter. Key documents used for abstraction of secondary data are: • Official policy and regulations documents published by Departments of Minerals and Energy, Science and Innovation, and Trade and Industry. Documents mainly cover relevant white papers, REIPPP, IRP, IEP and National Hydrogen Strategy. • South African Hydrogen Society Roadmap, 2021. • South African Hydrogen Valley Final Report. • Journal articles on barriers to adoption of GH in SA and other countries globally.	**Primary and secondary data analyses:** Primary data were grouped according to each interview question. The data were analyzed along with secondary data for derivation of sub-findings in response to Sub-question 1. **Secondary data analysis** Data were grouped according to the following key parameters: • Physical challenges • Socio-economic challenges • Financial challenges • SA's water crisis • Policy and regulatory challenges **Derivation of findings:** Sub-findings were derived as presented in Chapter 4.

<table>
<tr>
<td>Sub-question 2:
What is the status and planned future pathways of GH powerfuel adoption and diffusion in the South African market?</td>
<td>Primary data needed:
Primary data collected for this sub-question relate to understanding the status and planned future pathways of GH powerfuel adoption and diffusion in South African market. Data collected was in accordance with the following key parameters:

In understanding the status of green hydrogen diffusion and adoption in South Africa:
• The extent to which GH technology is being pursued in South Africa mainly in reference to key projects being implemented such as GH Valley, Sasol-Toyota GH project.
• What steps can be taken to further promote GH in SA?
• What policy currently exists to promote adoption of GH in South Africa?

Primary data tools:
In order to collect the necessary data needed to answer sub-question, interviews were conducted with leading energy experts in South Africa. The experts include electrical and mechanical engineers. The purposefully selected experts work in the energy industry and have extensive knowledge relating to renewable energy and GH, as well as the energy market in South Africa. Due to Covid-19 restrictions, the interviews were conducted via online platforms - zoom and MS Teams. Participant 1 was interviewed over 3 sessions, while participant 2 and 3 were interviewed over 2 sessions. Each session lasted between 45 minutes to 1 hour. Each interview was recorded using the recording function in MS teams. Each interview was converted into a transcript to avoid the loss of any information as MS Teams recording expired after one month.

Secondary data needed:
Data collected for this sub-question include current and planned status of the GH economy in South Africa.

The data parameters for secondary data collected followed the same as the primary data. Data collection was done to compare with response from primary data in order to fill in any gaps that may exist in data collected vs. data needed for each parameter.

Secondary data tools:
Key government documents and articles were selected and analyzed.</td>
<td>Primary data analyses:
Primary data were collected from three participants and grouped according to each question. The various answers were cross-referenced and analyzed in order to formulate a well-rounded view and response on each parameter.

Secondary data analyses:
Data from multiple key sources were collected according to each parameter. This information was grouped and analyzed according to each parameter. A conclusion was then drawn on the status and planned future pathways of GH powerfuel adoption and diffusion.

Derivation of findings:
Primary and secondary data were cross-referenced to each other to formulate a response on the status and planned future pathways of GH powerfuel adoption in the South African market.

Data and analyses for sub-question 2 are presented in Chapter 5</td>
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	Secondary data sources include: • Journal and web articles reviewed for current and future investments in GH technology in South Africa. Sources were centered around the Sasol-Toyota project and the Green Hydrogen Valley project in SA. • Webinar series on different aspects of GH in South Africa was also considered in terms of the parameters laid out above. • Official government document on review of existing and planning policy surrounding RE both in South Africa and globally. Polices included the White paper policy, REIPPP, IRP, IEP, and the National Hydrogen Strategy.	

<table>
<tr>
<td>Sub-question 3:
What is the relevance of IDZ as prototyping hubs in relation to the critical challenges in diffusion pathways in South Africa?</td>
<td>Primary data needed:
The following data parameters were applied for primary data collection and analyses:
• The nature of Atlantis IDZ relative to GH.
• Current and planned RE projects in Atlantis.
• The potential ability of Atlantis to overcome critical challenges faced in diffusion of GH in South Africa as set out under sub-question 2 (see Chapter 5).
• Understanding Atlantis IDZ as a starting point for diffusion of GH in South Africa.

Primary data tools: Data needed were collected through semi-structured interviews with experts on the Atlantis IDZ and the Green Cape. Interviews were conducted via online meetings.

An interview was conducted using MS Teams with a single participant (P4). The interview was conducted over a single session which lasted between 45 minutes to 1 hour. The interview was recorded using the recording function in MS teams. The interview was converted into a transcript to avoid the loss of any information as MS Teams recording expired after one month.

Secondary data needed:
The following secondary data was collected to fully answer sub-question:
• Definition of special economic zones (SEZ).
• Definition of IDZ.
• Role and aim of IDZ in South Africa.
• Special policy and regulation on IDZ as sourced from government official documents.
• Planned and current RE technologies within Atlantis IDZ.

Secondary data tools:
Official reports by Green Cape provided data required on Atlantis according to parameters set out above. Data from additional documents by relevant government bodies were abstracted and analyzed.</td>
<td>Primary data analyses:
Responses to interview questions were grouped according to the identified parameters. Analyses was mainly based on identifying key themes and perspectives from the structured responses.

Secondary data analysis: Secondary data were collected and analyzed along same parameters as for primary data.

Approach to derivation of sub findings: Cross-referencing the analyses of primary and secondary data facilitated the derivation of sub findings.

Data and analyses for sub-question 3 are presented in Chapter 6.</td>
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<td>Research Question:
With Atlantis (in Western Cape Province) as a case study, what is the relevance of IDZ as prototyping hubs for a GH economy in South Africa?</td>
<td colspan="2">Response to the overall research question was derived through a consolidation of sub-findings from Chapters 4, 5 and 6. Derivation process and presentation of overall findings and conclusions is captured in Chapter 7.</td>
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3.3. Key Ethics Issues of the Study

The following ethics issues were addressed in the process of conducting the study:

- Risk to the research and participants.
- Selection of participants.
- Financial or material interests.
- Consent, anonymity, and confidentiality of participants.
- Data collection and protection.

The research entailed minimal risk to the researcher as well as participants involved and did not expose participants to any potential risk or harm. The participants selected are experts and the study did not involve participants falling under categories commonly deemed to be vulnerable. There were no financial or material interest associated with the research and no participant was offered an incentive of any sort. In the case where familial relationships exist with one of the participants, potential conflicts of interest and coercion were mitigated during the interview process based on a semi-structured questions schedule.

Prior consent was solicited through participation information sheets and consent forms were signed by all participants. Confidentiality of responses from all participants were guaranteed during data collection process as well as in the presentation, analyses and reporting in the research report. Given that experts can be identified through their roles in respective organizations, anonymity could not be guaranteed in reporting of the research and participants were made aware of this.

Data from participants were collected through individual interviews, personal communication in the form of emails and audio recordings. Data protection both during collection and write-up stage as well as after the study was ensured through storing data in a password protected computer accessed only by the researcher. Participants were made aware that data will be stored for possible use and as secondary data for future studies, but with all identifying content of the participants excluded.

Ethics clearance process for the study was completed as required and the clearance certificate is presented in Appendix C.

4. What are the critical challenges in the diffusion pathways of green hydrogen in South Africa?

4.1. Introduction

This chapter presents data abstracted from both primary and secondary data sources to address Sub-question 1 on the challenges and barriers facing the adoption and diffusion of GH in South Africa. Analysis of the data collection provides insights into five key factors that hinder the uptake of the powerfuel. These factors include infrastructure, socioeconomic, economic, resource (water) as well as policy and regulatory barriers. The findings are consolidated in terms of these five key parameters and coupled with proposed solutions and guidance to address the barriers.

To identify the barriers, it must first be established what does exist and what needs to exist to enable a smooth transition into a GH economy. Thus, each parameter will first show what exists concerning RE sources, such as wind and solar infrastructure. Secondly, data and analyses focus on what is needed in terms of GH. The differences/gap is then analyzed, and the country's capacity to bridge this gap will be considered in terms of linking related barriers to each parameter. Key policies have been identified as they are crucial in the transition towards a greener economy while also playing a significant role in the adoption of RE and GH.

Data analysis and the derivation of sub-findings on the challenges hindering the diffusion and adoption of GH in South Africa have been presented as the concluding section of the chapter.

4.2. Data Overview

Primary data were collected by interviewing three purposely selected participants who have worked in the energy and RE landscape for over 30 years. Secondary data were extracted from various policy documents, official reports, and journal articles based on key parameters set out for Sub-question 1. Table 4.1 summarizes the respective data parameters and related data sources. Through the literature study conducted in chapter 2, these parameters were established as the foundational and most important starting factors for transitioning into a GH economy. The data and related analyses were then used to derive sub-findings on the critical challenges in the diffusion pathways of green hydrogen in South Africa.

Table 4.1: Summary of Data Parameters and Data Sources for Sub-question1

Key Parameters	Primary Data	Secondary Data:	Responsive Sub-findings:
Infrastructure challenges 3 participants were interviewed. what are the infrastructure and land related barriers slowing or preventing the adoption of GH powerfuel? 3 key themes were reviewed for data abstraction. • Existing RE infrastructure • GH infrastructure • Cost of GH infrastructure	Interview1 (P2) • Existing RE sources are considered less infrastructure intensive compared to a GH powerplant as well as compared to traditional coal powerplants. Interview 2 (P2) • More infrastructure required for GH increases associated cost of GH. • Equipping the country with the necessary infrastructure takes time. Interview 3 (P3) No response	Source1: (Office of Energy Efficiency and Renewable Energy, 2022, p1-7). • Solar systems require the least amount of infrastructure with the main requirement being land/roof space, panels, and grid connection. Source2: (Steen, 2016, p1-14) • Wind infrastructure is more complex than solar and requires more land. • Easily available infrastructure.	Sub-findings: Existing RE sources such as wind and solar require less infrastructure than GH and are more easily accessible. GH technologies (electrolysis, transport, handling and storage, conversion through fuel-cells among other options) are still emerging and therefore costly.
Socio-economic challenges 3 participants were interviewed. What is the level of technical skills required to develop, operate, and maintain GH technology and how does this differ from existing RE technologies? 2 key themes were reviewed for data abstraction. • Technical skills required for RE sources. • Technical skills required for GH.	Interview1 (P1) • An emergence of a professionals equipped to handle such expertise must emerge alongside the technology. • This results in a longer time frame for the successful adoption and diffusion of the powerfuel. Interview 2 (P2) • A learning curve that has the potential to prolong the smooth transition to a fully operational GH economy. • The limited technical knowledge of professionals in relation to GH will hinder the successful emergence of the technology initially. Interview 3 (P3) No response	Source1: (World Bank Group, 2021,18- 21) • Solar and wind are less technically intensive than GH. • Creates a technical skill gap.	Sub-findings: Currently there are few professionals equipped to operate, build, and maintain GH plants. With the technology being fairly new, a new generation of skilled professionals still needs to emerge. The lack of these qualified professionals creates a technical skills gap which slows down the adoption and diffusion of the powerfuel .

Economic challenges 3 participants were interviewed. How does the high cost of GH slow down the adoption rate of the powerfuel? 3 key themes were reviewed for data abstraction. • RE cost • GH Cost • RE and GH cost trends	Interview1 (P1) • Future of GH is profitable; the current cost of the technology hinders its growth in the country as most investors are waiting for costs to go down and demand to go up. • Ultimately the need for more infrastructure slows down the process because funding becomes difficult to obtain, and implementing infrastructure that requires drastic changes requires a lengthy amount of time especially in comparison to existing RE requirements. Interview 2 (P2) • Current low demand results in an increased price of GH. Interview 3 (P3) • Scale - the cost of GH becomes expensive, and investors hesitate because large costs are a large risk. • The cost has slowed down the adoption of the technology and costs will eventually fall but they will do so slowly initially.	Source2: (Noussan et al, 2020) • A study investigating the cost of green hydrogen found that GH only becomes cost competitive with existing sources by 2030. • long-term, the cost of GH to alternate pathways no longer pose a threat. Source 3: *(Institute for Energy Economics and Financial Analysis, 202, p1-7)* • A similar trend was found with RE sources and GH. Source 4: (*Bloomberg NEF, 2022, p4-9.)* • The associated cost in terms of infrastructure and production of the technology is significantly higher than existing energy production technologies. • Cost of GH in the long term is predicted to decrease, but the full implementation of the powerfuel only becomes financially feasible by 2030.	Sub-findings With GH being an emerging technology, the cost is still high in comparison to existing RE sources and traditional fuel sources. However, as the adoption of GH becomes more widespread the cost is predicted to decrease and follow the same pattern of existing RE sources, - which shows that the cost of RE sources decreased over time and will continue to increase, thus making the powerfuel cost effective and competitive.
Resource challenges 3 participant was interviewed.	Interview 1 (P1)	Source1: *Rekacewicz at al, 2015, 1-4* • State of water crisis predicted to increase further by 2050.	Sub-findings South Africa's current water crisis poses a threat to the rate of adoption of GH in the

How does South Africa's water crisis affect the adoption of GH? 2 Key themes were reviewed for data abstraction. • Role of water in GH • Water crisis in South Africa	• South Africa's water crisis poses a threat to the entire uptake of green hydrogen technology. • Alternate technologies such as water desalination can be used to produce GH however SA is not yet equipped with the necessary tools and testing to fully utilize this option. Interview 2 and 3 (P2 & P3) No response	Source2: *United Nations University Institute for Water Environment and Health (UNU-INWEH), 2022, p1-4.* • Most African countries have water levels below the threshold considered for water security.	country. With the water crisis predicted to get worse, SA needs to investigate alternate methods of producing GH such as water desalination.
Policy and regulatory challenges 3 participants were interviewed. How does the evolution of policy position GH in SA? How do policies enable the use of GH? 1 Key theme was reviewed for data abstraction. • Limitations of current policy and regulatory framework	Interview 1 (P1) • Need to have policies embedded in national, regional, and local governments. • Assist private sector with hydrogen energy incentives and mentorship. • Align policies to ensure that electricity regulations promote and support GH production. • Lack of clear targets and strategies at a sector level. Interview 2 and 3 (P2 & P3) No response	Source 1: Hydrogen Strategy (2021, 12-19) • Infrastructure, socio-economic, financial and water barrier exists. • Need for incentives, regulation, and allocation of water resources to GH.	Sub-findings Various policies addressing GH and RE exist. However, they lack incentives and clear targets needed to ensure a successful transition to a GH economy. New policy and regulation need to be introduced that address these challenges and further promote adoption of the powerfuel.
Sub-findings on Sub-question 1 based on consolidation of sub-findings across the five key parameters.	• Infrastructure, socio-economic, financial, water scarcity, and policy and regulatory differences exist between GH and current RE sources. These differences need to be overcome in order for GH to successfully be implemented into the country. • Infrastructure barriers relate to storage and mobility available for GH. • The differences in technical skills required for RE vs GH create a learning curve that professionals are not equipped to handle. This results in the need for the emergence of new qualified and specialized professionals. Such a difference creates a barrier to the emergence of GH, which results in a slower rate of adoption of the powerfuel. • GH requires high capital investment cost and funds, such as development funds, available by the IDC are not prioritized for such projects. The inaccessibility to funds creates a barrier in funding GH project in the country. • GH is highly water intensive, and availability constraints coupled with water restrictions create a challenge in the adoption of GH. Alternative solutions such as the desalination of water to overcome these challenges must be investigated as a viable solution. • The absence of policy to alleviate the mentioned challenges creates a barrier. Existing policy must evolve to target specific differences and challenges and guide a successful adoption of GH in the country.		

4.3. Challenges facing Green Hydrogen implementation in South Africa

South Africa is widely considered a prime area for the adoption and diffusion of GH technology due to its extensive natural resources for RE generation especially from solar and wind energy. However, despite this vast opportunity, the country faces various challenges in the adoption and diffusion of GH technology. These challenges can be categorized around multiple parameters such as infrastructure and socio-economic differences, water resources, costs versus financing, policies, and regulations.

4.3.1. Infrastructure Related Differences

Existing RE sources require specific infrastructure to allow for the smooth operation of a system. The infrastructure requirements vary across each RE source. However, these have been widely and rapidly diffusing in the market for over three decades now. As an energy storage/medium rather than an energy resource by itself, GH requires more intensive infrastructure beyond what is required for conventional RE technologies. Given that such complementary technologies are still at prototyping stages, they are not yet readily available and equally related skills and expertise of designing, implementing, and operating/maintaining, are not yet in place.

Solar PV systems require the lowest levels of infrastructure investments. For commercial, industrial, and wheeling uses, the main demand is for large areas of land needed to hold the infrastructure. This land is chosen subject to peak radiation levels. From there, energy can be supplied to a pool through connection to the grid and subsequently distributed to different points of consumption. For connection to the grid, required infrastructure includes necessary substations, power conditioning equipment, safety equipment and meters, and other instrumentation (Office of Energy Efficiency and Renewable Energy, 2022). In the case of decentralized solar plants, adequate roof space of the required structural integrity must be provided, and if this requirement cannot be met, adequate land space for the system on site must be available. Due to the wide adoption of solar PV globally, additional infrastructure items such as the panels themselves, mounting and meters are widely produced and readily available at competitive prices, thus making solar-PV infrastructure easily accessible for expedited uptake. This demonstrates the fact that, as part of national GH system, scale-up solar-PV generation is unlikely to be a critical barrier.

Wind energy-related infrastructure requires large land areas with foundations strong enough to support the swaying wind turbines which can rise up to 100m or more (Steen et al., 2018). However, like solar, wind energy has seen rapid adoption globally, as well as in South Africa. This has made such infrastructure much more readily available at increasingly affordable costs. However, suitable areas for wind energy generation are relatively limited compared to areas suitable for solar-PV. In contrast, variability in wind energy generation is less compared to solar-PV because suitable areas have more stable wind patterns in terms of direction and speed. Technology availability and affordability means that wind-energy technology costs are unlikely to be a major barrier to GH-adoption globally or in South Africa.

In comparison to RE technologies, GH has not yet been subject to rapid adoption as it is still an emerging technology which is yet to be widely tested and adopted. With very few fully operational GH plants in existence, related infrastructure remains inaccessible and expensive to procure in the open market. To create GH, energy produced from RE resources needs to go through electrolyzers where electricity splits water into hydrogen and oxygen, thus converting it into hydrogen. Electrolyzers themselves are currently scarce and expensive due to minimal demand in the market. They are at a stage where any order would call for custom made systems almost in a manner similar to prototyping. In addition, due to the low demand related cost are high, thus posing an additional barrier to the adoption of GH (see Section 4.3.3. for further details on costs and affordability barrier).

Secondly, storage systems are required for the hydrogen once it has been generated. Such storage mediums need to be robust enough to handle pressurized storage and transportation of GH safely. Even though many industry experts argue that existing pipelines used for natural gas can, to an extent, be used for GH, their storage capacity is limited. Additional pipelines and alternatives such as salt caverns are required for the long-term storage of GH. However, these require large areas of underground space, which call for a lengthy process of building and testing before they can be used. Without such additional infrastructure, levels of GH production will remain constrained thus hindering the country's emergence into a GH economy. Inability to have immediate access to such infrastructure thus creates a barrier in the timeline towards adoption and diffusion of GH in South Africa.

Finally, high portability of GH requires additional infrastructure to ensure the country is equipped to transport the powerfuel both in-house (nationally) and for export. The export of GH is critical in establishing South Africa as a leading GH economy. In order to transport GH, the necessary roads, rail, ports, and sea tankers need to be available and equipped to allow for the safe and smooth transportation of the powerfuel. Thus, GH plants need to be strategically located in areas with easy access to main roads, railways, and ports. Even though there are select areas such as Atlantis in Western Cape where this infrastructure already exists, widespread adoption of GH will require new roads, railways, and port facilities to ensure more adequate and safe infrastructure for transport/handling of the powerfuel.

4.3.2. Socio-economic Related Differences – The Skills Gap

Production, handling, and transport of GH is an emerging sector. In an interview conducted with an industry professional, he claims that there are no qualified professionals locally who can build, "monitor, and operate integrated fuel cells and hydrogen systems". Technical skills required for GH surpass those required for existing RE technologies. This difference creates a barrier to the rapid adoption of GH in South Africa.

With any technology, new or existing, a certain level of technical skill and understanding is required to design, operate, and maintain the technology. The higher the availability of the skills, the more readily adoptable a technology becomes, and its applications in the market can evolve and advance. Compared to solar-PV and wind, technical skills for designing GH systems are far more complex. Solar and wind systems are energy producers, they are essentially limited to their own system, but a GH system is a storage medium which relies on external systems to generate the initial energy to be converted into GH for storage. RE systems supply electricity required by electrolyzers, which convert water into storable hydrogen. The technical skills needed involve all three of these systems, how they play into each other, and the additional skills of running a GH plant itself. Given that, unlike solar or wind, hydrogen in general is an unstable chemical, when dealing with GH, an individual or entity needs to be fully equipped with a wide range of knowledge to properly apply the technology, especially during the transitioning stages towards a GH economy. The current difference in knowledge and lack of qualified professionals with the necessary experience and capabilities can only be addressed through a new generation of experts which in turn will lead to a longer time frame for the successful adoption and diffusion of the powerfuel.

4.3.3. Cost Related Constraints

With GH systems being an emerging technology, capital outlay required to procure the technology far exceeds prevailing costs of RE technologies. As a result, the South African economy has not yet reached a stage where the cost of GH is affordable in the market at a scale which would warrant the investment. An energy expert who has worked in the renewable energy field for over 35-years states that although the future of GH is profitable, the current cost of the technology hinders its growth. As a result, most investors are waiting for costs to go down in order for demand to rise to a level which would catalyse investors. This poses critical uncertainties on timelines for GH adoption and diffusion despite prevailing interest in the power fuel.

Current market prices suggest that GH has an estimated energy equivalent cost ranging from US$250 to US$400 per barrel of oil at the factory gate (International Renewable Energy Agency, 2021, 3).Whereas future cost reductions are forecast envisaged levels and rates of reduction are uncertain. At current oil prices of around $100 a barrel, this indicates GH-equivalent is over four times the cost. In an attempt to illustrate the current financial challenges faced by GH, a study was conducted to illustrate the cost differences between blue hydrogen (produced from coal and gas) and GH. The study found that the cost of GH can be expected to become competitive compared to conventional energy sources possibly by 2030 (Noussan et al., 2020, 298). Figure 4.1 illustrates the global average cost of GH in relation to alternative options.

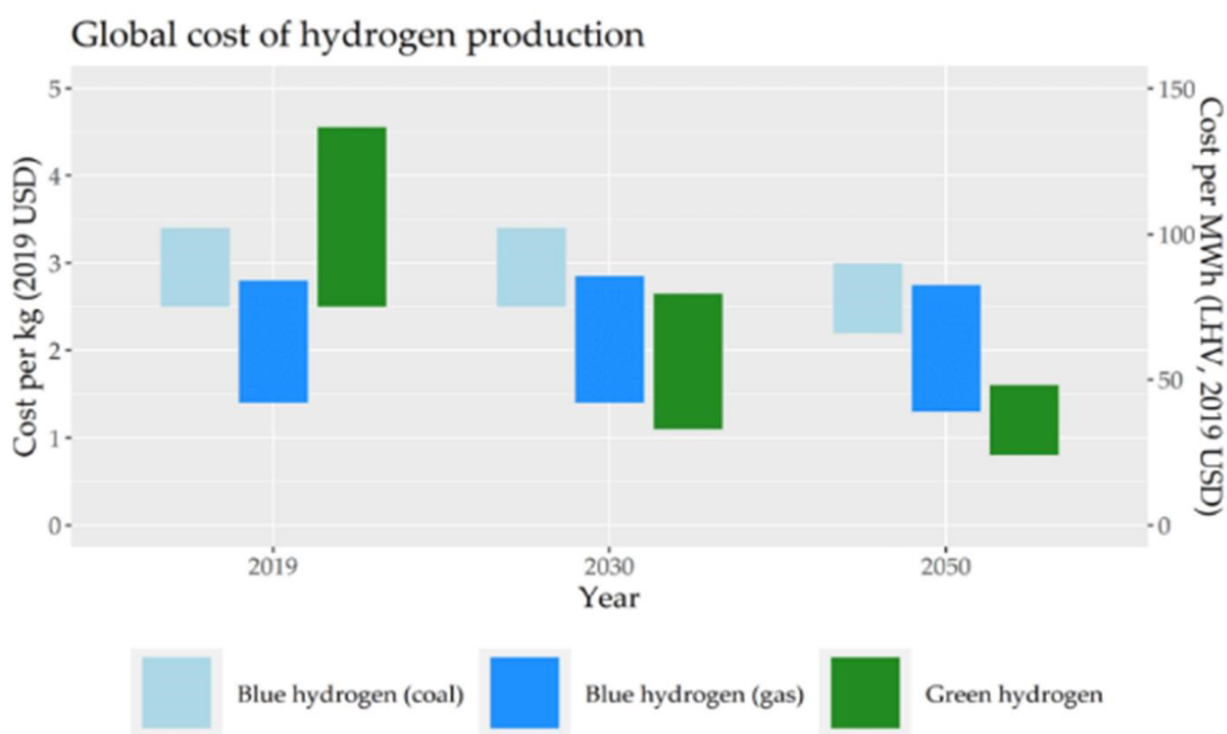

Figure 4.1: Current and future hydrogen costs for different pathways. Source: Noussan et al., 2020,102

In the long-term, the cost of GH in comparison to alternate hydrogen pathways will no longer pose a critical threat from 2030 onwards. However, for the immediate adoption of GH, the associated high cost hinders investment in the technology. As they initially emerged, A similar trend initially prevailed for RE technologies till their adoption became more widespread and as a result their related costs significantly decreased (see Figure 4.2). As illustrated in Figure 4.3, prevailing costs of RE technologies have now fallen far below conventional energy technologies and the same is predicted for GH within the next 10 years.

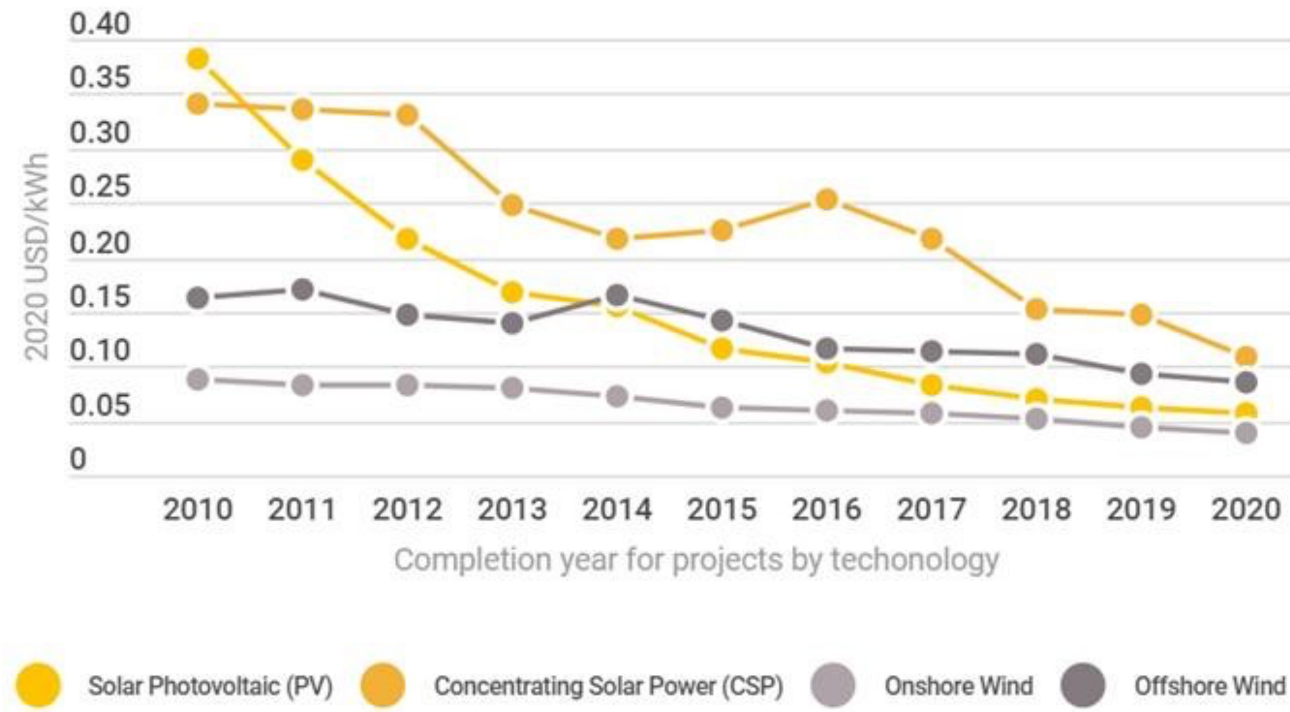

Figure 4.2: The declining cost of RE technologies between 2010 and 2020. Source: Institute for Energy Economics and Financial Analysis, 2021, 2

Given the additional costs related to GH, there is still a large need for new infrastructure development before a complete transition into a GH economy can occur. With GH being infrastructure-heavy and requiring expensive infrastructure, the initial cost of this must be considered as well. An energy expert goes on to say, since GH is not yet cost-effective, prevailing investment in the technology is far less than it is for RE technologies. Ultimately the need for more infrastructure slows down the process because funding becomes a critical constraint while implementing infrastructure that requires drastic changes takes much longer than, say, securing funding for a piece of land. Equipping the country with the necessary infrastructure requires a large sum of money and a long period of time. The full adoption will therefore take much longer, especially in comparison to wind and solar. However, as Figure 4.3 illustrates, the same market adoption and cost-decline trends are likely to prevail.

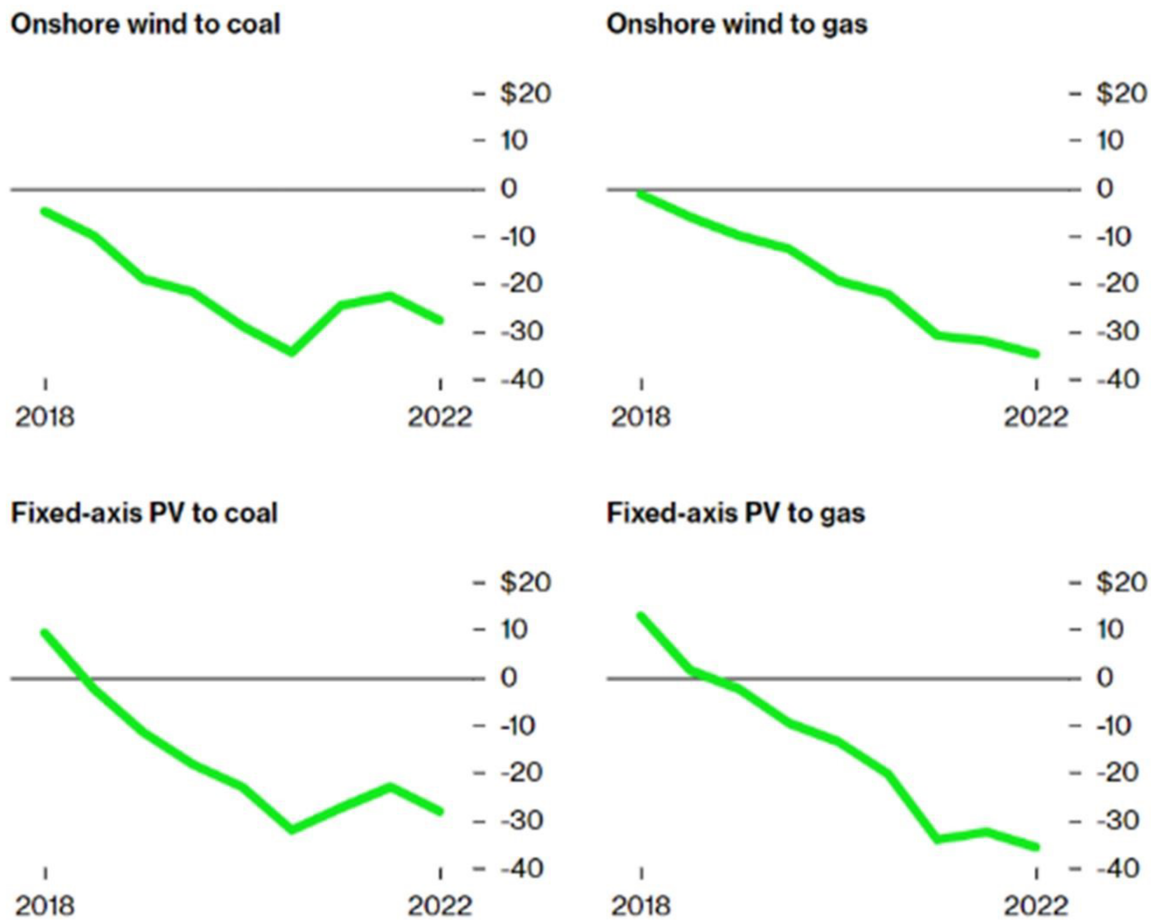

Figure 4.3: Difference between solar and wind, and coal-and gas fired energy. Source: BloombergNEF, 2022,19

4.3.4. Water resource scarcity

In order for electricity from existing RE sources to be converted into GH, water is used to drive an electrolysis process which splits water into hydrogen and oxygen. This translates into a highly water intensive process. South Africa is currently facing a water crisis with water shortages already being experienced across the country especially over the last decade. This increasing intensity of water scarcity which is also a critical resource for GH production poses an additional threat to the adoption and diffusion of GH technology.

A senior mechanical engineer working in the RE field responded that the South African water crisis poses a threat to the entire uptake of GH technology. He further responded that although there are various ways that GH can be generated without using water, South Africa is nowhere close to understanding, let alone implementing, such alternative technologies. In addition, such alternatives are at a lower level of development globally (mostly at a theoretical stage) and not yet as widely tried and tested as the electrolysis process. However, the desalination of water should be considered as a potential solution to the current water resource barrier. Desalination of sea water is "the process of removing salt and other impurities from sea water in order to produce drinkable clean water" (Water corporation, 2022, 3). A number of seawater desalination technologies have been developed during the last several decades to augment the supply of water in arid regions of the world (Water corporation, 2022, 4). Due to the constraints of high desalination costs, many countries are unable to afford these technologies as a freshwater resource.

However, the steady increase in usage of seawater desalination has demonstrated that seawater desalination is a feasible water resource free from the variations in rainfall. A seawater desalination process "separates saline seawater into two streams: a freshwater stream containing a low concentration of dissolved salts and a concentrated brine stream" (Water corporation, 2022, 4). The process requires some form of energy to desalinate and utilizes several different technologies for separation. Given that this process requires sea water, this solution is particularly favorable to coastal regions. The water crisis currently facing South Africa is only predicted to increase. Given that the water crisis is predicted to intensify in the future, Figure 4.4 illustrates the envisaged state by 2050 thus indicating that South Africa is predicted to remain in a high-stress status both in the short and long-term (Rekacewicz et al., 2015, 2). An additional study conducted by United Nations University Institute for Water Environment and Health (UNU-INWEH, 2022) applied indicators to quantify water security in African countries. Study findings indicate that only 13 out of 54 countries reached a modest level of water security in recent years while a further 19 countries are deemed to have levels of water security below the threshold of 45 on a scale of 1 to 100.

Thus, the current and predicted water crisis in South Africa coupled with on and off-water restrictions implemented within the country, pose a severe threat to the rate of GH adoption in the country. For GH to be successfully implemented in South Africa, external factors such as the water crisis need to be addressed and alternative solutions for providing water need to be further investigated. Additionally, early research into alternative technologies of producing hydrogen which is less water-intensive needs to be pursued if South Africa aspires to remain a front-runner in GH and create a leading GH economy.

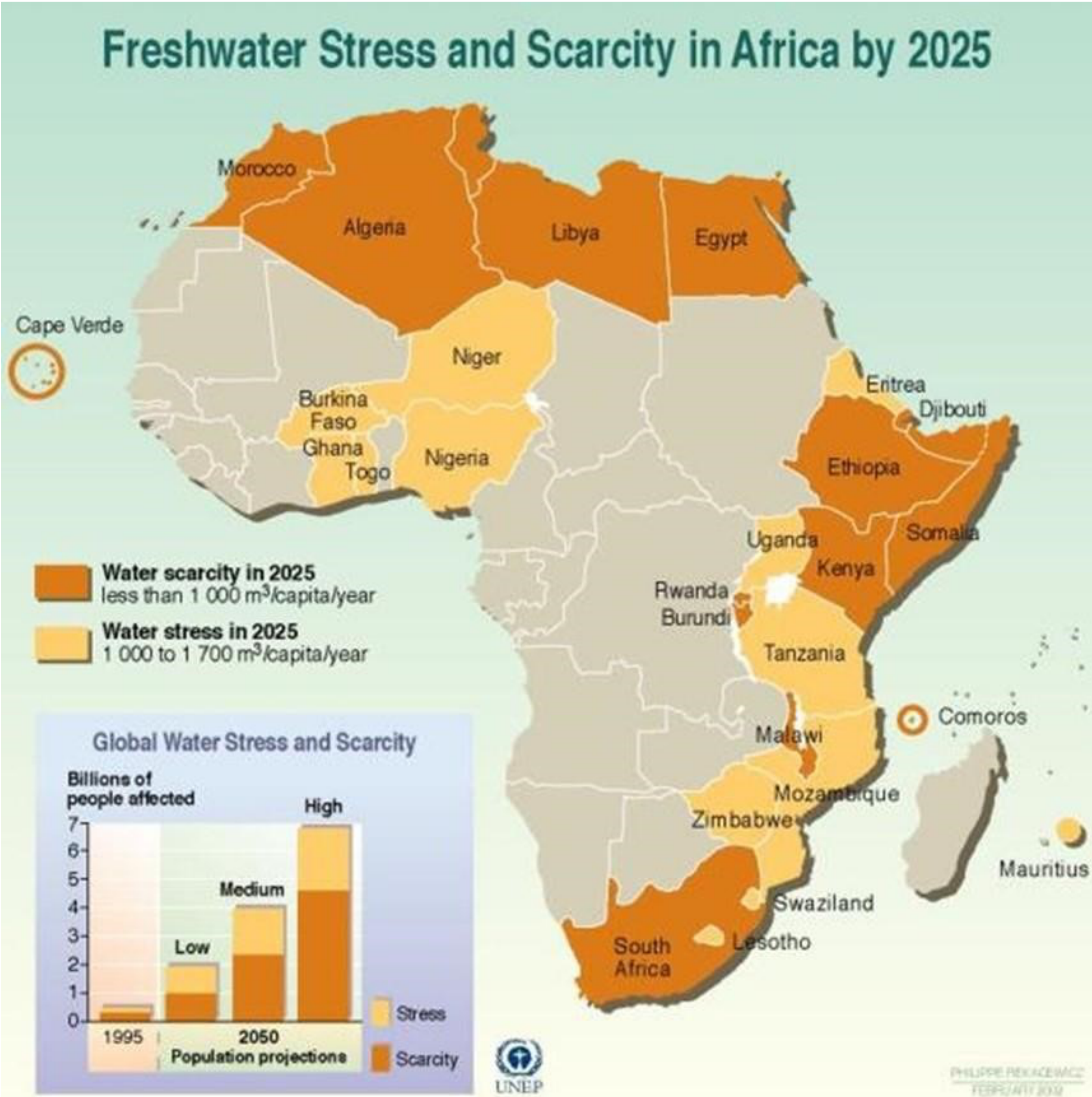

Figure 4.4: Map illustrating the predicted water stress and scarcity across Africa in 2050. Source: Rekacewicz at al, 2015,2

4.3.5. Policy and related regulatory barriers.

South Africa has put various policies in place to facilitate tapping into the opportunities in RE and GH for related socio-economic and climate-change mitigation benefits. These policies include White Paper on Renewable Energy Policy (2003), The South African Hydrogen Society Roadmap, and the Integrated

Resource Plan. Although these policies have been implemented to facilitate the adoption of renewable energy technologies and green hydrogen, there are various factors that create barriers to the uptake of the powerfuel that have not been systematically addressed in these existing policies so far. As summarized in Table 4.2 the key policy gaps relate to infrastructure, socio-economic, financial, and resource considerations.

In addition to these challenges that can be addressed through policies, additional barriers also exist that must be considered for the smooth transition into a GH economy. Firstly, there is a need to have policies embedded in national, regional, and local governments to guide future expectations of GH in South Africa. In particular, this would translate into establishing the role of GH within the country's long-term energy strategy. Secondly, new entrants or firms that express interest in GH generation supply, distribution, and infrastructural development projects usually bear the highest risk at the deployment stage, especially those in the private sector. There is therefore a need to incentivise private sector investors with GH-economy mentorship, incentivize loans, provide guarantees, and tax rebates on project developments as was initially done for RE-technologies.

There is also a need to align policies to ensure that electricity regulations facilitate GH production. This can be done by establishing the role of GH within long-term energy strategies. Currently, there is a lack of clear targets and strategies at a sector level, implying a lack of guarantees for future demand for GH production this inhibits deployment of GH at a GW (gigawatt) scale. In addition, there is a lack of clarity on the permitting procedure for GH (as opposed to RE technologies) coupled with existing cumbersome regulations, including EIA. Existing policies also do not address issues of storage, safety, and transportation. As such, GH regulations around technical, safety, and commercial operation standards as well as transport and storage hazards need urgent development.

Amendments to existing policy measures will be required to 'jump-start' the GH economy to a point where normal market forces take over and such an economy becomes self-sustaining. South African legislation will require significant development to address the gaps in the current regulatory framework if the introduction and development of a GH society are to be achievable. In particular, the regulations should cover the entire GH value chain to ensure safety and security in production, storage, distribution, and transport, as well as end-user application

Table 4 2: Barriers that need to be addressed in relation to key parameters affecting the uptake of GH in South Africa (HSRM, 2021)

Infrastructure	Socio-economic	Financial	Water Resource
• Align policies to ensure that electricity regulations facilitate promotion of GH development. • Incentivise higher electrolyzes manufacturing capacity to rapidly scale GH economy. • Attend to missing GH transport and storage regulation around technical, safety, and commercial standards to address GH transport and storage hazards.	• Facilitate incentives to secure professionals with the technical skills needed for GH. • Facilitate academic incentives at tertiary level to ensure emergence of a qualified generation to support GH technology and economy in general.	• High electricity CAPEX for new RES: despite solar energy reducing by around 30% in 2030, green electricity production remains capital intensive and comprises 50% of hydrogen production costs in the South African Hydrogen Valley. • High electrolyzes costs: The predicted electrolyzes costs will decrease by 60% between today and 2030, and yet their cost remains high, with production costs of GH heavily depending on the investment cost of the electrolyzes.	• Challenges with water access and licenses: the process remains difficult and lengthy. • No allocation of water resources to RE technology that secures water supply. • Cost and related factors that hinder the use of desalinated water as a solution to the water challenges facing GH.

4.4. Key sub-findings and conclusions

Key sub-findings are related to the barriers that exist in the adoption and diffusion of GH in South Africa due to the differences that exist between current established RE sources (Wind and Solar) and GH, and the differences in what is needed for each. These differences were considered in terms of five key parameters being infrastructure, socio-economic, economic, water scarcity, and policy and regulatory barriers. Key challenges/barriers exist mainly because GH is still an emerging technology that has not been widely tested or adopted. The differences between RE and GH results in various infrastructure and socioeconomic barriers. Infrastructure barriers relate to absence of storage infrastructure for GH such as salt caverns as well as transport infrastructure such as pipelines, roads, and port facilities. This is since existing RE sources do not require this sort of infrastructure as they are not mobile.

There is a major learning curve that exists in terms of understanding and technical competence that goes into creating GH, and with it being an emerging technology, professionals with these skills sets are scarce. Current professionals proficient in RE sources hold some foundational skills relevant to GH and thus hold the ability to learn the new relevant skills, but this will still take time as RE sources differ from GH in various ways, the main one being that they are a storage medium and not a generational plant. With GH being an emerging technology, GH requires high capital investment cost and funds are not prioritized in South Africa as the county has other development priorities. The inaccessibility to funds creates a barrier in the uptake of projects and investigation into GH itself and prevents the country from emerging into a GH economy. As it currently stands the price of coal is still cheap and GH is not at a point where it can be cost competitive soon. This is a result of various barriers as appraised in this chapter. However, it was established that GH is predicted to trend in the same manner as RE sources (wind and solar) and the cost of GH can be expected to become cost effective in roughly 10 years.

South Africa's water crisis also creates a key barrier in the adoption of GH given the fact that it is water intensive. Water availability coupled with ongoing restrictions pose a threat to the adoption of GH. Without a secured source or allocation of water for the technology it creates uncertainties on long-term availability if GH-demand rises. Water challenges can potentially be overcome by investigating technologies for desalination of sea water and related factors such as cost. Whereas this study does not investigate the feasibility of desalination of sea water, it has highlighted it as a potential solution for water resource barrier. More systematic studies therefore need to be conducted to determine the feasibility and effectiveness of this solution.

Finally, the absence of policy and regulatory framework to address these challenges creates a key barrier in the uptake of GH. The absence of policy responses towards the diverse challenges creates a barrier because the steps needed to enable adoption and diffusion of GH are not in place yet. Existing policy must evolve to target specific differences and challenges and thus guide a successful adoption of GH in the country.

5. Status and planned pathways for GH adoption and diffusion in South Africa

5.1. Introduction

This chapter presents data abstracted from both primary and secondary data sources to address Sub-question 2 on the status and planned pathways of the adoption and diffusion of GH in South Africa. Analysis of the data provides insights on the four key parameters of the sub-question. These are the key GH projects currently being implemented in SA, current and planned investments being made into GH in SA, the steps that can be taken to further promote the use of GH in SA, and existing policy and regulatory framework towards promoting the adoption and diffusion of GH in SA. Sub-findings in response to the sub-question are consolidated in terms of these four parameters.

This chapter is presented in three parts in accordance with the key parameters. The first part explores the status of GH in SA. To understand the status of GH, we must first consider key current and future projects in the country alongside key investments in GH. The second part focuses on key steps that can be taken to further promote the adoption of GH. Finally, part three focuses on key policy and regulatory frameworks that could enable the adoption of GH both directly and indirectly via RE. Data analysis and derivation of sub-findings on the status and planned pathways for the adoption and diffusion of GH in South Africa have been presented as the concluding section of the chapter.

5.2. Data Overview

Data were collected through primary and secondary data. Primary data were collected by interviewing three participants who have worked in the energy and RE landscape for over 30 years. Secondary data were extracted from various policy documents, official reports, and journal articles guided based on the parameters set out for Sub-question 2. Table 5.1 summarizes the respective data parameters and related data sources. The data and related analyses were then used to derive sub-findings on the status and future pathways of GH in South Africa.

Table 5.1: Summary of Data Parameters and Data Sources for Sub-question 2

Key Parameters	Primary Data	Secondary Data:	Responsive Sub-findings:
Key GH projects that currently exist in SA 3 participants were interviewed. How do the Sasol-Toyota and GHV (green hydrogen valley) projects establish SA as a GH economy? 3 key themes were reviewed for data abstraction. • GH infrastructure and mobility • Hydrogen Corridors • GH Application and economic activity	Interview1 (P1) • Promotes cheap production of GH. • Creates local and international partnerships. • Positions SA as a GH economy. • Creates local expertise and competence in the GH economy.	Source 1: (Sasol, 2021) • Exploration and development of GH mobility in SA. • Expansion of mobility through the N3 freight-corridor. • Investigating and testing the use of GH vehicles.	Sub-finding 1: Toyota-Sasol joint venture is key in prototyping the use of GH in the mobility sector. Both this and the GHV enable SA as a leading GH economy and enables SA with the necessary skills and tools to maintain that status.
	Interview 2 (P2) • Sasol-Toyota is the foundation for large scale adoption of GH. • Creates attention and interest in GH. • GHV is key for transitioning to a GH economy.	Source 2: (Bowden,2021) • Feasibility of implementing GH filling stations in SA.	Sub-finding 2 Toyota-Sasol project will also consider GH fuel stations to power GH motor vehicles. This venture is foundation for the adoption of GH whereas the GHV is critical for the transition to a GH economy.
	Interview 3 (P3) • Sasol-Toyota venture is critical for the adoption of GH in SA. • GHV establishes a roadmap for GH in SA. • Addresses GH related challenges. .	Source 3: (Whyte, 2022) • GHV develops catalytic hydrogen hubs and establishes GH corridors in SA. • Potential for foreign investments.	Sub-finding 3: GHV established critical hubs that are specifically positioned to encourage foreign trade and investments and position SA as a leading GH economy. The GHV also attempts to combat many GH challenges.
Current and planned investments being made into GH in SA 3 participants were interviewed. SA Future plans and investments in GH 3 key themes were reviewed for data abstraction. • GH fuel cells • Foreign partnerships • Research and development within GH industry	Interview1(P2) • Investments mainly into research. • Sasol announcement of GH infrastructure. Interview 2 & 3 (P2 & P3) No response	Source 1: (Whyte,2022) • Hydrogen fuel cells to replace diesel generators. • Creation of strategic international partnerships.	Sub-finding 1: Partnerships with international countries for the export and generation of GH are beings explored to ensure a successful GH economy.
		Source 2: (Sasol,2022) • Development of GH infrastructure nationwide for future low-cost GH.	Sub-finding 2: Sasol has invested in developing GH infrastructure around the country in preparation for new GH products and the shift towards a GH economy.
		Source 3: (Nzimande, 2021) • Research, development, and innovation to decrease GH related costs.	Sub-finding 3: To ensure the widespread adoption of GH investments are being made into research and innovation surrounding GH to create low-cost and more efficient GH.
The steps that can be taken to further promote the use of GH in SA 3 participants were interviewed. What steps can be taken to further promote the use of GH in SA?	Interview1 (P1) • Net-zero initiatives • Providing incentives for capital expenditure on GH infrastructure. • Improve regulation to speed up infrastructure. • Government guaranteed funding for GH initiatives preferential interest rates and easier terms for borrowing. • Government can provide incentives for foreign trade foreign investment in GH in SA.	Source 1: (ACWA,2022) • SA Net zero 2050 target relies on GH. • Dubai-SA partnership to accelerate GH economy in SA. • IDC signed MoU for development of GH.	Sub-finding 1: To further promote the adoption of GH in SA factors such as cost, net-zero, tax incentives and foreign investments must become tools for enhancing the adoption of GH. Certain of these factors such as foreign trade incentives and government financial institutions supporting the development of GH are currently in motion.

4 key themes were reviewed for data abstraction. • SA Net-Zero 2050 Goal • Capital Expenditure • Government Funding • Foreign Investments	Interview 2 (P2) • Widespread investment into researching. • In-depth and specific policy concerning what is needed for GH in SA. • Investigating a way to decrease the cost of GH both in the present and the future. Interview 3 (P3) No Response	Source 2: (Green Building Africa, 2022) • 8 REDZ's subject to basic EIA assessments not full reports. • Fast track RE projects.	Sub-finding 2: Additional research into the use of GH as well as offsetting the cost is necessary to further promote GH. Like REDZs, EIAs for GH need to be fast tracked to increase adoption rate.
Policy and regulatory framework that exist to promote the adoption and diffusion of GH in SA 3 participants were interviewed How does the evolution of policy position GH in SA? How do policies enable the use of GH? 4 Key themes were reviewed for data abstraction. • RE Generation • Re development • GH Generation • RE Policy evolution	Interview 1 (P1) • Policy still needs to evolve to include GH adoption incentives. • Encourage spin-off industries. • RE policy promotes cheaper production of GH.	Source 1: (Department of Minerals and Energy, 2004) • White Paper Policy on RE. • Promotion of RE technologies.	Sub-finding 1: Policy regarding RE still needs to evolve to specifically promote the adoption of GH. The White Paper on Renewable Energy of 2003 laid the foundation for promoting renewable energy technologies
	Interview 2 (P2) • Promote RE generation both in the public and private sector. • Removes major generation boundaries. • Allows for more base-load power from RE sources.	Source 2: (Department of Minerals and Energy, 2018) • Integrated Resource Plan. • Transition to low carbon economy. • RE Generation through IPPs and public Entities.	Sub-finding 2: The IRP is essentially an electricity capacity plan with how electricity demand is to be addressed. This is critical in adopting GH as the plan can set out a certain level of energy generation from specific RE sources, ensuring that these sources are available for adopting GH.
	Interview 3 (P3) • Policy aims at increasing RE generation. • RE is essential for GH production. • Roadmaps and frameworks such as the HSRM (hydrogen society roadmap) allow for easier adoption of GH.	Source 3: (Departments of Mineral and Energy, 2021) • REIPPPP • Enhance country's generation capacity. • Contribute to broader national development objectives.	Sub-finding 3: REIPPP enables the adoption of GH by promoting RE Sourcing by allowing IPPs to participate in tenders. The amendment of generation capacity further facilitates this.
		Source 4: (Department of Science and Innovation,2022) • HSRM • Navigation of GH in SA.	Sub-finding 4 HSRM is a crucial step towards enabling a hydrogen economy in South Africa. The policy gives the necessary foundations to create a policy framework surrounding green hydrogen, outlines goals attracting investment into hydrogen projects, and brings awareness to the benefits and potential of green hydrogen in South Africa.

Key Sub-findings on Subquestion 2 based on consolidation of sub-findings across the four parameters	• Current projects such as Sasol-Toyota and GHV position SA and a leading GH economy. • Current and planned investments in GH infrastructure, development and innovation exist to ensure a sustainable GH economy. • Further initiatives regarding polices, tax-incentives, and foreign partnerships need to be put in place to promote the use of GH in SA. • Current policy focuses on enabling the production of RE which allows for the cheap production of GH. • Further policy needs to be developed to enable successful and sustainable adoption of GH in SA.

5.3. The Status and Planned Pathways for GH in South Africa

GH is produced from renewable energy sources such as wind and solar energy. GH is portable and thus offers export potential of the powerfuel and transportation within the country from generation sites to where it is needed. Additionally, GH can be used across industrial, agricultural, and transportation sectors. In view of its envisaged role towards zero-carbon economy society for SA and globally, further steps need to be taken to promote the adoption and diffusion of GH in South Africa.

5.3.1. Key GH Projects in South Africa

South Africa is currently pursuing two major GH projects. The first one was announced in April 2021 as a joint venture between Sasol and Toyota (Sasol, 2021). The venture focuses on the implementation of GH in the automotive sector. The second is the formation of South Africa's GHV (green hydrogen valley) which was announced in October 2021 (Department of Science and Innovation, 2021).

In April 2021, Sasol and Toyota Africa Motors (TSAM) announced a joint venture focusing on exploration and development of GH mobility ecosystems in South Africa (Sasol, 2021). This venture intends to develop a mobility corridor and expand the demonstration to a pilot project using one of South Africa's main freight corridors, such as the N3, for hydrogen-powered heavy-duty long haul freight vehicles (ibid). Further, this venture will also investigate feasibility of implementing hydrogen refueling stations in South Africa (Bowden and Kassier, 2021). "To unlock green hydrogen opportunities, we are pursuing various demonstration opportunities and partnerships, as with Toyota, with the intent of enabling and taking advantage of technology developments and breakthroughs" said Fleetwood Grobler, CEO and President of Sasol (2021, 6).

Grobler stated that one of the focus areas for Sasol in South Africa is to provide a comprehensive and sustainable mobility solution. Hydrogen and electric vehicles with refueling and charging infrastructure form part of this sustainable future. Grobler (2021, 7) further states that "we believe hydrogen mobility is a real opportunity for the country to decarbonize the sectors of long-haul and heavy-duty transport, mining, and others and see the creation of hydrogen hubs, or ecosystems, as a practical and affordable way to scale the deployment of hydrogen in the transport sector." Sasol's joint venture with Toyota aims to create end-to end infrastructure specifically for the mobility of GH in South Africa (ibid).

The joint investment venture of Sasol and Toyota not only paves the way for new interest and investment in GH projects in South Africa but also sets a guideline for future projects within the automotive industry. The venture also instills confidence in the country's potential and adoption of green hydrogen. This project is a critical starting point for the large-scale emergence of the technology in the country. With Sasol being a significant contributor to the industry and especially with it being so widely recognizable alongside Toyota, it is likely to stimulate more confidence in the technology.

The second and most critical GH project active in South Africa is the Green Hydrogen Valley (GHV). Also referred to as The Platinum Valley Initiative (PVI). South Africa's GHV was launched to develop catalytic GH hubs which would then constitute a "Hydrogen Corridor" (Whyte, 2022, 2). The PVI will support the increase in hydrogen consumption via the introduction of heavy-duty fuel-cells and contribute to a just energy transition, the facilitation of job creation, and an increase in GDP (ibid).

The hydrogen valley is expected to serve as an industrial cluster, bringing various hydrogen applications in the country together to form an integrated hydrogen ecosystem. Natascha Viljoen, CEO of Anglo American's PGMs business (2022), states that "the opportunity to create new engines of economic activity through hydrogen has been validated through this feasibility study with our partners" (Amplats, 2022, 4). These include investing in innovative ventures, enabling technologies, and forging wide-ranging collaborations across the industry to fully harness the transformative potential of GH for South Africa's economy.

The GHV is structured around the convergence of three hydrogen hubs (Johannesburg, Durban and Richards Bay, and Mogalakwena and Limpopo). The hubs were prioritized based on the high potential of GH supply and potential towards facilitating just energy transition. Within these hubs, various proposed GH projects relate to the infrastructure, demand and supply, and transportation of GH. GHV also addresses GH's water-related challenges by considering investments in water infrastructure that could mitigate prevailing water supply risks. Policies such as the REIPPP and IRP enable the GHV further. Associated limitations of these policies relative to GH are addressed in the GHV. These policies will be analyzed in further detail in part five of this chapter.

The feasibility study identifies nine hydrogen-related projects across the mobility, industrial, and construction sectors that could be used as a springboard for establishing the hydrogen valley. One of these nine projects will focus on converting heavy-duty diesel-powered trucks to fuel cell-powered trucks in support of increased hydrogen consumption in the transportation sector. The projects will also facilitate commercialization of publicly funded intellectual property while contributing to the beneficiation of PGMs in targeted geographic areas.

Therefore, establishing a South African hydrogen valley is seen as an opportunity that has great potential to unlock growth, revitalize the industrial sector, and position South Africa as an exporter of cost-effective GH globally. The hydrogen valley will be used to establish, accelerate, and embed niche innovations through upscaling and replication. These include investing in innovative ventures, enabling technologies, and forging wide-ranging collaborations across industries to fully harness the transformative potential of GH for the South African economy. The GHV will kick-start the country's hydrogen economy, bring significant public awareness around renewable energy solutions, and contribute significantly to the national and provincial objectives for new investments, jobs, renewable energy sources, and export markets. South Africa is well-positioned to be part of the local and international needs for the hydrogen economy. This initiative thus underpins a growth market for the South African economy.

5.3.2. The Future of GH in South Africa – Current and planned investments in GH

South Africa has invested in and planned various GH projects. Although most are on a much smaller scale than previously mentioned, they are still crucial in creating a GH economy for the country.

First, South African government recently noted that installing hydrogen fuel cells to power data centres to replace the currently used diesel power generators, is under consideration for the Limpopo Science and Technology Park. In addition, earlier this year, plans were announced to develop a green ammonia plant in Nelson Mandela Bay by 2025 (Whyte, 2022).

In response to the future of GH in South Africa, Nzimande (2021, 6) states that as a country, "we will put strategic international partnerships, especially with countries looking to import and trade in the global hydrogen value chain. We will also ensure that our local universities and private sector are given an opportunity to play a pivotal part in the green hydrogen economy. Our research, development, and innovation will be critical to ensure that the cost of electrolyzer technology is reduced and that green hydrogen and power fuels production is scaled up to bring the price of the commodity at parity with grey hydrogen."

Sasol has also announced that they have invested in building GH infrastructure around the country to facilitate GH adoption. Sasol expects to have multiple fully functional GH plants by 2050. Industry professionals believe the adoption of GH will pick up within the next 5-10 years especially considering the rapid rate at which RE is expanding and electrolyzer technology is evolving, and the energy crisis in SA is intensifying. The future of GH in South Africa is already underway.

This is being pursued through a mix of energy and process efficiencies, investments in renewables, and a shift to incremental natural gas as a transition feedstock for the South African value chain. Large contributors to the GH landscape such as Sasol have more than one viable pathway to get to its net zero ambition by 2050, with different options to transform its South African value chain by progressively shifting its feedstock away from coal, towards more transition gas, and then, GH over the longer term. As economics improve for these options, South Africa holds significant promise for renewables and low-cost GH production for own use and export opportunities.

5.4. Key Policy and Regulatory Framework Regarding Green Hydrogen in South Africa

The adoption and diffusion of GH is primarily facilitated by enabling policy and regulatory framework. Various legal frameworks exist that address the facilitation of RE coupled with a few frameworks that directly address GH. Key policies and regulatory frameworks are presented and analyzed in this section These include the White Paper Policy on Renewable Energy, Integrated Resource Plan (IRP), the South African Hydrogen Society Road Map (HSRM), and REIPPPP. Table 5.2 summarizes the above key policies in addition to other policies concerning GH in South Africa.

Table 5.2: Link between existing policies and GH adoption in South Africa (Green Hydrogen Valley Report, 2021)

Policy	Link to Green Hydrogen
White Paper on Renewable Energy Policy (2003)	Increased RE contribution to the energy mix, which requires support from energy storage technologies.
HySA Strategy (2007)	Supports the development of hydrogen and fuel-cell technologies through the 15-year Hydrogen South Africa RDI Programme.
National Energy Efficiency Strategy (2008)	Supports the development and deployment of energy-efficient technologies.
Beneficiation strategy for minerals industry of South Africa (2011)	Supports the development of technologies that beneficiate the country's mineral resources locally for increased revenue.
Department of Public Works and Infrastructure Green Building Policy (2018)	Given their low-carbon footprint, hydrogen fuel cells are a viable option for deployment in public buildings and to power critical infrastructure.
Green Transport Strategy for South Africa (2018)	Advocates for the deployment of electric vehicles, including hydrogen fuel-cell powered vehicles, as a means for decarbonizing the transport sector.
Integrated Resource Plan (2019)	Increased contribution of RE in the energy mix would require hydrogen for optimal usage and long-term storage.
National Development Plan 2030	Advocates for the transition to a low-carbon and diversified energy system.

5.4.1. White Paper Policy on Renewable Energy

The White Paper Policy on Renewable Energy of 2003 laid the foundation for promoting renewable energy technologies such as solar, hydro, biomass, and wind. The key objectives of the White Paper on Renewable Energy of 2003 were as follows (Department of Minerals and Energy, 2004):

- Ensure that an equitable level of national resources was invested in renewable technologies.
- Direct public resources to the implementation of renewable energy technologies.
- Introduce suitable fiscal incentives for renewable energy.
- Create an investment climate for the development of the renewable energy sector.

5.4.2. Integrated Resource Plan (IRP)

In line with the country's goal to transition to a low-carbon economy, the Integrated Resource Plan (IRP 2010) set a target of 17 800 MW of renewable energy to be achieved by 2030. Under this plan, 5000 MW were planned to be operational by 2019, with a further 2000 MW expected to come online by 2020. Implementation of the IRP 2010 is carried out through Ministerial Determinations, which are regulated by the Electricity Regulations on New Generation Capacity based on the Electricity Regulations Act No. 4 of 2006 (Government Gazette, 2006). Already in 2017, 6 422 MW of electricity had been procured from 112 Renewable Energy Independent Power Producers (IPPs) using the competitive bidding process known as bidding windows. Out of this total, 3 162 MW of electricity generation capacity from 57 IPP projects was connected to the national electricity grid by the end of June 2017 (Barret, 2021).

The IRP is essentially an electricity capacity plan focusing on how electricity demand is to be addressed. This is critical in adopting GH as the plan can set out a certain level of energy generation from specific RE resources, ensuring that these resources are increasingly tapped to supply required carbon-neutral electricity for production of GH. Further amendments can be made to allocate a specific energy capacity in the form of GH, thus securing supply for the powerfuel.

5.4.3. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP)

REIPPPP was established by the Department of Energy (DoE) in conjunction with the National Treasury and the Development Bank of Southern Africa (DBSA) at the end of 2010 (Department of Minerals and Energy, 2021). The REIPPPP is one of South Africa's attempts to enhance the country's power generation capacity. Its main objective is to secure private sector investment to develop new electricity generation capacity. Further, the REIPPPP has also been designed to contribute to broader national developmental objectives such as job creation, social upliftment, and economic transformation, primarily through broadening economic ownership.

The REIPPP enables the adoption of GH by promoting supply of RE through allowing IPPs to participate in generation and supply to the grid. The amendment of generation capacity for own consumption further enhances RE-supply for GH. According to the amendment, generation projects up to 100MW are now exempt from the protracted NERSA licensing requirements, thus making generation from RE resources easier and the potential of GH generation more accessible.

5.4.4. The South African Hydrogen Society Roadmap (HSRM)

In February 2022, the South African Hydrogen Society Roadmap (HSRM) was published by the South African Department of Science and Innovation, thus marking an important milestone in the launch of South Africa's hydrogen economy. The roadmap was published to act as a navigation system in the country's just energy transition.

The policy focuses on national ambitions, sector prioritization, overarching policy framework, and the macro-economic impact of the hydrogen economy throughout South Africa. The policy outlines several targets, including the creation of an export market for GH and ammonia, the implementation of a Center of Excellence in manufacturing hydrogen products, the development of domestic hydrogen supply chains, the production of 500 kilotons of GH by 2030, and a long-term target of 15 GW power generation based on hydrogen by 2040. Other targets include a one-megawatt small-scale electrolysis facility piloted by 2025 and the deployment of 10 GW electrolyzes in the Northern Cape, and 1.7 GW electrolyzes in the Hydrogen Valley by 2030 (Department of Science and Innovation, 2021).

This policy is a crucial step towards enabling a hydrogen economy in South Africa primarily because it gives the necessary foundations for a policy framework surrounding GH. It also outlines goals on attracting investment into hydrogen projects and raising awareness of the benefits and potential of GH in South Africa.

5.5. Steps to Further Promote the Adoption and Diffusion of Green Hydrogen in South Africa

To ensure the future of GH in South Africa, several key factors must be addressed in order to secure the adoption of the powerfuel. These factors range from policy enablers to pressure within the economy itself.

With carbon emissions being one of the biggest global issues currently, technologies like GH become crucial as they are considered to be net-zero carbon. The results of the increasing carbon emissions problem put pressure on companies who either produce carbon emissions or are associated with companies that produce carbon emissions. As the carbon issue becomes increasingly problematic, companies are left with no choice but to consider alternative forms of production, regardless of costs.

To increase the rate of GH adoption in the country, increasing pressure needs to be put on companies emitting high levels of CO2. This can be done in the form of carbon taxing. Carbon tax not only effects the primary producer, but the market and related off takers as well. So, in circumstances where increasing amounts of CO2 are being produced, for example in steel making, the carbon needs to be taxed. This will reduce the use of traditional fossil fuels and increase the adoption of alternate sources such as GH which would ensure transitioning to green steel. Thus, to drive the adoption of GH and secure the future of the powerfuel in country, pressure needs to be put on high carbon markets, especially from government.

In line with tax incentives are tax breaks that can be introduced for companies adopting GH. Given that there is currently a high capital cost associated with GH, many companies are reluctant to make the move over to the powerfuel. Thus, to incentivise the switch and cushion the higher capital costs for early adopters, tax incentives like tax breaks, or tax windows could be introduced. This is a concept that already exists with solar energy. So, to increase and secure the future of GH in South Africa, incentives for mitigating capital costs on GH technologies need to be implemented.

As a flexible energy source GH requires large-scale infrastructure development that takes time to implement. The development of new infrastructure is slowed down by capital cost as highlighted above as well as policies and regulations such as EIAs (environmental impact assessments). When building new infrastructure, one of the most protracted processes is the EIA approval process which thus makes the development of new infrastructure unattractive and costly. To combat this and promote the uptake of GH, the EIA process needs to be fast-tracked. Government has approved that in 8 different REDZ's environmental impact assessments can be fast tracked by only requiring basic EIA assessments and not full reports, thus shortening the process (Green Building Africa, 2022). The same incentives, and policy need to be applied to GH projects to increase the rate of adoption and promote the use of GH.

In terms of the high associated cost of GH, funds need to be made not only available, but guaranteed. Government entities such as the IDC and DBSA need to guarantee funds and incentive interest rates that secure the adoption of GH in the country. This can be done by providing lower interest rates and higher levels of approved loan amounts. With GH being cost intensive, funding GH projects poses a major threat to the adoption of the powerfuel. A secure stream of funding should therefore be made available to make the financing of the powerfuel more accessible. Recently, the IDC has signed a memorandum of understanding with ACWA Power that secures a steady stream of funding for the development of GH in SA (ACWA, 2022). A challenge will still exist in eventually implementing similar incentives across private banks in order to further enhance access to finance. This is mainly due to the nature of private banking being risk-averse in view of the yet unproven track record of GH investments.

To further promote GH adoption and diffusion in South Africa, specific departments like that of the Department of Trade and Industry can provide incentives for foreign investments. South Africa is one of the most advantageous countries in the world in terms of RE-resources, which potentially makes it a key player for the GH value-chain. Thus, special trade incentives like those mentioned earlier (tax incentives) can be applied to foreign investors to promote the production and development of infrastructure for GH in the country. Planning for such international partnerships is currently in progress. As a key example, earlier this year, South Africa partnered with Dubai to accelerate the adoption and diffusion of GH in South Africa and accelerate the country's status as a leading GH economy (ACWA, 2022).

Finally, with GH as an emerging technology, a major technical difference exists between existing RE sources and GH as established in chapter 4. However, for GH to be adopted successfully and for South Africa to become a leading GH economy, this skills gap needs to be closed. Thus, to increase understanding and the technical skills surrounding GH, government must develop centres of excellence within tertiary/academic and research institutions that would promote the necessary expertise and offer the knowledge needed in the direct field as well as related fields. As the level of understanding and the ability and skill to work with GH increases, the adoption, innovation, and diffusion of GH as well as the various applications of GH will increase.

5.6. Key sub-findings and conclusion

Two key projects are currently under implementation in SA that enable the adoption and diffusion of GH. The first one is within the mobility industry and is a joint GH venture between Toyota and Sasol which aim to test a fleet of hydrogen vehicles. The second is the Green Hydrogen Valley which establishes 3 main hydrogen hubs around the country, new GH related infrastructure and framework for the future scale-up of GH. Current and planned investments concerning GH infrastructure, development and innovation exist to ensure a sustainable GH economy. These projects address some of the related differences and barriers presented in the adoption of GH, mainly the allocation of resources and funds to implement new infrastructure necessary for GH, as well as secured funding for these projects to ensure the uptake of GH in the country. Partnerships with countries such as Dubai are also envisaged to produce and export GH from SA thus establishing the country as a leading GH economy. It also promotes the adoption of GH through securing foreign investments across the GH value-chain.

In terms of promoting the adoption of GH further, current policy primarily focuses on increasing RE into the energy mix and supporting the development of RE and GH. There is a still a short fall where policy does not directly address key concerns and challenges around GH as established in chapter 4, nor how to overcome them. New policy towards incentivising the use of GH on a production front and user front needs to be introduced. Such incentives can include tax breaks which would mitigate the higher cost of developing GH infrastructure. Further steps could include secured funding from government bodies and increasing pressure through mechanisms such as tax penalties on coal-based energy users in order to nudge them towards adoption of GH. Finally, key policies surrounding RE such as the IRP promote the use of RE and thus enable GH indirectly. Policy frameworks such as the HSRM are a critical step towards enabling the country to transition towards a GH economy. However, further policy mechanisms need to be developed and implemented to enable the successful and sustainable adoption of GH in SA.

6. What is the relevance of Special Economic Zones and Industrial Development Zones as prototyping hubs in relation to the critical challenges in the diffusion pathways in South Africa?

6.1. Introduction

This chapter presents data abstracted from both primary and secondary data sources to address Sub-question 3 on the relevance of Industrial Development Zones (IDZ) as prototyping hubs in relation to the critical challenges in the diffusion pathways in South Africa. Data analyses provides insights into five factors that were identified as key constraining factors to the adoption and diffusion of GH. The factors include infrastructure and land, socio-economic, financial, resource (water), and policy and regulatory barriers. This chapter presents the gaps between the barriers and ongoing initiatives and how Atlantis IDZ is equipped to close these gaps. The findings are consolidated in terms of these five key parameters.

In order to establish the relevance of Atlantis as a prototyping hub, the IDZ must first be established as a zone that can overcome key constraining factors. As such, this chapter evaluates how Atlantis is equipped to overcome infrastructure and land challenges by evaluating the potential of Atlantis as a hub for testing and implementing green technologies. It identifies education incentives which could be specifically implemented in partnership with Atlantis to bridge the gap between existing knowledge and knowledge needed for emerging green technologies. Data presentation and analyses also considers the steady stream of investment into the testing and implementation of green technologies in Atlantis in order to address financial challenges relating to GH. The chapter also considers the possibility of combating water-related challenges by considering the location and resources specifically allocated to Atlantis IDZ. Finally, it will consider the special legislation and regulatory framework put in place in Atlantis IDZ to promote green technologies and how this could mitigate identified within current policy shortfalls in South Africa as identified in Chapters 4 and 5.

Derivation of sub-findings on the relevance of IDZs as prototyping hubs in relation to the critical challenges in the diffusion pathways in South Africa have been presented as the concluding section of the chapter.

6.2. Data Overview

Data were collected through primary and secondary data. Primary data were collected through interviews with a single participant who works within Atlantis IDZ. Secondary data were extracted from various policy documents, official reports, and journal articles and were guided by the parameters set out for Sub-question 3. Table 6.1 summarizes the respective data parameters and related data sources. The findings from data and analyses are combined with responses from interview participants to generate sub-findings on the potential of Atlantis IDZ to combat critical challenges in the diffusion pathways of GH in South Africa.

Table 6.1: Summary of Data Parameters and Data Sources for Sub-question 3

Key Parameters	Primary Data	Secondary Data:	Responsive Sub-findings:
Atlantis in overcoming Infrastructure challenges. 1 participant was interviewed. How is Atlantis equipped to overcome infrastructure challenges related to GH? 1 key theme was reviewed for data abstraction. • Existing infrastructure to support GH.	Interview 1 (P4) • Central location of Atlantis in relation to various ports and major national roads (Saldanha port, N1, N2 and N7 routes) allows for easy import and export of GH.	Source 1: Atlantis, 2022 • large tracts of industrially zoned land with appropriate bulk infrastructure in place. • Atlantis is advantageously located near various ports and major national roads such as Saldanha port, N1, N2 and N7 routes.	Sub-findings: Atlantis central location and existing infrastructure offers a solution to infrastructure challenges and in addition advantageously positions Atlantis as a GH hub .
Atlantis in overcoming economic challenges. 1 participant was interviewed. How is Atlantis equipped to combat economic challenges related to GH? 1 key theme was reviewed for data abstraction. • Nature of Atlantis – investments available	Interview 1 (P4) • Partnerships already exist between Atlantis and the government, a large range of institutions, business, and labour.	Source 1: Atlantis, 2022 • Atlantis holds a strong investor base. • Steady international support. • Special incentives exist for investors.	Sub-findings: Atlantis has a steady stream of investments into green technologies which can be used for the prototyping of GH. This stream of investments secures capital needed for the technology thus facilitating for its adoption. Coupled with different incentives that could mitigate the high cost, GH technology then becomes more affordable within a shorter timeline.

<table>
<tr><td>Atlantis in overcoming Socioeconomic challenges.

1 participant was interviewed.

How can Atlantis address the technical skills gap hindering the adoption of GH?

1 key theme was reviewed for data abstraction.
• Current incentives and drives put in place to minimize skills gap</td><td>Interview 1 (P4)
• Atlantis is also working with various youth organizations, schools, and tertiary institutes to provide a skills development drive.</td><td>Source 1: Atlantis, 2022
• Attracts a large range of unskilled, semiskilled, technical, and professional candidates.</td><td>Sub-findings:
Atlantis is actively educating young professionals with the necessary tools and skills needed to function in a green economy. This suggests that as the country transitions to becoming a GH economy, it is equipped with the necessary professionals needed to ensure a smooth and efficient transition and adoption of GH technology.</td></tr>
<tr><td>Atlantis in overcoming Resource challenges.

1 participant was interviewed.

How is Atlantis equipped to deal with the water scarcity issue threatening GH adoption in SA?

2 key themes were reviewed for data abstraction.
• Ability of Atlantis to overcome resource challenges.
• Location of Atlantis</td><td>Interview 1 (P4)
• No way of immediately addressing water scarcity-related barriers.
• Resources can be allocated to finding a solution to this issue to ensure successful adoption of the powerfuel.</td><td></td><td>Sub-findings:
Atlantis has no immediate solution to addressing the water scarcity barrier in the adoption of GH. However, due to the nature of Atlantis, the IDZ has the necessary resources and capital needed to test alternate solutions to producing GH. One of the alternative solutions ideally suited for Atlantis is desalination.</td></tr>
<tr><td>Sub-findings on Sub-question 3 based on consolidation of subfindings across the four key parameters</td><td colspan="3">• Atlantis is uniquely positioned to combat various challenges affecting the adoption of GH in SA
• The nature of Atlantis results in key infrastructure and a steady stream of investments available and could be channelled to GH technologies.
• A secured line of investment into Atlantis means capital available that can be allocated for the required infrastructure and skills for the powerfuel.
• skills development drive. This will aid in enabling professionals with the necessary skills and knowledge needed for the successful implementation and operation of GH plants.
• Special policy exists that incentivizes the use of green technologies within the zone.
• The nature of Atlantis can result in fast-tracked special policy and allocation of resources that can tackle these challenges.
• The potential of Atlantis for the prototyping of GH in South Africa becomes favorable as it is well equipped to adopt the powerfuel and overcome various barriers that would be difficult to address within non-IDZs areas.</td></tr>
</table>

6.3. Special Economic Zones (SEZs)

SEZs are key tools used by South African government for driving industrial and economic development. Industrial Development Zones (IDZ's) is one special sector covered under SEZs. This chapter will look specifically at Atlantis as an IDZ and explore related green technologies and policies within the sector.

SEZs are "geographically designated areas of a country set aside for specifically targeted economic activities, supported through special arrangements such as legislation and governance systems that are often different from those that apply to the rest of the economy" (Department of Trade, industry, and Competition, 2021, 2). In the 2014 Industrial Policy Action Plan (IPAP), SEZs were identified as "key contributors to economic development" (Department of Trade, industry, and Competition, 2021, 1). The Role of SEZs is to act as "growth engines towards government's strategic objectives of industrialization, regional development and employment creation" (ibid). Special Economic Zones commonly fall into four distinct sectors as follows:

- Industrial Development Zones: purpose-built industrial estate that leverages domestic and foreign fixed direct investment in value-added and export-orientated manufacturing industries and services.
- Free Port: duty-free areas adjacent to a port of entry.
- Free Trade Zones: duty-free areas offering storage and distribution facilities.
- Sector Development Zones: a zone focused on the development of a specific sector or industry.

6.4. Industrial Development Zones and the case of Atlantis

IDZs are established as a way for the South African government to reposition itself in the world economy. They focus primarily on attracting "foreign direct investment and export of value-added commodities" (Department of Trade, industry, and Competition, 2021, 5). The aim of IDZs was thus to "increase industrial growth" (Ibid). There are currently five operating IDZs in South Africa. They are Atlantis, Nkomazi, Coega, Richards Bay, and East London (ibid).

The formation of Atlantis in recent years was developed as part of the City of Cape Town's initiative to establish a "Greentech manufacturing hub" (Department of Trade, industry, and Competition, 2021, 4). Greentech describes "green technologies that reduce or reverse the impact of people on the planet" (ibid).

These technologies include all forms of renewable energy, electric vehicles, material recycling, and green building materials (ibid).

This is particularly relevant when considering the adoption and diffusion of GH, mainly because the technology relies on other renewable technologies to generate the electricity required for electrolyzing GH from water. In designated zones such as Atlantis, which are developed specifically for the implementation of these technologies, the potential adoption of GH becomes easier and more beneficial than in other IDZs which are not dedicated to Greentech.

6.4.1. Renewable Energy Technology and Investments in Atlantis

Atlantis was originally established as a newly developed town with an industrial zone designated as a relocation point for coloured individuals who were forcibly displaced during the apartheid era. In the early 1990s, it experienced a significant economic downturn and disinvestment due to the removal of subsidies. Consequently, the area witnessed a rise in poverty and unemployment (Issuu, 2023, 1-2)

However, since 2010 and onwards, a deliberate effort has been made to rejuvenate the region and attract fresh investments. The existing industrial area, already equipped with essential infrastructure and substantial land holdings, combined with the continuous improvement of transportation links and the expansion of Cape Town, presented new growth opportunities (Issuu,2023,3). Atlantis emerged as a result of these revitalization endeavours and stands as a collaborative response involving all three tiers of government. Around 2013, the Renewable Energy Independent Power Producer Programme (REIPPP) emerged as, and continues to be, a promising avenue for fostering the expansion of green technology manufacturing, as such the evolution of Atlantis aligned with the REIPPP, allowing it to be a catalyst for the further development of the IDZ into what it is today.

The recent development of Atlantis was thus done in response to the Department of Energy's Renewable Energy Independent Power Producer Program (REIPPPP) and "capitalizes on the provinces currently booming renewable energy and green technology sector. Industries for renewable energy technologies such as wind turbines and solar panels are currently operational within Atlantis" (Department of Trade, industry, and Competition, 2021, 4). Roughly 60% of successful renewable energy projects under REIPPP are due to "geographic advantage and an ecosystem that's enabling of other developer, service providers, and manufacturing" (ibid). Atlantis houses diverse infrastructure that range across various services and manufacturing opportunities, thus, making Atlantis a prime location for the implementation of successful

REIPPP projects. More than this, however, the existing infrastructure under Atlantis is suitable for GH adoption. As discussed previously, GH requires vast infrastructure for production, storage, and transport. In areas such as Atlantis, where a majority of the infrastructure currently accommodates this, the cost relating to the adoption of GH decreases. Once again, proving Atlantis to be not only a relevant hub for the adoption of GH but a cost-effective one too.

Atlantis is home to a vast range of renewable energy technologies and has room for further expansion and testing of new technologies. These technologies include solar energy, wind power, CSP hybridization, biofuels, water, and waste energy (Atlantis, 2022, 1). To date, a total of R790 million (ibid) has been invested in Atlantis for the expansion of renewable energy and the testing of new green technologies (Personal Communication, October 2021). Atlantis Hub has already attracted four large Greentech investors: Gestamp Renewable Industries (GRI), a wind tower manufacturer, has invested R475 million into a wind power plant in Atlantis, and the project is currently in full-scale production (Atlantis, 2022, 3). An Atlantis expert (2021) comments on this by adding that the company originally only invested R300 million but increased their investment as they found Atlantis to be a highly suitable and profitable location for their venture. A secondary wind turbine project is set for Atlantis, with Resolux investing R25 million into a wind turbine venture. Additionally, Kaytech expansion, a geotextile company, has invested R130 million for a project in Atlantis. Finally, Skyward Windows Expansion invested R50 million into a Greentech project within Atlantis (Atlantis, 2022, 2). The increasing volume of capital investment into renewable energy projects in Atlantis is beneficial towards enhancing the area as a prototyping hub as the generation capacity of GH would be set to increase in line with the increasing renewable energy technologies in the region. This further iterates the high potential of the IDZ as a prime hub for the scaleup and adoption of GH in South Africa.

6.5. Atlantis in overcoming critical challenges faced in the diffusion and adoption pathways of green hydrogen in South Africa

As discussed earlier, South Africa faces various economic, socio-economic, legislative, resource, and infrastructure challenges regarding the adoption and diffusion of green hydrogen. The unique setting of Atlantis as an IDZ under SEZs, however, appears to combat many of these challenges.

In combatting infrastructure challenges, Atlantis offers “large tracts of industrially zoned land with appropriate bulk infrastructure in place” as well as new “new public transport links and fibre connectivity” (Atlantis, 2022, 3). As earlier stated, GH technology requires intensive infrastructure for the production, storage, and transportation of hydrogen. With Atlantis already equipped to manage the GH technology, infrastructure challenges as well as associated costs concern diminish.

Additionally, Atlantis is advantageously located near various ports, such as Saldanha, airports, and Cape Town city (Atlantis, 2022, 3). In an interview conducted with an Atlantis expert (2021), the expert goes on to suggest that the somewhat central location of Atlantis to various ports allows for easy import and export of GH if the powerfuel were to be implemented in the zone. Further, Atlantis has easy access to major national roads, including the N1, N2, and N7 (Atlantis, 2022, 3). This not only offers a solution to infrastructure challenges but further advantageously positions Atlantis as a GH hub for export of the powerfuel, thus further positioning South Africa as a key hydrogen economy globally as set out by the South African government.

In combating economic and financial challenges, Atlantis holds a strong investor base. Atlantis holds partnerships and relationships with various big investors and corporations that "facilitate investments" (Atlantis, 2022, 4). An Atlantis expert (2021) suggest that partnerships already exist between Atlantis and the government, a large range of institutions and businesses, as well as labour. Further, Atlantis has steady international support from the International Clean Tech Network which provides further connection to "clean technology clusters across the globe" (Atlantis, 2022, 4).

Finally, as Atlantis IDZ falls under SEZs, special incentives exist for investors. These include both local and national incentives (ibid). National incentives include12I tax allowance, which supports capital investments and training, and other tax incentives, while local incentives refer to incentives that fall within the City of Cape Town. These include the following: (Atlantis, 2022, 6)

- Attractive land purchase and lease arrangements for greenfield sites with environmental authorizations in place.
- The fast-tracked application process for business sites.
- Fast-tracked development approvals for land use and building plan applications.
- Zero fees relating to land use and building plan applications and development contribution deferrals.
- Municipal electricity tariff subsidy.

In addition to the above-mentioned incentives, various tax incentives exist under SEZs for investors. These include preferential corporate tax and tax relief, building allowance and tax relief, employment tax incentive, and customs-controlled area tax relief" (Department of Trade, industry, and Competition, 2021, 7).

Under preferential corporate tax and tax relief, a company may qualify for a "reduced corporate income tax rate of 15%" (Atlantis, 2022, 6). This is only valid until 2024, says Atlantis expert (2021). Building allowance and tax relief allow a business operating in an SEZ to qualify for "accelerated depreciation on buildings" (Atlantis, 2022, 6). Over 10 years, the rate equals 10%p.a. Employment tax incentives apply to any employee employed in an SEZ who earns below R600 000 p.a. This incentive reduces pay-as-you-earn taxes and leaves employees with a higher net salary (ibid). An Atlantis expert (2021) suggests that the employment tax incentive is aimed at creating jobs for the younger population with the aim of decreasing unemployment rates amongst this age group. Finally, custom-controlled area tax relief allows for VAT and customs relief in accordance with relevant legislation (ibid).

What these incentives do is attract a steady rate of capital investment into Atlantis by giving growing benefits to the investors. In a country like South Africa where tax is a day-to-day challenge for many entities, tax relief incentives become a large selling point to investors, and the investment can be more profitable than alternative options without such incentives.

The tax incentives implemented in Industrial Development Zones (IDZs) and Special Economic Zones (SEZs), such as those implemented in Atlantis, are primarily designed to benefit business owners and entities, rather than individual taxpayers. These incentives are strategically directed towards businesses with the aim of promoting investment, economic growth, and job creation within the designated zones. They are also designed to attract businesses by making the process of setting up a business within these zones more efficient and beneficial than in other areas. They offer various advantages, including reduced corporate income tax rates, customs duties and import VAT relief, payroll tax incentives, accelerated depreciation allowances, and skills development levy relief, all of which are geared to lower the tax burden and operational costs for businesses operating within these zones. This not only secures investments but sets up these SEZs as business hubs, thus securing various streams of investment into the area. In terms of relevance towards GH, this reduces the barrier associated with the cost of emerging GH technologies thus making the adoption of the technology more favorable.

In combatting socio-economic setbacks, Atlantis, in collaboration with the City of Cape Town and the Western Cape province, offers a large range of unskilled, semi-skilled, technical and professional candidates. An Atlantis expert (2021) adds that Atlantis is also working with various youth organizations, schools, and tertiary institutes to provide a skills development drive. In doing so, younger generations can learn the necessary skills and knowledge needed to operate and maintain emerging and existing renewable energy. This suggests that as the country transitions to becoming a GH economy, it is equipped with the necessary professionals needed to ensure a smooth and efficient transition and adoption of GH technology.

Currently, Atlantis IDZ has no way of immediately addressing water scarcity-related barriers. However, being equipped with the necessary resources available, in the event of GH adoption within the IDZ, resources can be allocated to finding a solution to this issue to ensure successful adoption of the powerfuel. One of the options which could be prioritized for further research and development is desalination with the objective of bringing down the costs of related technologies. This is particularly favorable given the location of Atlantis.

Finally, in relation to policy and regulatory barriers, in terms of the actual adoption of GH, there are no special policies within Atlantis. Current policies that are unique to Atlantis mainly focus on investments such as the tax incentives as reviewed in previous sections. However, due to the nature of Atlantis, it would become easier to adopt and implement new required policies to aid in facilitating the adoption of GH. Even though such policies may initially be limited to Atlantis, they could potentially serve as a critical starting point which could guide the way for national adaptation and application.

6.6. Key sub-findings and conclusions

Given the nature of Atlantis as a hub specifically created for the testing, prototyping and production of green technologies in order to facilitate their scale-up and adoption, this IDZ is uniquely positioned to combat various challenges affecting the adoption of GH in SA, as set out in Chapters 4 and 5. An increase in RE technologies within Atlantis are key in enabling GH in South Africa. The nature of Atlantis results in key infrastructure and a steady stream of investments becoming available for GH. Infrastructure such as ports and freight (roads and rail in particular) already exist which would in turn reduce the high cost normally associated with scale-up of GH for adoption at national and global level. This would therefore expedite the adoption of the powerfuel. A secured line of investment into Atlantis means capital available that can be allocated to the adoption of the powerfuel. Atlantis is also working with various youth organizations, schools, and tertiary institutes to provide a skills development drive. This will aid in enabling professionals with the necessary skills and knowledge needed for the successful implementation and operation of GH plants.

Special policies also incentivize the use of green technologies within the IDZ. These mainly include tax incentives which offer tax breaks not only to those producing GH but consumers as well. Barriers still exist in terms of water scarcity and allocation as well as related policy and regulatory framework. Though Atlantis has no direct means of dealing with these barriers, the nature of Atlantis can result in fast-tracked special policy and allocation of resources that can tackle these challenges. Overall, Atlantis therefore emerges as a significant, if not critical, zone to combating challenges facing the diffusion of GH in South Africa. The potential of Atlantis for the prototyping of GH in South Africa becomes favorable as it is well equipped to adopt the powerful and overcome various barriers non-IDZs areas would find difficult to address.

7. Findings, recommendations, and conclusion

This chapter will focus on answering the main research question primarily through consolidation of sub-findings obtained from Chapters 4, 5, and 6. The chapter also covers recommendations for future research in relation to this research topic and then consolidates the conclusion on the key findings of the research.

7.1. With Atlantis in the Western Cape as a case study, what is the relevance of IDZs as prototyping hubs for a GH economy in South Africa?

To produce GH alternative renewable energy technologies must exist in combination with GH technology. As discussed previously, GH is hydrogen generated with electricity from renewable energy sources such as wind and solar. South Africa has one of the richest RE resources in comparison to the rest of the world, South Africa appears to be becoming one of the global leaders in the production of RE. This advantageously positions South Africa as a potential leader in GH technology and thus in the transitioning to a GH economy.

This potential, however, is met with various challenges. Despite South Africa's current and planned investments in GH across various sectors - namely the Sasol and Toyota joint green hydrogen venture in the automotive industry and the green hydrogen valley across various sectors – and the different policy and regulatory frameworks that exist to incentivise and guide the transition to GH in South Africa, multiple barriers still exist. As part of initiatives for addressing these barriers, zones such as Atlantis IDZ have been proven to be equipped with the necessary infrastructure, incentives, and regulations to mitigate most of these challenges.

In instances where there is no existing pathway to combat certain barriers to GH diffusion, Atlantis provides a unique opportunity to adopt and prototype novel solutions. For example, as established in Chapter 4, a key challenge to GH adoption in South Africa is that of South Africa's water scarcity. Electrolyzes used to produce GH require large amounts of water. Research has been done, and the topic continues to be investigated in using desalinated sea water to produce GH. Given the convenient location of Atlantis, the IDZ has access to sea water that can be desalinated for production of GH. Although not yet tested in the IDZ, the mere fact that Atlantis has a steady stream of investments means the resources are available to prototype the solution and combat another challenge faced by the IDZ. Related cost implications of using desalinated water to produce GH has not been investigated in this study.

SEZs and more specifically Atlantis IDZ, was set up to test and implement renewable energy and new Greentech in South Africa. Atlantis is currently home to a vast number of renewable energy technology businesses and is still attracting increasing investments in new ones. The fact that Atlantis was specifically created with the intention of testing and implementing new Greentech means it is equipped to overcome the various challenges facing South Africa in relation to adoption and diffusion of GH. This is mainly because the zone is built specifically for prototyping and testing of Greentech and is thus equipped with the necessary infrastructure to implement GH technologies.

In addition, existing infrastructure in Atlantis makes the IDZ well equipped with the necessary means to export GH. Atlantis is located near major ports and has access to main railways and roads needed for both internal and export freighting of GH. This perfectly positions Atlantis to become a key exporter of GH almost immediately at relatively low additional infrastructure cost. This is particularly relevant given that GH can be used across multiple industries. Easy and fast access to the necessary routes for export would thus ensure it can be used not only within the country but globally as well, thus establishing SA as a leading GH economy. Further, with the automotive industry being one of the most efficient and fastest ways of testing GH, the nature of Atlantis coupled with existing infrastructure further positions the IDZ as a crucial prototyping hub for the powerfuel.

A strong investment base is further strengthened by various incentives and policy conditions, making investment more attractive, thus decreasing capital-related challenges of GH technology. These are the very steps that were established in Chapter 1 as critical towards promoting the adoption and diffusion of GH. The same holds true with foreign investments. As established in Chapter 5 (see Section 5.4), securing foreign investments through different tax incentives for the production and exportation of GH, and in creating global partnerships towards establishing SA as a leading GH economy, is crucial for the adoption and diffusion of GH. With the necessary incentives in place in Atlantis IDZ, it is already established and able to create such partnerships.

A similar standing holds true in bridging the gap of technical skills and knowledge needed for the uptake of GH. As mentioned in Chapter 5 (see Section 5.4), to further promote the adoption of GH and specially to secure a successful future of GH in South Africa, steps need to be taken to equip professionals with the necessary tools. Although currently on a very small scale, Atlantis is in partnerships with various institutions to not only educate professionals but emerging professional with the aim of securing a future with capable individuals equipped to ensure a successful GH economy. However, this still needs to be rapidly adopted and scaled up based on the prototyping and production opportunities already in place at the zone.

Finally, the location of Atlantis IDZ makes it a key area in providing energy for surrounding municipalities. As an example, in an interview conducted with a lead engineer he stated that a GH project, currently in its early stages is being developed in close proximity to the IDZ. This project has a PPA with a surrounding municipality to provide energy produced from GH. In pursuing this PPA, the company investigated the extent to which other municipalities would be interested in similar agreements. Their study found that over 60% of municipalities were willing to get their energy supply from GH. This extent of interest opens an opportunity for IDZs like Atlantis not only to export GH globally, but also to use the energy within the country itself and to aid in bridging electricity gaps that exist in SA, thus bringing the country one step closer to a net-zero carbon emission status.

What all of this translates to is that IDZs, such as, Atlantis are highly optimal as testing hubs for the adoption and diffusion of GH by enabling a quick, efficient, and cost-effective implementation of the technology into the area while already taking the necessary steps to secure a GH future for the country. Furthermore, Atlantis was designed with the capacity to handle innovative green technologies meaning that as the interest and investment in GH expands and demand increases as predicted, zones such as Atlantis are equipped with the required land, infrastructure, and complementary renewable energy technologies to keep up with related innovations within related technology ecosystems. Even though a GH project is being considered for Atlantis, it is currently at feasibility stages and the specifics could not be disclosed by the parties concerned. IDZs such as Atlantis are therefore not only relevant as prototyping hubs for a hydrogen economy in South Africa but are perfectly positioned to create the most beneficial testing hubs for the technology within South Africa and also globally position the country as a leading GH economy.

7.2. Recommendations for future studies

This study focused specifically on identifying the relevance of Atlantis as a prototyping hub for the diffusion and adoption of green hydrogen in South Africa and therefore serves as foundational research in transitioning to a GH economy for South Africa. The particulars relating to the generation capacity of GH from existing renewable energy projects within regions surrounding Atlantis would need to be assessed as well in order to gauge potential capacity for scale-up and growth. Further, the extent of GH generation capacity within Atlantis in aiding in South Africa’s energy crisis as well as in reaching the country's net zero goal calls for additional studies.

Further studies should also consider the expansion of GH technology in the long term and how other IDZs besides Atlantis can be used as facilities for expediting adoption and diffusion of GH technology for the rest of the country. Finally, although the cost of implementing GH technology in hubs such as Atlantis was mentioned, a full in-depth feasibility study considering the actual cost difference between prototyping GH within Atlantis as a starting point versus elsewhere in the country needs to be conducted in order to understand the extent of the economic benefit.

7.3. Conclusion

Sub-question 1 was addressed through assessment of the challenges which hinder the adoption of GH. Given the nature of Atlantis as an area to test and implement new green technologies, Atlantis was designed with the capacity to handle innovative green technologies meaning that as the interest and investment in GH expands and demand increases as predicted, Atlantis and other such zones are equipped with the required land, infrastructure, investments, and renewable energy technologies to keep up with the growing demand of the technology. On the status of GH in SA, sub-findings on sub-question 2 establish that, although there is a presence of GH and steps are being taken to enable a GH economy, in order to further promote the adoption of GH in the country key steps such as policy incentives, liaison between government and tertiary education systems need to be considered to equip students in the relevant fields with knowledge to ensure the sustainable growth of GH. Areas such as Atlantis IDZ already have these steps in place thus giving them the potential to fast track the adoption of GH and secure a GH future.

Based on the nature of Atlantis and increasing availability of RE resources within its surrounding regions, location of GH technology firms within the IDZ would result in decreased costs associated with GH and increased availability of sources needed to expedite adoption and diffusion of GH. The location of Atlantis and existing infrastructure thus perfectly position the IDZ as a supplier and exporter of the powerfuel which would in turn promote foreign trade investments in GH in South Africa. Further, Atlantis is in a prime location and position to test alternative methods to combat the water challenge which is envisaged to hinder further scale-up of GH in the country. In addition, the study finds that interest from surrounding municipalities to source energy from GH creates a unique opportunity for the IDZ as well as facilitating in overcoming the country’s energy crisis and moving towards a net-zero carbon status. The study therefore concludes that Atlantis is not only an optimal testing hub but a crucial hub for the adoption and diffusion of GH primarily through enabling faster, efficient, and cost-effective prototyping and production of the technology within the zone and thus facilitating for scale-up and adoption in the country in general.

The findings of the study may be applied to different IDZ's as follows: Industrial development zones in South Africa can benefit significantly from the establishment of green hydrogen or similar green technologies in several ways.

- Job Creation: The development of green hydrogen and related technologies can create a substantial number of jobs. This includes positions in research and development, manufacturing, construction, operations, and maintenance. South Africa can use this opportunity to address unemployment and boost economic growth in the region.
- Sustainable Energy Supply: Green hydrogen can serve as a clean and reliable source of energy. This can help industrial zones reduce their reliance on fossil fuels and contribute to a more sustainable and secure energy supply. This can lead to cost savings and increased energy resilience.
- Export Opportunities: Green hydrogen and related technologies can be exported to international markets, contributing to South Africa's economy. The global demand for clean energy solutions is increasing, and South Africa can position itself as a key supplier of green technologies.
- Foreign Investment: The establishment of green technology projects can attract foreign investment and partnerships. International companies may be interested in collaborating with South African industrial zones to develop and scale up green hydrogen and related initiatives.
- Environmental Benefits: By transitioning to green technologies, industrial zones can reduce their carbon footprint and environmental impact. This can help South Africa meet its climate commitments and improve air quality, which is beneficial for public health.
- Innovation and Research: The development of green hydrogen and related technologies requires innovation and research. South African universities and research institutions can play a pivotal role in advancing these technologies, leading to knowledge transfer and expertise development.
- Infrastructure Development: The establishment of green hydrogen production and distribution infrastructure can lead to the creation of new industrial facilities and support services. This can stimulate economic growth in the region.
- Energy Security: South Africa can enhance its energy security by diversifying its energy sources with green hydrogen. This can reduce the vulnerability to energy supply disruptions and price fluctuations associated with fossil fuels.
- Government Incentives: The South African government may provide incentives, tax breaks, and subsidies to promote green technology development. Industrial zones can take advantage of these opportunities to lower their operating costs.
- Sustainable Development Goals: The adoption of green technologies aligns with global sustainable development goals, and it can improve the overall quality of life in the region by addressing environmental and social challenges.

To maximize the above-mentioned benefits, it is essential for industrial development zones to collaborate with the government, private sector, and international partners to create a conducive regulatory environment, secure investment, and develop the necessary infrastructure. This can help South Africa position itself as a leader in the green technology sector and realize its economic and environmental goals

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Appendix A: List of Interviewees

Participant	Expertise	Date of Interview
Participant One	Participant One is a mechanical engineer with over 30 years of experience in the energy sector. Participant One works specifically in the renewable energy industry and holds a BSc (Electrical Engineering), MSc (Mechanical Engineering), and MBA. Participant One has been responsible for managing renewable energy projects across the world for leading companies such as Worley, Yellow Door Energy, and GSE. This participant sits on the Green Hydrogen Board of South Africa and has recently signed a deal to develop a green hydrogen project in the Western Cape.	October 2021 January 2022 August 2022
Participant Two	Participant two is an electrical engineer with over 25 years of experience in the energy sector. Participant two works specifically in the renewable energy industry and holds a BEng (Electrical Engineering) from the University of Cape Town. Participant two has been responsible for designing solar and wind projects across the country.	September 2021 October 2022
Participant Three	Participant Three is a chemical and electrical engineer with over 20 years of experience in the energy sector. Participant Three works specifically in the renewable energy industry and holds a BEng (Electrical and Chemical Engineering) from the University of the Witwatersrand. Participant Three has been responsible for working on various RE projects across the country.	February 2022 August 2022
Participant Four	Participant Four was previously employed as the head of energy in Atlantis IDZ. This participant has first-hand knowledge of the various factors affecting RE in this zone as well as the potential of the zone in combatting certain challenges faced by GH adoption in South Africa.	December 2021

Appendix B: Interview Questions for Interview Participants

Three renewable energy and development participants were interviewed using the below questions. These participants have vast knowledge and experience in the renewable energy field. All participants have chosen to remain anonymous. The following questions were used to interview these participants.

In addressing sub-question one: What is the status and planned future pathways of green hydrogen powerfuel adoption and diffusion in the market in South Africa?

1. Recently South Africa has announced the Sasol Toyota and Green Hydrogen Valley projects, amongst others, how do these establish SA in terms of being a GH economy and what do they mean for the future of GH in the country?

2. Do you foresee South Africa expanding its GH presence and how long do you think it will take for the widespread adoption of the powerfuel in SA?

3. What steps can be taken to further promote the use of green hydrogen technology in South Africa?

of ion with hydrogen, you don't emit, you're avoiding co2 emissions altogether, right.

4. What sectors, industrial, commercial, residential, or otherwise, can green hydrogen be tested in to ensure the most efficient and effective prototyping?

5. How do projects like the GHV establish SA in terms of being a GH economy and what does it mean for the future of GH in South Africa?

6. How does the evolution of policy position South Africa as a Green Hydrogen Economy?

In addressing sub-question two: What are the critical challenges in the diffusion pathways of green hydrogen in South Africa?

7. In relation to the adoption and diffusion of GH in SA what infrastructure and land related exist that slow down or prevent the adoption of the powerfuel?

8. There is a level of technical skill required to operate implement and maintain GH technology which differs from existing RE technologies. What is this difference and how does it pose a challenge to the adoption? i.e. What socio-economic challenges exist in the diffusion of green hydrogen in South Africa?

9. Over the years we've seen the cost of RE sources decrease, with a predicted significant further decrease overtime. However, with GH still emerging the related cost is still considered significantly high. In relation to adoption and diffusion of GH how does this pose an immediate and challenge to the adoption and diffusion of the powerfuel? i.e. What cost related barriers exist in the adoption and diffusion of green hydrogen in South Africa?

10. What policy and regulatory challenges exist in the diffusion of green hydrogen in South Africa?

In addressing sub-question three: What is the relevance of Industrial Development Zones as prototyping hubs in relation to the critical challenges in the diffusion pathways in South Africa?

11. How does Atlantis help in enabling the testing of green hydrogen in comparison to other places in the country?

Participant four has firsthand knowledge on the various factors affecting RE in this zone as well as the potential of the zone in combatting certain challenges faced by GH adoption in South Africa.

The following questions are used to answer sub-question three:

1. To what extent is the use of green hydrogen technology being explored in South Africa?

2. Atlantis is a fairly new industrial development zone, what is the development status of Atlantis? i.e. is it still under development or is it completed and if not to what extent is it completed and when is it planned to be fully developed?

3. Atlantis was developed in response to the growing attraction of renewable energy. What renewable energy technology is currently being used?

4. Are there any additional renewable energy technologies planned for use in Atlantis?

5. Is Atlantis designed in such a way as to allow for the testing and implementation of new technologies such as green hydrogen, and if so how and to what extent?

6. Green hydrogen relies on renewable energy for production, in your opinion do you think industrial development zones such as Atlantis are the best zones to consider for prototyping the technology?

7. Green hydrogen technology faces various physical, socio-economic, policy and regulatory related challenges (these will be listed once identified), do you think that places such as Atlantis can be effective in overcoming these challenges, and if so how and to what extent?

8. How can the testing of green hydrogen within Atlantis be applied to different specialized economic zones and sectors within South Africa?

Appendix C: Ethics Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG | SCHOOL OF ARCHITECTURE & PLANNING

Dear Fadheelah Madhi (1633697)

This letter confirms that your clearance application has been approved. Your protocol/clearance number is: SOAP118/06/2021

Yours sincerely

Lerato Nkosi

lerato nkosi

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