Turning Points for Green Hydrogen in Energy Storage: Insights from Techno-Economic Analysis and Transition Theory

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ABSTRACT

Solar and wind energy offer the opportunity to decarbonise energy generation. However, these energy sources are intermittent, leading to a mismatch between energy availability and demand and creating the need for energy storage. Green hydrogen could be the solution to this imperative; however, it is presently only available in small quantities and is expensive relative to conventional energy technologies based on coal and gas. The difference in cost raises the important question of what needs to be implemented or developed so that green hydrogen can become a viable technological solution for accommodating renewable energy intermittency.

This research considered the question using a sequential mixed methods approach. In the first quantitative phase, standard techno-economic analysis was used to calculate the levelised cost of storage (LCOS) and the necessary turning points at which green hydrogen could be widely deployed as a storage solution. The LCOS is estimated to be \$0.228/kWh which is still fairly higher than the literature value of \$0.13/kWh for lithium-ion (Li-ion) batteries and \$0.11/kWh for pumped hydro storage. Lazard's 2024 analysis gives the LCOS for green hydrogen to be around the range \$0.20 to \$0.40 per kWh.

In the second qualitative phase, the results of this analysis were calibrated against the perspectives of industry personnel with at least 5 years' experience in the sector. The respondents noted the high differential between the LCOS for green hydrogen and alternative energy storage technologies such as Li-ion batteries. Their view was that significant intervention would be required at least initially with support mostly from the government in cost reduction and attract investors. Approaches such as support for the establishment of energy infrastructure, tax incentives and penalties for carbon emissions were mentioned.

Key Words

energy transition, techno-economics, energy storage, turning points, grid stability, green hydrogen, intermittent power, renewable energy, levelised cost of storage (LCOS), multi-level perspective

DECLARATION

I, Allen Manyere, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree Master of Management in Energy Leadership at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Name: Allen Manyere   Signature: A.Manyere

Signed at Pretoria

On the 4th day of December 2024.

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LIST OF ACRONYMS & ABBREVIATIONS

BES	Battery Energy Storage
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbines
CO_2	Carbon Dioxide
CHP	Combined Heat Plant
CSP	Concentrated Solar Plant
EL	Electrolyser
ESS	Energy Storage System
FES	Flywheel Energy Storage
FBES	Flow Battery Energy Storage
FC	Fuel Cell
GH	Green Hydrogen
GW	Gigawatts
GWh	Gigawatt Hour
HES	Hydrogen Energy Storage
HPP	Hydrogen Power Plant
PHES	Pumped Hydro Energy Storage
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEP	Integrated Energy Plan
IRP	Integrated Resource Plan
KW	Kilowatt
kWh	Kilowatt Hours
LCOS	Levelised Cost of Storage
MW	Megawatt
NGO	Non-governmental organisation
PPA	Power Purchase Agreement
PV	Photovoltaics
RE	Renewable Energy
RSA	Republic of South Africa

SADC	Southern African Development Community
SCES	Super Capacitor Energy Storage
SMES	Superconducting Magnetic Energy Storage
TES	Thermal Energy Storage.
TWh	Terra Watt Hours
USD	United States Dollar
VRE	Variable Renewable Energy
ZAR	South African Rand

CHAPTER 1. INTRODUCTION

1.1 Purpose of the Study

The main objective of this study is to identify and describe critical turning points for the uptake of green hydrogen as a means of energy storage in South Africa. The study has two components. In the first component, it will seek to proportion the relative merits and influence of possible turning points, including their cost as measured by the levelised cost of storage (LCOS), social factors, and the broader economic issues.

In the second component, the study will consult industry stakeholders on the validity of the identified turning points, and what factors, in addition to the techno-economic considerations, that will need to be considered in the wider scale adoption of green hydrogen as an energy storage technology in South Africa. This research will adopt the analytical framework of a multi-level perspective which proposes that transitions in socio-technical systems take place at specific 'windows of opportunity', marked by the growing strength of new systems and the weakening of the present regimes.

The need for energy storage within national electricity systems has grown because of an increasing reliance on intermittent energy sources such as wind and solar (known as variable renewable energy or VRE). Green hydrogen has been proposed as a possible solution to both the energy storage issue and the imperative for the decarbonisation of energy systems.

The technology is conceptually straightforward. Excess power from wind and solar is passed through water, a process called electrolysis, to produce hydrogen which is then stored in hydrogen tanks and later utilised to generate electricity by way of a fuel cell or gas turbine. In the case of South Africa, energy storage, when combined with VRE, could assist in building reliable generation capacity and hence reducing the extent of load shedding.

1.2 Context of the Study

The climate change crisis has increased the imperative to transition from fossil fuels, as a source of energy, to greener technologies and fuels. However, peak power demand in South Africa occurs in the evenings and mornings, and at that time, there is insufficient solar energy to supply electricity to the grid. Green hydrogen can be used to meet such demand in the absence of VRE, by storing excess solar or wind generation during the day and then feeding electrons back to the grid via fuel cells as demand increases in the peak periods (Wright, 2019).

In South Africa, the government has an electricity plan termed the Integrated Resource Plan (IRP) which seeks to accelerate economic growth and achieve energy security through a sustainable energy supply for the country as the electricity demand grows. Recently, the Department of Mineral Resources and Energy, through the Electricity Regulation Act, gazetted Schedule 2 which will allow private players to generate up to 100MW of distributed generation without a licence, thereby allowing increases in VRE capacity within the country.

This development, together with decreases in solar and wind electricity costs, opens an opportunity for green hydrogen as energy storage, although the technology remains expensive (Andreoni & Roberts, 2022; Lin, Wu, Chen, Yang, Guo, Lv, Lu, Song & McElroy, 2021; Maurya, Gemechu & Kumar, 2023; Razi & Dincer, 2022; Walwyn, 2021). It is noted that most auction bids now fall below US2c/kWh and the world record is down to US1c/kWh; with its higher cost of capital and economic development add-ons, South Africa is likely to see prices closer to ZAR50c/kWh, but maybe below ZAR40c (Wright, 2019).

Ongoing modelling and the current revised IRP 2019 point to a rapid shift to the adoption of renewable energy sources paving the way to move away from coal. The latest revision being the updated draft IRP 2023. The South African government through its climate change commitments has pledged to reduce emissions by at least 42% lower than the business as usual case by the year 2025. The IRP will be implemented via a mix of fossil fuels and RE based sources mainly wind and solar which have a positive environmental effect. The IRP seeks to permit 17.8 GW of capacity from renewable energy sources that will generate approximately 9% of the electricity in the supply mix by the year 2030 (Wright, 2019). One possible scenario from energy models for South Africa to install 96 GW of VRE by 2050 is shown in Figure 1: Generation expansion to reach variable renewable energy target of 96 gigawatts (Chartan, Reber & Brinkman, 2017).

1.3 Research Problem

The problem is that solar and wind are intermittent sources which suffer from resource unavailability and must be supported by significant investments in energy storage and/or gas peaking plants if a reliable supply of energy is required.

The potential of green hydrogen opens several important questions for energy storage. Can it become a viable technological solution for balancing renewable energy sources looking at the present LCOS, as a large-scale energy storage technology relative to other technologies like batteries? Can green hydrogen be stored and used to generate power back into the grid as electricity to be dispatched during peak demand periods and what economic, financial, and engineering factors need to be addressed for it to be competitive? With many electrical power plant closures and the decline of fossil fuels, is green hydrogen the answer? Hydrogen is nothing new, but could it be used in a new way? (Lin, Zhao & Wu, 2020).

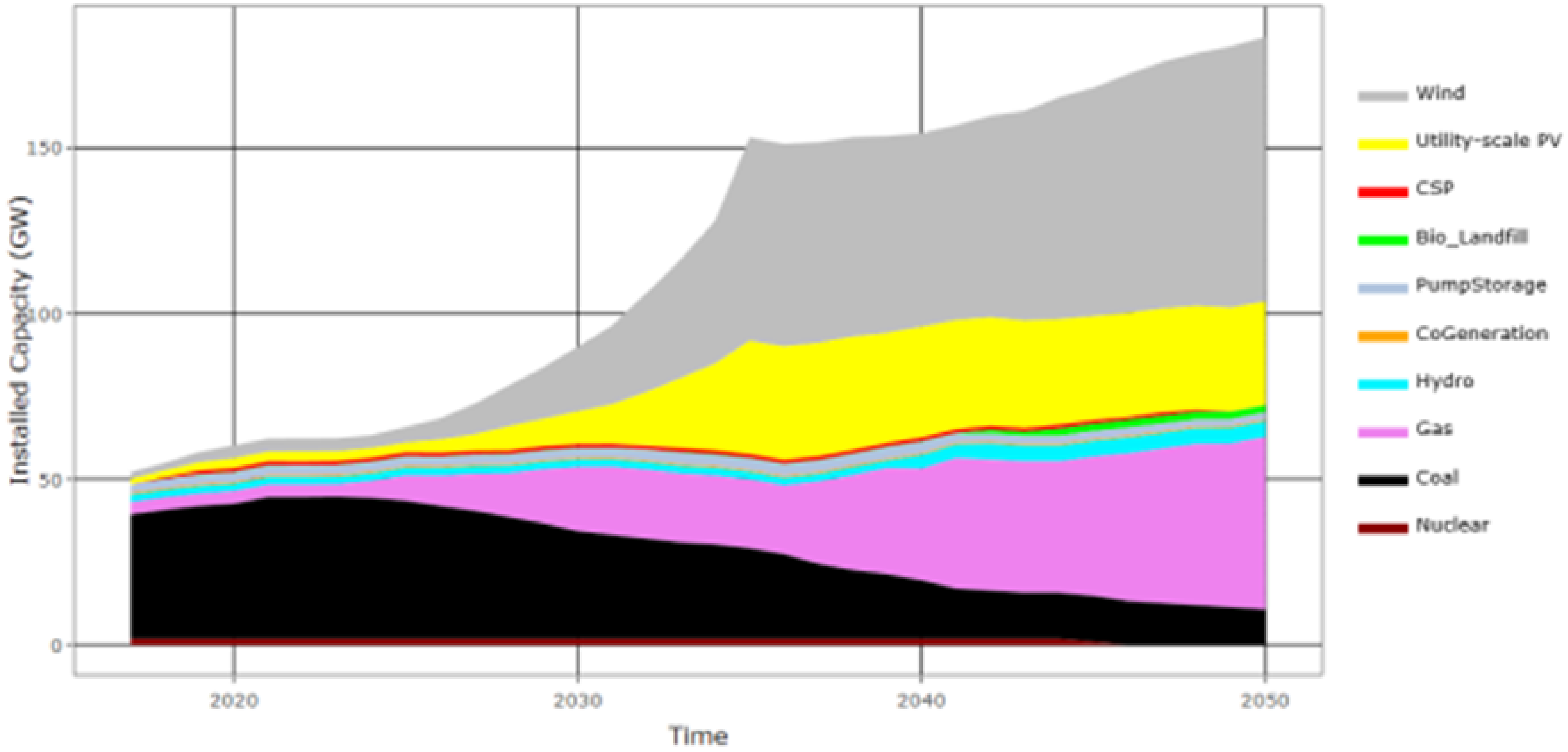

Figure 1: Generation expansion to reach variable renewable energy target of 96 gigawatts (Source: Chartan et al., 2017)

1.4 Research Questions

The research questions in this project are:

1. What is the present levelised cost of storage (LCOS) for green hydrogen, relative to competing technologies such as the lithium-ion (Li-ion) battery and pumped hydro storage?
2. What economic, financial, and engineering factors (referred to as turning points) would need to be addressed for the technology to be competitive?
3. Based on the framework of the multi-level perspective (MLP), which policy strategies that can implemented on the fossil fuel regime that will result in the adoption of green hydrogen as a viable energy storage technology?

1.5 Significance of the Study

The research builds upon previous and current research in the transition to lower carbon sources to mitigate the effects of global warming and climate change. Past research work on adding renewable energy sources onto the electricity grid mainly concentrated on particular aspects such as the curtailment of wind power or adjustment of network parameters while, recently, attention has shifted to implementing energy storage. Green hydrogen is convenient for long term and seasonal energy storage. Pumped hydro is a mature technology however it has a negative learning rate mainly because a lot of appropriate locations for pumped hydro are already in use(Sebastiaan Mulder & Sikke Klein, 2024). Batteries are practical for short term storage. Early studies and research show that green hydrogen could be produced from excess electricity in times of over-generation, following which it could be stored and later used to generate electricity back to the grid in times of high consumption or electricity shortages, such as load shedding (Quarton, Tlili, Welder, Mansilla, Blanco, Heinrichs, Leaver, Samsatli, Lucchese, Robinius & Samsatli, 2020).

It is of interest to evaluate the critical turning points for green hydrogen as an alternative energy storage technology in South Africa through the energy stakeholders in South Africa, because they are decision makers, and their perspectives will determine the future of the technology. The introduction of green hydrogen in the energy mix can be a useful tool to maximise renewable power integration in relation to a constrained grid.

However, certain conditions may have to be fulfilled first, such as capital investments and green hydrogen storage constraints. As more renewables are being integrated into the electricity networks, new methodologies of managing the energy supplies should be implemented because the addition of more intermittent VRE to municipal electricity networks can result in complex problems related to operating those networks.

New techniques to regulate and operate these networks are required. This will ensure their safe operation with optimal use of the VRE. Intelligent energy storage methods and closer integration of different energy vectors can help in accommodating these intermittent sources of energy. Hydrogen has a high energy intensity per unit mass compared to batteries and can be transferred to storage as intermittent renewable energy, an energy carrier or as fuel for vehicles (Carr, Premier, Guwy, Dinsdale & Maddy, 2014).

Globally, there have been changes in energy policies as renewable energy sources have increasingly started contributing to power generation. The innovations and introduction of new energy technologies offer sufficient reason to discuss South Africa's energy policy with regards to green hydrogen. The tenets of South Africa's existing energy policy should also be presented in the context of the green hydrogen economy. The possibilities and limitations regarding the shift to green hydrogen power in South Africa should be discussed, factoring in a number of aspects that include the level of development of the electric power infrastructure, the current and future electricity consumption patterns, the current geopolitical and economic situation of South Africa and its membership of the South African Development Community (SADC) region (Stygar & Brylewski, 2013).

This study is seen as being useful to support decision makers, stakeholders, and local authorities in the implementation of a green hydrogen policy push since the South African government has allowed municipalities to procure renewable energy from sources other than Eskom. The study analysis can give the energy industry players and investors an understanding of the potential economic barriers to the uses of green hydrogen in the South African context, including potential early adopters. It can be noted that apart from the benefits of grid stability through Eskom or municipal grids, green hydrogen has various uses and consumers who could also benefit from its production as illustrated in Figure 2 below.

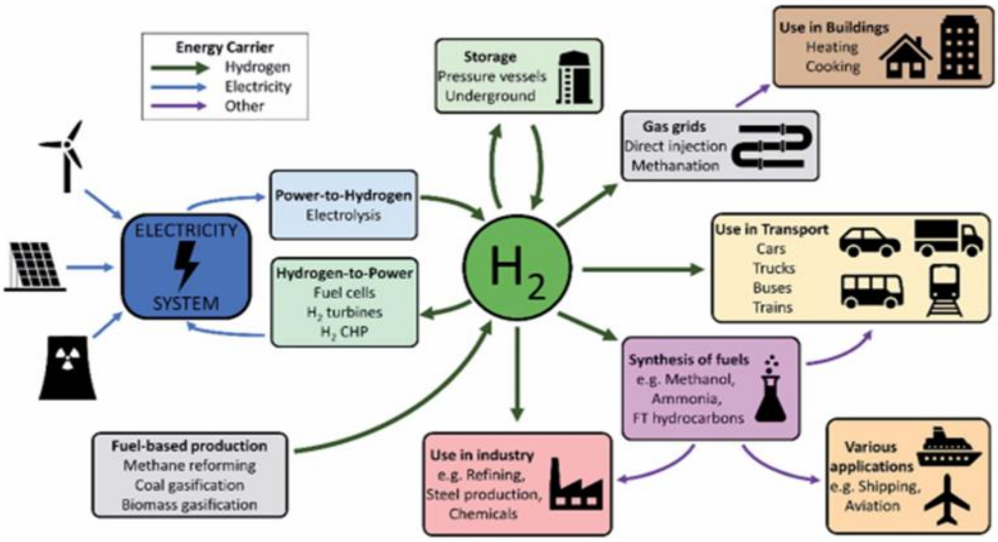

Figure 2: Use and production of green hydrogen (Source: Quarton et al., 2019)

Green hydrogen can be used in gas turbines for power generation to increase power system flexibility. Hydrogen and hydrogen-based fuels are potential carriers of energy from renewable sources over long distances. Hydrogen is also a potential source for seasonal energy storage apart from its long term energy storage capabilities.

1.6 Limitations of the Study

The main limitation of this study is the size of the sample participants. This may produce a bias in the final outcome of the results that may not precisely represent the majority of the population.

1.7 Definition of Terms

1.7.1 *Energy storage*

Energy storage is the process of storing any form of energy be it chemical, electrochemical, mechanical, electromagnetic, and thermal for future use.

1.7.2 *Green hydrogen*

Green hydrogen refers to a form of hydrogen gas produced by passing electricity through water. The electricity is generated from renewable power sources like wind and solar PV.

1.7.3 *Grid stability*

Grid stability is the ability of a power grid to be resilient to large disturbances (Auer, Kleis, Schultz, Kurths & Hellmann, 2016).

1.7.4 *Integration of renewables*

This refers to the addition of distributed renewable generation sources to the electrical grid at the low-power consumer level, micro-grid level and the main grid level (Hussain, Rahim, Nadeem, Fatima, Iqbal, Asif & Javaid, 2018).

1.7.5 *Intermittent power*

This refers to power from renewable energy sources, mainly wind and solar PV which are dependent on weather patterns. The electricity they generate is variable (Mills, 2011).

1.7.6 *Renewable energy*

This is energy produced from natural resources that self-replenish such as sunlight, wind, rain, tides and geothermal heat (Gorjian, 2017).

1.7.7 *Levelised cost of storage*

This is a tool used to calculate the ratio between the total costs incurred in acquiring and operating a storage technology to the total lifetime energy in kWh or MWh generated or discharged from that storage device (Cristea, Tîrnovan, Cristea & Făgărășan, 2022).

1.7.8 *Techno-economics*

This is a technique used to evaluate the economic performance of systems or processes in industries. A techno-economic analysis will have to be carried out and has a consecutive pattern starting with process design, modelling, equipment sizing, capital cost estimation, operating cost estimation and cash flow analysis (Chai, Phang, Yeo, Lock & How, 2022).

1.7.9 *Turning point*

A period or time where a change happens also called a crucial moment.

1.8 Assumptions

The study is based on the following assumptions:

a) Honest answers: The research assumes that participants will answer the survey questionnaire truthfully. This is mainly because the participants might have different views and vested interests with respect to renewables and hydrogen usage.
b) Participant sincerity: The research assumes that participants are genuinely interested in being part of the study and do not have any other

motives such as strengthening business and personal relationships with the researcher.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

It is crucial to acknowledge the background and development of green hydrogen including such aspects as the policy framework, the value chain and the global political economy of energy production, particularly in South Africa. The literature review chapter is conceptualised within the objectives and research questions of the study. The purpose of the chapter is to critically review the green hydrogen economy and introduce transition theory which is used as the main guideline for this project. The chapter focuses particularly on green hydrogen as an alternative energy storage technology in the South African energy context, the country's hydrogen development plan, its policy and the policy pressure that can be exerted on the fossil fuel regime for the adoption of green hydrogen as a large-scale energy storage technology. It also covers which technology path can be used to convert stored hydrogen back to electricity, the cost of green hydrogen particularly the LCOS and at what point this cost would be sufficiently attractive to warrant investments in systems that use green hydrogen as an energy storage technology.

The sources of information for this chapter consist of scholarly journals, theses, dissertations, books, references quoted in books, papers presented at conferences and the internet.

2.2 South African Electricity Sector

The production of electricity in South Africa is dominated by fossil fuels, mainly coal, with an increasing percentage of renewable contributions in the year 2020. Electricity generation is mainly from coal with a total contribution of 83.5% in 2020 translating to 8 351 844 TWh. Nuclear had 52 115 TWh, renewables had 105 23 1 TWh and diesel had 19 TWh. A total of 5.6% of the power in the system was generated from wind, solar PV and CSP, as depicted in Figure 3 below (Calitz & Wright, 2021).

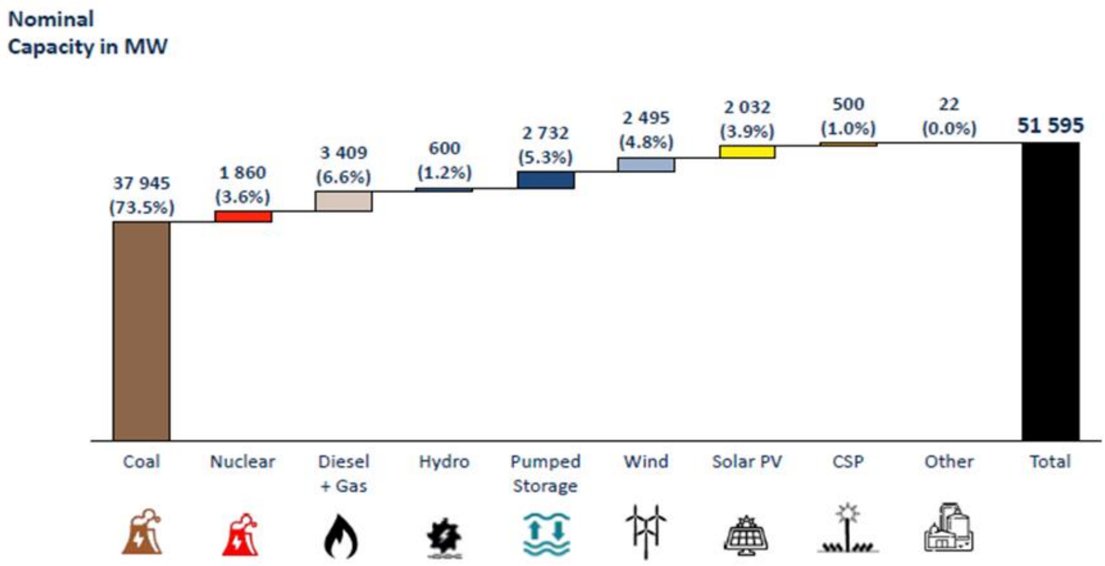

Figure 3: Electricity mix in South Africa (Source: Calitz & Wright, 2021)

South Africa has a lot of energy sources that can drive economic growth and social development for the benefit of its populace. The electricity market is shifting globally from a centrally controlled supply side which South Africa should consider implementing as well. The changes in technology, latest infrastructure, and lower production costs are making supply management complex. A variety of energy sources such as renewables and distributed generators make performance monitoring important. Electricity consumption patterns are changing with additional self-generation, energy efficiency and energy storage technologies. Large, rigid and vertically integrated organisations such as Eskom are struggling to adjust to the new market conditions. De-carbonisation pledges to address climate change are accelerating investment in renewable infrastructure that improves both supply and demand management, including new technology such as smart grids and digitisation(Department of Mineral Resources and Energy, [DMRE], 2019).

Energy security for economic growth is crucial. Across the globe, energy is changing. New technologies, shifting customer needs, and the effects of climate change are affecting how electricity is generated, supplied and consumed. As South Africa reacts to these changes, it must address the challenges that pose a threat to its electricity supply, and which include storage for economic growth. Energy reforms were proposed in the past with the 1998 white paper on energy policy playing a crucial role. In that paper, the South African government pointed out reforms necessary for the electricity supply, including the restructuring of Eskom so as to ensure a reliable, competitive and transparent system (DMRE, 2019).

South Africa has committed to a Renewable Energy Independent Power Producers Programme which has numerous projects in the pipeline at various stages. According to the 2024 South African Renewable Energy Grid Survey (SAREGS), contracts of about 133GW RE capacity are in the pipeline with wind at 48GW (RenewAfrica.Biz, 2024). Eskom has also embarked on a capacity expansion programme with the last unit of Kusile power station to be completed in 2022. This is expected to provide enough capacity to cover the projected consumption and decommissioning of plants up to approximately 2025. The Integrated Resource Plan (IRP) shows the implementation plan that is required (Refer Table 1 below) with the latest release being the draft IRP 2023.

Table 1: Integrated Resource Plan of 2019 (Source: DMRE, 2019)

Recommended plan IRP 2019	Coal		Nuclear	Hydro	Storage	PV	Wind	CSP	Gas & Diesel	Other
Current Base	37149		1860	2100	2912	1474	1980	300	3830	499
2019	2155	-2373					244	300		
2020	1433	-557				114	300			
2021	1433	-1403				300	818			
2022	711	-844			513	1000	1600			
2023	750	-555				1000	1600			
2024			1860				1600			500
2025						1000	1600		1000	500
2026		-1219					1600			500
2027	750	-847					1600			500
2028		-475				1000	1600		2000	500
2029		-1694			1575	1000	1600			500
2030		-1050		2500		1000	1600			500
Total Installed Capacity by 2030(MW)		53364	1860	4600	5000	8288	17742			
%Total Installed Capacity(% of MW)		43	2,36	5,84	6,35	10,52	22,53			
% Annual Energy Contibution(% of MWh)		58,8	4,5	8,4	1,2	6,3	17,8			
	Installed Capacity									
	Committed/Already Contracted Capacity									
	Capacity Decommisioned									
	New Additional Capacity									
	Extension of Koeberg Plant Life									
	Distributed Generation Capacity for Own Use									

Since the promulgation of the IRP2019, a couple of changes have occurred in the energy landscape resulting in the draft IRP2023. It has two horizons,1 (2023-2030 & 2 (2032-2050). Horizon 1 has set targets of 4.5GW for wind power, 3.6 GW for PV solar, and considerable investments in battery energy storage of about 4.1GW (DMRE, 2024).

South Africa recognises the climate change crisis facing the planet and human-kind. According to DMRE (2019), research data indicates that climate change will affect poor people the most, and the African continent is particularly vulnerable. Thus, climate action plans to meet the objective of limiting changes in global average temperatures to 1.5 degrees are needed. South Africa is committed to attaining its nationally determined contribution to achieving emission targets as per the United Nations Convention to Combat Climate Change, the Kyoto Protocol, and the Paris Agreement. The just energy transition presents an opportunity for a systematic transformation from coal and other fossil fuels to an increased reliance on renewables and other energy sources as in the IRP (DMRE, 2019).

Considering the existing energy mix, the mitigation challenge faced by South Africa is considerable. According to the Green Cape (2024), edition of its annual green economy market intelligence reports, large-scale renewable energy experienced a tremendous growth in 2023. The removal of licensing requirements for RE projects and efforts to tackle the shortages of electricity have all enhanced this growth. ERSA has recorded a tremendous growth even in private registrations from 2021 to 2023 as shown in Figure 4 below (GreenCape, 2024).

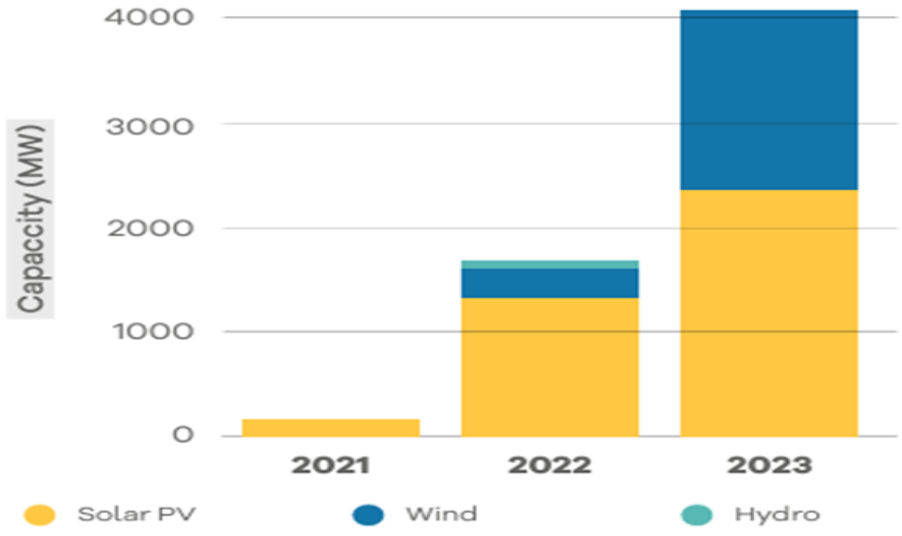

Figure 4: Total registered private projects from 2021(Source: GreenCape, 2024).

As the integration of renewables increases, the total annual energy served by VRE will also increase thus adding to the complexity of how the South African grid can be managed. In the current state, without enough energy storage, all energy produced up to and beyond this amount will have to be curtailed.

2.3 Renewables and Green Hydrogen

Hydrogen is not new but emerging low carbon and carbon free applications make it a powerful potential option to achieve carbon reduction goals. According to Mitrova, Melnikov and Chugunov (2019), the International Energy Agency forecast that by 2040 between 20% and 35% of global electricity production will be from solar PV and wind power plants. Another forecast by Bloomberg New Energy Finance estimates that it will be around 40%. Hence, the number of renewable plants to be brought online is expected to increase. An emerging steady demand for energy storage technologies is necessary because of this development. Energy storage will be crucial for output fluctuations, in both the short-term and long-term (Mitrova et al., 2019).

Hydrogen is being considered as a means for long-term energy storage. Currently, the long-term energy storage market is dominated by hydroelectric pumped storage, with approximately a 99% share of the storage capacity in the world providing support for renewable sources. Some drawbacks for pumped storage hydro power plants are that they require specific sites that can accommodate two reservoirs with a specific amount of pressure between them, relatively high costs of construction, high costs for operation and maintenance, as well as prolonged periods on return of investments (Ali, Stewart & Sahin, 2021).Despite the drawbacks, pumped hydro remains a proven and mature technology with a high energy density. It is envisaged that battery storage will occupy the space of short-term energy storage facilities complementing the other technologies. For long-term storage, relatively low-cost excess electricity generated from renewables can be used in a process called electrolysis in which water is split into hydrogen and oxygen. This is represented in Figure 5 below (Dufo-López, Bernal-Agustín & Mendoza, 2009).

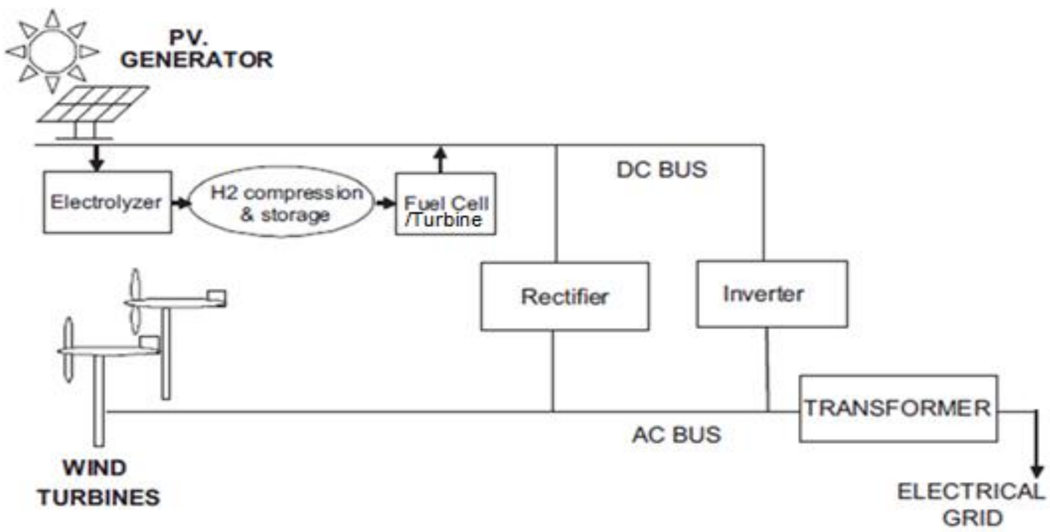

Figure 5: Green hydrogen for generating electricity (Source: Dufo-López, Bernal-Agustín & Mendoza, 2009)

The green hydrogen from this process can be stored for a long period of time using various means, such as underground storage facilities, salt caves and repurposing existing underground natural gas storage facilities. The hydrogen gas can be used for electricity generation at a convenient time (Mitrova et al., 2019).

According to Becherif et al (2015), hydrogen is a very simple molecule with the lowest energy content by volume and has the highest energy content compared to other fuels like coal by weight. Because of its high energy content, it is mostly used as a fuel in fuel cells and rockets. Green hydrogen (GH) energy is derived from a process of electrolysis that produces zero harmful emissions, unlike fossil fuels. The heating value of hydrogen is almost three times higher when compared to petroleum.

According to Thapa and Thapa (2020), hydrogen demand is expected to increase 10 times by 2050 compared to the demand in 2015, however the latest trends according to the IEA (2024) reveals that the demand for hydrogen grew around 3% in 2022, and still remains centred in traditional applications with slow growth rates in new uses. The increase in demand was expected to come mostly from new sectors, such as transportation and industrial energy. Future demand for hydrogen should be supplied as green hydrogen but according to the IEA (2024) low-emission hydrogen production lingered below 1% of the total hydrogen production in 2022. This will significantly delay meeting global emission targets.

Developments in electrolyser technologies are increasing, scaling up from megawatt (MW) to gigawatt (GW) scales. The costs of electrolysers are projected to be halved between 2040 and 2050, from USD840 per kilowatt (kW) currently, with renewable electricity costs expected to continue falling as well. It is expected that renewable hydrogen will also become cheap as RE costs continue to fall. Water efficiency in the production of green hydrogen is a key element to be considered. To produce 1 kilogram of hydrogen using electrolysis, approximately 9 litres of water is consumed. Water for green hydrogen production must be pure to eliminate contamination of the electrolysers as this results in a reduction of efficiency. To purify the water, more energy is required for evaporative processes. Research into the use of salt water as an input to the electrolysers is ongoing. With the proposed scale of future green hydrogen production, there is a need to secure access to reliable and sustainable supplies of water. This is an important factor in locating hydrogen projects on top of other factors (Thapa & Thapa, 2020).

Recent studies have continued to recognise the drawbacks of green hydrogen to grid scale electricity. This is mainly in relation to the cost of production, transportation and storage. Other additional factors relate to the conversion efficiency. In the process of electricity-hydrogen-electricity, the energy cycle efficiency is reduced to the amount of heat produced (Leijiao Ge et al., 2023).

The South African power system is expected to connect higher penetrations of variable renewable energy (VRE) over the coming years, as the costs of solar PV and wind continue to decline becoming more competitive with fossil fuel sources such as coal. Wind and solar power projects being implemented in the renewables programme have become cheaper than many conventional newly-built alternatives in South Africa. Trends suggest a continued increase in the sharing of renewable energy on South Africa's grid with adoption of coal experiencing a huge reduction in capacity. Consequently, it is important to assess how green hydrogen can be integrated into the grid to balance the system from the effects of potential high penetrations of renewables (Chartan et al., 2017).

2.4 Energy Storage Technologies

In Becherif et al (2015), the European Commission highlighted the importance of energy storage as a key element in achieving energy sustainability goals that lead to energy and cost savings. The electricity transmission and distribution sectors that will most probably have power quality and energy management problems are the potential areas where energy storage systems (ESSs) can be fully used. Energy storage strengthens the existing power plants and, at the same time, avoids expensive infrastructure upgrades. Energy storage could act as a regulator that manages the fluctuations of electricity from renewable energy (RE) resources, especially long-term storage via green hydrogen (Becherif et al., 2015).

The literature identifies different forms of energy storage which includes compressed air energy storage (CAES), flywheel energy storage (FES), pumped hydro energy storage (PHES), battery energy storage (BES), flow battery energy storage (FBES), superconducting magnetic energy storage (SMES), super capacitor energy storage (SCES), hydrogen energy storage, synthetic fuels and thermal energy storage (TES). These energy storage systems are viable for different applications depending on numerous characteristics such as parameters for energy and power density, response time, cost and economies of scale, efficiency, operating constraints, and monitoring and control equipment (Becherif et al., 2015).

An appropriate energy storage system must have a number of suitable properties such as a high power density. It should be relatively easy to deploy and integrate with RE sources and the existing energy network. It must be economically viable and energy efficient. The system has to be reliable and have a high degree of operational safety.

Table 2 shows a comparison of different types of energy storage systems. These systems can be used for either power-intensive operations (use of power for relatively short periods of time) or energy-intensive operations (energy needed for relatively long periods of time). Batteries are suitable for short storage systems. Batteries have a low energy storage density and they self-discharge. This limits their use as a long-term storage solution. Presented with such a challenge, energy storage systems based on hydrogen technologies are becoming one of the most interesting options. These hydrogen-based systems use excess electricity that is converted to hydrogen through an electrolyser and stored in pressurised tanks. The stored hydrogen can later be used to produce electricity in a fuel cell (Becherif et al., 2015), however there isn’t a consensus in the literature as some critics have pointed out challenges with implementing green hydrogen for electricity production.

According to Liebreich (2023), the process of hydrogen conversion and back to electricity is very inefficient with energy losses of between 50%-75%. He argues that it is also expensive to convert hydrogen rather than just use the electricity directly. The author proposes the use of pumped hydro and batteries as they are more efficient and fare equally well in terms of costs for storing and generating electricity (Michael Liebreich, 2023). In the 2023 annual renewables report, the IEA revised downwards the green hydrogen growth prospects by about 50% for the continent of Europe. They pointed out the cost of infrastructure to get the green hydrogen economy up and running which hinders hydrogen production for electricity generation (Polly Bindman, 2024).

Table 2: Energy Storage Systems (Source: Becherif et al., 2015)

Technology	Capital Costs($/kWh)	Durability (Year)	Power Density(W/kg)	Gravimetric Energy Density(W/kg)	Energy Efficiency (%)
Li-ion Battery	600-2500	2-50	100-5000	75-250	85-90
Super-capacitor	300-2000	25+	500-5000	0.05-30	97
Pumped-hydro	5-100	40-100	-	0.5-1.5	70-87
Hydrogen	2-20	30	-	400-1000	-
Flywheel	1000-5000	15-20	400-1600	5-130	80-99
Pressurised air	2-50	20-100	-	30-60	40-80

To deal with renewable energy integration, power grids employ technologies such as backup peaker power plants and other dispatchable sources. These tools are sufficient for low levels of RE penetration. However, the introduction of high levels will require the use of other storage technologies like green hydrogen.

Countries such as Germany have already recorded a high penetration of VRE. For instance, on 9 March 2019 the VRE level was 90%. In order to accommodate the planned increase in the average annual share of RE predicted globally (65% by 2030), the available technologies will have to be complemented with new storage technologies (Mitrova et al., 2019).

2.5 Transition Theory

Transitions occur because of windows of opportunity or a scenario where multiple events happen at the same time. This brings about change forced by techno-economic events, participation by niche players strong enough to challenge the status quo, destabilisation of the status quo and changes in the political landscape (Walwyn, 2020). Transitions in energy markets occur because of changes in technology that result in major economic as well as commercial benefits. The climate change narrative has led to more research in sustainable transitions as economies shift from a high carbon to a greener economy such as the use of green hydrogen. This has resulted in the formulation of energy transition policies with the sole aim of decarbonisation (Mittha, 2021).

The transition to low carbon sources like green hydrogen also brings with it the energy trilemma and according to Heffron, Mc Cauley & Sovacool (2015), the objective is to attain a form of system balance in economics, politics and the environment (refer to Figure 6) hence the need for sustainable transitions.

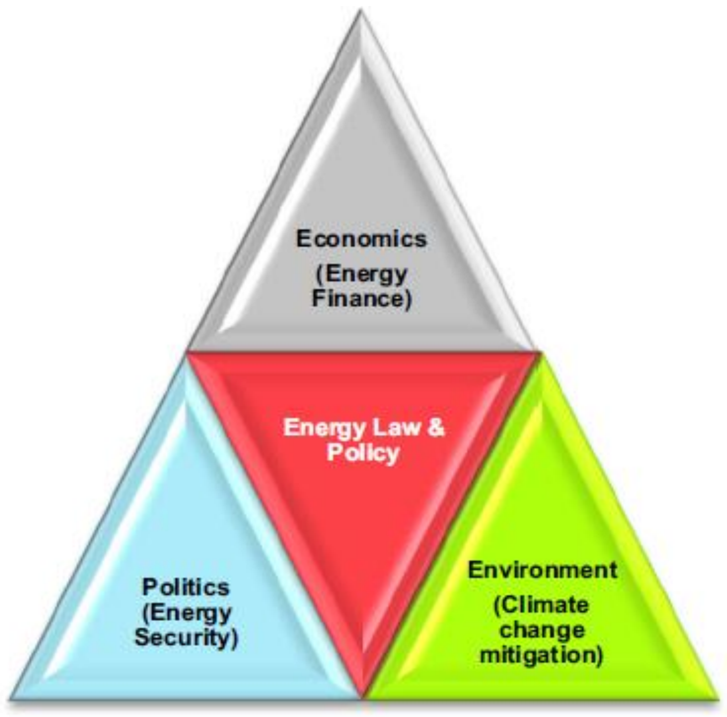

Figure 6: The energy trilemma (Source: Heffron et al., 2015)

Resolving the trilemma requires a sustainable transition and energy justice. This brings about a just and equitable balance amongst the three competing aspects of the energy trilemma.

2.5.1 *Sustainable energy transition*

Energy transitions have occurred before in the past. A complete shift from a fossil fuel-based energy system to a sustainable one is extraordinary on a large scale. This requires a social paradigm shift. The concept of a sustainable energy transition (SET) covers environmental factors, availability of resources, justice and equity as well as factors covering the energy and economic accounting areas (Sgouridis & Csala, 2014).

Society has not yet experienced large scale SET. Past transitions were only based on fossil fuel primary energy. The study of energy transitions is an evolving field as identified by Grubbier (2012). He identified that:

- Energy consumption will always be higher than the available generation capacity.
- Transition in energy is different when comparing nations. In large, developed economies it is slow, but it is faster in small, developing nation economies which do not have a complex infrastructure.
- Energy transitions move through a certain path. It starts with the experimentation phase and moves on to the production of detailed dominant designs that start as a niche but are gradually accepted by all, standardisation, economies of scale and spreading from developed countries to less developed nations.

Economics dictates that the transition should be smooth but empirical evidence shows that the energy system itself is complex creating some inertia in the price response system. This is expected as well in the transition to green hydrogen. This creates a policy problem which needs sound policies to avoid the prospect of a market failure in energy transitions, taking cognisance of climate change limitations (Sgouridis & Csala, 2014).

2.5.2 *The multi-level perspective*

When applied to socio-technical transitions, MLP is a theory that visualises dynamic patterns in transitions (Geels, 2011). (Refer Figure 7). The framework includes the following concepts:

- Economics which encompasses studies of trajectories, niches, path dependencies like the whole green hydrogen value chain.
- Science and technology which covers, for example, social networks and innovation.
- Structuration and neo-institutional theory which covers rules and institutions.

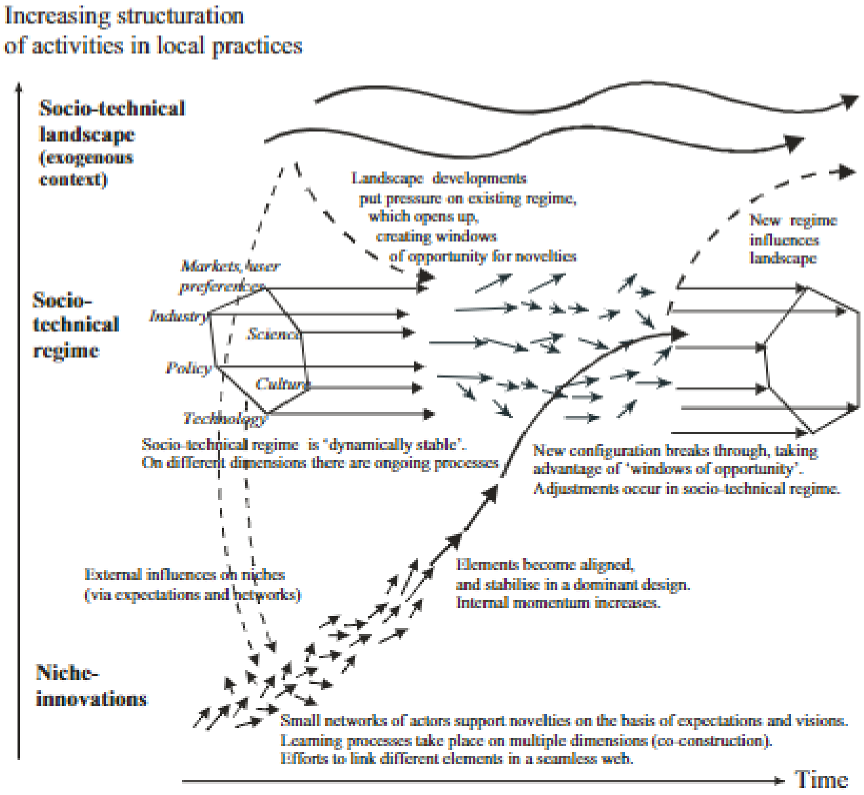

Figure 7: Multi Level Perspective theory on transitions (Source: Geels, 2011)

The MLP considers transitions to be illogical processes as products of the interaction of three systematic levels niches, socio-technical regimes and an exogenous socio-technical perspective. Each level has a mixture of elements arranged in some order. Levels that are higher are stable when the number of actors and the proportion of sequence among the elements is considered. Transitions are described as movements from one regime to the other such as from fossil fuels to green hydrogen. The niche as well as the landscape levels are viewed as acquired concepts and are described in association with the regime.

2.6 Green Hydrogen Electricity Generation

Figure 8 represents the relationship between green hydrogen and renewable electricity. The green hydrogen produced can be used for electricity storage and distribution which assists with the integration of renewables into the grid. Electrolysis is the process used for the production of green hydrogen. This is done when there is an excess of renewable power. The hydrogen stored can be used to generate electricity back to the grid using fuel cells and turbines when the demand for power exceeds the generation. Long distance transportation of hydrogen is feasible through pipelines to remote locations where it is needed (Dincer & Acar, 2018).

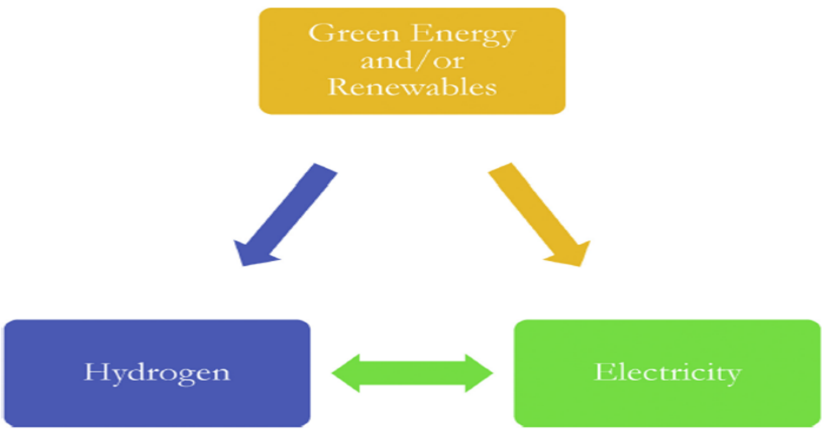

Figure 8: Integration options of green hydrogen with electricity (Source: Dincer & Acar, 2018)

Green hydrogen has the potential to play a crucial role in the power sector, where it can be used in hydrogen fired gas turbines and large scale stationary fuel cells. These can then complement renewable sources of electricity and replace fossil fuels in the energy mix.

2.6.1 *Hydrogen-fired gas turbines*

Hydrogen can be used to provide grid and off-grid power. It can replace conventional fossil fuel power generation sources as a heating fuel. It can be used in flexible simple cycle hydrogen peaking turbines (refer to Figure 8). Combined cycle hydrogen turbine technology can also be used for baseload deployed to assist the grid.

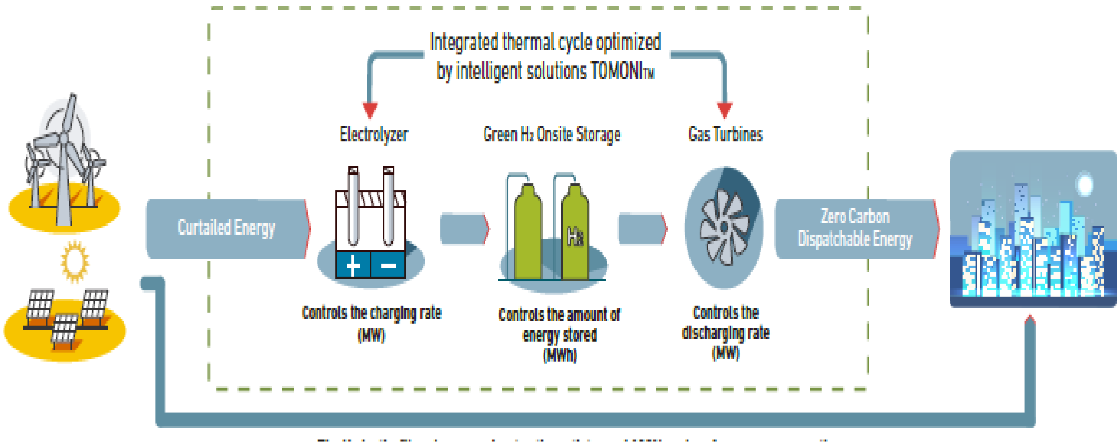

Figure 9: Hydrogen-gas powered turbine (Source: IGEM, 2020)

Traditionally, power systems have been providing flexible, stable and resilient generation using fossil fuels. In recent years, there has been an increase in RES deployments with solar PV and wind accounting for more than 50% of new power stations being added onto the power grids worldwide. Flexible generation and storage are becoming a necessity. Deployment of hydrogen turbines will offer an alternative way to provide grid stability and meet climate change goals as the stored hydrogen can then be used for the generation of low carbon electricity when demand increases (IGEM, 2020). Hydrogen, be it in liquid or gas form, contains more energy per kilogram in comparison to other fuels (refer to Table 3).

Table 3: Hydrogen parity with other fuels (Source: Felseghi, Carcadea, Raboaca, Trufin & Filote, 2019)

Fuel Type	Energy/Mass Unit(J/kg)	Energy/Volume Unit(J/ m^3	Energy Reserve Factor	Carbon Emission Specific (kgC/kg Fuel)
Liquid Hydrogen	141,90	10,10	1,00	0,00
Hydrogen Gas	141,90	0,013	1,00	0,00
Fuel Oil	45,50	38,65	0,78	0,84
Gasoline	47,40	34,85	0,76	0,86
Jet Fuel	46,50	35,30	0,75	_
GPL	48,80	24,40	0,62	_
GNL	50,00	23,00	0,61	_
Methanol	22,30	18,10	0,23	0,50
Ethanol	29,90	23,60	0,37	0,50
Biodiesel	37,00	33,00	_	0,50
Natural Gases	50,00	0,04	0,75	0,46
Coal	30,00	_	_	0,50

According to IGEM (2020), hydrogen has been shown to be viable when deployed in both peaking plants, providing short term power, or in CCGT, providing long term power. Large volumes of hydrogen can be stored at low costs with cavern-based storage expected to reach about USD 0.30 per kilogram of hydrogen when compared to battery storage. Hydrogen offers an advantage of long-term storage over batteries with varying times ranging from five hours to days and weeks. The round trip efficiency via electrolysis for power generation is about 45%. In other applications, hydrogen based fuel cell generators have been deployed as backup power generators in hospitals and remote locations (IGEM, 2020).

2.6.2 *Fuel cells*

By 2018, over 850MW of stationary fuel cell technology with more than 200kW was in operation globally, generating electricity and combined heat plant (CHP) applications. Much research is ongoing into fuel cells presenting an opportunity for energy generation. These fuel cells use hydrogen which solidifies the case for green hydrogen production. Fuel cells are electrical cells that are fed fuel with electrical power produced and being maintained indefinitely. Fuel cells convert hydrogen directly into electrical power which is the opposite of electrolysis (see fuel cell components in Figure 10 below). Electricity is produced by an electro-mechanical reaction hence offering the advantage of efficiency when compared to thermal plants powered by fossil fuels. Fuel cells offer no noise pollution or emissions.

2.6.2.1 *Components of a fuel cell*

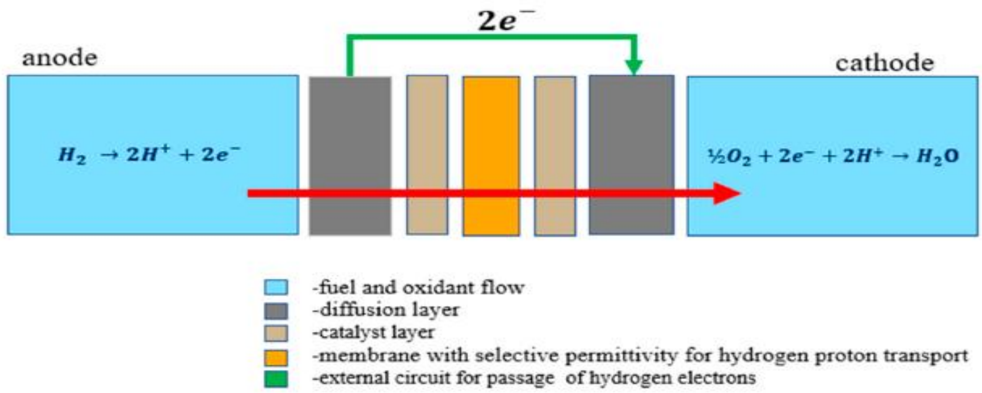

Figure 10: Components of a fuel cell (Source: Felseghi et al., 2019)

The fuel cell consists of the electrolyte, the catalyst layer, and the bipolar plate. Most electrolytes are liquid electrolytes. The electrochemical reactions occur in the catalyst layer. The electrodes are dipped in catalyst particles which increases the reaction rate of the fuel cells. The bipolar plates direct the gases to the electrolytic exchange surface and push the produced current. Bipolar plates have high conductivity, are corrosion resistant and must be chemically inert (Felseghi et al., 2019).

The different types of fuel cells all employ the same operating principle. The hydrogen starts at the anode where the catalyst separates the electrons from the positive ions (called protons). Oxygen combines with electrons at the cathode thus producing hydrated water. The electrons that are produced at the anode then form an electrical circuit that determines the electrical current. Alternative efficient technology combines hydrogen fuel cells and turbines to generate power. Heat that is produced from this process is recovered and used for power generation or space-heating purposes (IGEM, 2020).

2.7 Hydrogen Economy in South Africa

A few pilot projects involving hydrogen have been completed on a small scale and are operational in South Africa. There is no large-scale hydrogen infrastructure currently. The draft IRP for 2018 to 2019 does not include hydrogen. However, according to Hoffmann (2019), recent developments indicate that Sasol will play a significant role in this space, and this is expected to result in notable growth in the domestic hydrogen market. Proposals for a hydrogen valley infrastructure are being put in place. Most of the hydrogen in the South African market is made from methane and steam reforming. No hydrogen is being produced from renewables which is problematic with regard to emissions. Most of the hydrogen is used in the manufacture of fertilisers (Hoffmann, 2019).

South Africa has high quality and low cost renewable resources, mainly solar PV, and wind energy. These can be leveraged to produce green hydrogen at a competitive cost. Hydrogen appears to offer an alternative way of storing energy and can easily be used to re-generate electricity back into the grid. Production of hydrogen through electrolysis helps with grid balancing services(Hoffmann,2019). The potential for electricity to hydrogen integration makes it an interesting option for South Africa considering the shortage of electricity the country has been experiencing. Producing green hydrogen presents an alternative pathway for managing the electrical network better. Lower costs of production can be expected by exploiting the available renewable resources potential.

2.7.1 *Acceptability of green hydrogen technology*

For green hydrogen technology to be successful it does not depend on technical issues only such as efficiency and production costs, but also on the way the final users view it (Kovač, Paranos & Marciuš, 2021).

The literature on the social acceptance of new technologies begins with an in-depth analysis of the origins, forms, and the effect it has on society as a whole. For a more effective analysis, differentiation of technology from technology at work and large-scale technology is applied. Hydrogen technology is closely compared to lithium-ion batteries. The emphasis is mainly on efficiency. This creates biased views in terms of acceptability and implementation ability of hydrogen technologies. A transition to a low carbon future requires new technologies and infrastructure and social acceptance is one of the issues that has to be addressed. Studies and surveys are useful tools to gauge the chances and risks of acceptance (Glanz & Schönauer, 2021).

According to a 2021 study in Germany, there was a generally positive social acceptance in the population to the implementation of green hydrogen technologies based on the argument of energy transition. However, there were different views on how to reach those targets. This suggests that the success of implementing new technologies is also related to other elements, such as consequences and goals (refer to Figure 11). The JET conversation focuses on environmental concerns, adoption of renewables and grid decentralisation. The energy companies are viewed as mainly interested in making profits. In South Africa, it is a different field altogether as the economy is mainly based on fossil fuels. Implementation of these new hydrogen technologies might face some resistance. The view is that South Africa’s supply might not be secured to guarantee low-energy prices without fossil fuels such as coal (Glanz & Schönauer, 2021).

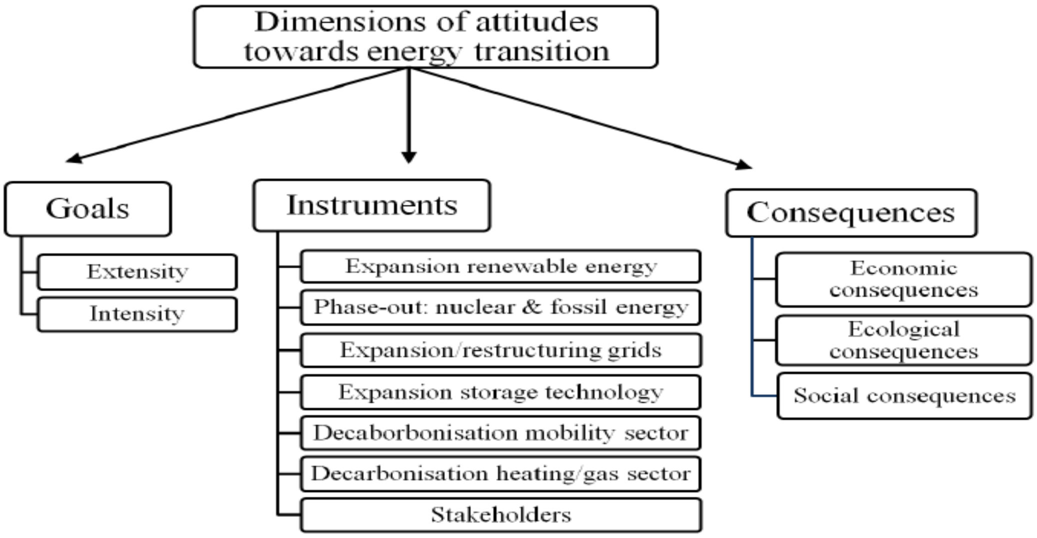

Figure 11: Dimensions of energy transition (Source: Glanz & Schönauer, 2021)

The path to a low carbon economy with new hydrogen technologies also affects society to a degree. This may be in the way members of society will have to change their lifestyle and consumption patterns, change energy infrastructure and accept new energy costs. In the past, large energy infrastructure projects did not gain social acceptance which, in turn, led to protests. For successful implementation of the green hydrogen economy and guided decision making, social acceptance is important (Glanz & Schönauer ,2021). Most critical boundaries for acceptance cover the negative and positive associations, the benefits and the perceived risks, concerns about land rehabilitation, inclusive participation, and the open sharing of information (Glanz & Schönauer, 2021).

Social acceptance is critical for an energy transition to prosper. The most crucial step to achieve carbon neutrality is the integration of renewable energy sources (RES) to replace fossil fuels. With the intermittency that comes along with RES, energy storage plays a critical role in transition. The hydrogen economy and the technology that comes with it are currently being researched globally (Kovač et al., 2021).

2.7.2 *Social and safety aspects of hydrogen*

Hydrogen has had some safety concerns when it applies to handling the element. Hydrogen can burn violently hence there is always an element of fear of explosion. Hydrogen has a combustion range, even static electricity can set it alight. A lot of challenges must be overcome to have hydrogen fuel mixes of over 30% (Kovač et al., 2021).

Another challenge in the development of hydrogen technology is access to financial support. Globally, governments are realising the potential and importance of hydrogen technologies. Money is needed for research and development, upskilling of employees, and product manufacturing. The problem is government uses taxes to finance such developments as well as private funders, and that money is public money. Public buy-in is thus needed to support such investments in hydrogen infrastructure. Projects must have a clear and simple definition of the goals on carbon neutrality and must be convincing enough for society to support it (Kovač et al., 2021).

An aspect that concerns society is how the adoption of hydrogen will affect their lives. The introduction of a new energy technology on a large scale could have an impact on social and economic wellbeing with the main concerns being accessibility, affordability, and reliability. Different communities have different views on the adoption of new technologies. Most of these questions have not been explored in sufficient depth to give feedback to scientists and engineers who are at the forefront of hydrogen technology development. The energy transition covers techno-economic and social aspects with hydrogen often seen as a dangerous gas. When it is in liquid form, hydrogen must be treated with due care, especially at low temperatures. Skin contact can result in hypothermia and inhaling the vapour might cause respiratory infections (Kovač et al., 2021).

When it comes to storage equipment, valves and storage vessels could be damaged by ice formation from moisturised air. This could lead to material failure if more pressure is added with a consequent explosive release of hydrogen gas.

The dangers linked to hydrogen can be physiological, for example, frostbite and respiratory ailments; physical, for example, component failures; or chemical, for example, ignition and burning. Usually, a combination of the above is a realistic representation of these dangers (Kovač et al., 2021).

Governments worldwide are carrying out innovative sustainable policies with RES at the forefront of replacing fossil fuels. Advances in hydrogen technology are compelling nations to incorporate hydrogen in legislation and energy development plans. This is enough evidence to reflect the importance of hydrogen storage in a green energy society. Industry and energy experts, companies, environmental associations, and consumer advisors are all involved in setting out national hydrogen strategies (Kovač et al., 2021).

2.8 Green Hydrogen Costs

The biggest challenge to widescale production of green hydrogen is economic viability as its production is more expensive than fossil fuels. On top of greater efficiencies to reduce costs, thermodynamic and technical limits must also be considered (Wanner, 2021). For green hydrogen to be economically attractive, its cost must be the same as that currently pegged for the production of grey hydrogen and fossil fuels (refer to Figure 12) (IRENA, 2021).

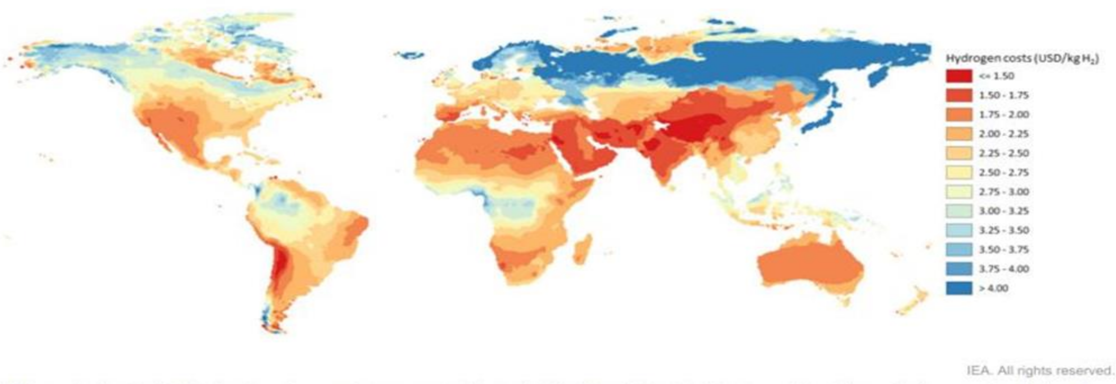

Figure 12: Cost of green hydrogen from wind and solar by 2030 (Source: IRENA, 2021)

As renewables continue to be cheap with a high number of operating hours being achieved, green hydrogen is expected to be produced in relative cost to hydrogen from fossil fuels. Research has proven that, on a large scale, hybrid solar PV and wind have capacity factors that go beyond 5000 hours per year. For green hydrogen to be economically viable, capacity factors of between 3000 to 4000 hours are required (IRENA, 2020).

2.8.1 ***Levelised cost of storage***

Previous studies have analysed the economics of hydrogen via the levelised cost approach. Fundamentally, the LCOS formula is derived from the levelised cost of energy formula which is extensively applied in the renewable energy sector where the Life Cycle Cost (LCC) of renewable energy like hydrogen is presented in terms of cost per energy output unit (Viktorsson, Heinonen, Skulason & Unnthorsson, 2017). According to IRENA (2020), the LCOS is:

$$LCOS = \frac{\sum_{n=1}^{N}(I_n + M_n + F_n).(1+i)^{-n}}{\sum_{n=1}^{N} E_{n.}(1+i)^{-n}} \quad (1)$$

Where: I_n=initial investment cost for year n,

M_n=maintenance cost in year n,

F_n=fuel cost in year n,

E_n=energy generation in year n,

i=discount rate,

N=lifetime

LCOS calculates the electricity cost in which the revenue from electricity sales would be at parity with the cost of generating it. LCOS has been applied in past techno-economic studies for integrating cost analysis together with investment costs, component life, escalation ratio and discount rate. LCOS factors include equipment costs, total installed costs, capacity factors, operations, and maintenance (O&M) costs in addition to other elements of the weighted average capital cost (WACC) (Perez, 2021).

Used in conjunction with LCOS is the Discounted Cash Flow (DCF) method. This is applied to evaluate hydrogen costs by factoring in investment costs, discount rates, operations and maintenance expenses. The DCF can project future investment outcomes and hydrogen production scenarios will be used to ascertain the most viable economic path for hydrogen. In this report, LCOS is used to frame the LCOS. DCF is applied to determine future hydrogen costs. The levelised cost method is relatively simple, permitting substantial flexibility in refining important LCOS parameters like electricity cost, CAPEX, and the utilisation factor.

2.8.2 *Costs of production*

Costs of production for green hydrogen depend on the costs associated with electrolysers and electrolyser capacity. They also depend on the costs associated with power generated from renewables. This electricity can be produced onsite or bought via the use of power purchase agreements (PPAs). Financing for green hydrogen projects is important as these projects are capital intensive. Alkaline electrolyser costs stood at USD 750-800 per kilowatt (kW) in 2020 and the sensitivity to capacity was a bit high promising to double below 1MW of capacity (IRENA, 2021).

2.8.3 *Costs of conversion*

Hydrogen will have to be compressed for trucks and the costs are around USD 1-1.5/kgH2 inclusive of the compression plant and electricity usage costs. On top of that additional costs of around USD 2-3/kgH2 to liquefy are added. The conversion process using ammonia is in the range of USD 0.4-0.9/kg. It has been projected that for the conversion and then extraction, the hydrogen will cost around USD 1.3-2.3/kg by the year 2030 (IRENA, 2021).

2.8.4 *Costs of transportation*

Hydrogen transportation comes with costs too. It is cheap to manufacture and consume onsite but the transportation costs for green hydrogen are high in addition to conversion costs. Electrolysers will have to be constructed close to the demand sources. The volume of the hydrogen being transported, the distance and the energy carrier all determine transport costs. Additional costs will also come in the form of infrastructure such as pipelines and other operational costs (IRENA, 2021).

2.9 Hypothesis and Propositions

The prior discussion leads to the following hypotheses and propositions:

2.9.1 *Hypothesis 1*

The LCOS for green hydrogen has to be sufficiently competitive for it to be deployed as a large-scale energy storage technology in the South African energy mix.

The cost of producing green hydrogen is a critical factor for it to be competitive. It is our proposition that with the large deployment of solar PV in South Africa, green hydrogen is economically viable with capacity factors of between 3000 to 4000 hours required.

2.9.1 *Hypothesis 2*

Green hydrogen could be a competitive storage technology should the cost of storage be reduced to a more competitive level.

It is our proposition that the cost of hydrogen storage should be competitive to fossil fuels or and Lithium-ion batteries at $0.13/kWh with pumped hydro at $0.11/kWh.

2.9.2 *Hypothesis 3*

With a more supportive policy framework, green hydrogen could become an economic storage technology for specific applications.

It is our proposition that with more government support like tax cuts/rebates on green hydrogen technologies, it is a viable technology for storage.

2.10 Conclusion

The evolution of green hydrogen, and especially the falling costs of hydrolysis/fuel cells, presents an opportunity to introduce hydrogen as a competitive technology for large-scale energy storage within the national electricity grid.

Furthermore, green hydrogen production could be a key component in the decarbonisation of the grid and reaching a net zero carbon economy (Bennoua, Le Duigou, Quemere & Dautremont, 2015).

In this project, the critical turning points for the introduction of green hydrogen as an energy storage technology have been reviewed. The background literature on the technology, and on the multi-level perspective have been presented. It is concluded that the research questions remain relevant and important. The following hypotheses is thus explored in this work.

Hypothesis /Proposition 1

The LCOS for green hydrogen has to be sufficiently competitive for it to be deployed as a large-scale energy storage technology in the South African energy mix.

The cost of producing green hydrogen is a critical factor for it to be competitive. It is our proposition that with large deployment of solar PV in South Africa, green hydrogen is economically viable with capacity factors of between 3000 to 4000 hours required.

Hypothesis/Proposition 2

Green hydrogen could be a competitive storage technology should the cost of storage be reduced to a more competitive level.

It is our proposition that the cost of hydrogen storage should be around USD 1.3-2.3/kg.

Hypothesis/Proposition 3

With a more supportive policy framework, green hydrogen could become an economic storage technology for specific applications.

It is our proposition that with more government support like tax cuts/rebates on green hydrogen technologies, it is a viable technology for storage.

CHAPTER 3. RESEARCH METHODOLOGY

This chapter covers the method and design used to find the answers to the three research questions and test the hypotheses from consistency table 4 (refer to Table 4: Research questions, sampling strategy and data collection). The chapter covers the methods used in collecting data and presents the case that justifies the obtained results. From the collected information, the crucial data for this research was sorted, analysed, and organised in an orderly way (Saunders, Lewis & Thornhill, 2007). Secondary data was used from articles, books, research papers and websites.

The study focuses on green hydrogen energy storage used for electricity generation with research question one answered by a techno-economic analysis study using Homer Pro. For research questions two and three, samples were chosen specifically from energy professionals because they are knowledgeable about current trends with regard to green hydrogen, and they have a better understanding of the questions posed. A structured questionnaire was developed using qualitative questions that focused on why, what, and how and was followed by interviews to gather more detailed responses. Each question attempted to address or seek to test the hypotheses. The questionnaire was distributed by email to a sample of participants and followed up with an online interview. Descriptive statistical data analysis and tests were implemented on the results using a qualitative computer package, CAQDAS (NVivo).

3.1 Research Approach

This is a mixed method study in which qualitative and quantitative methods of data collection and analysis are used. This approach allowed the researcher to acknowledge complex phenomena qualitatively as well as to explain the phenomena through numbers, charts and basic statistical analysis (Creswell, 1999). Question one was answered through a techno-economic analysis and by integrating data analysis methods, the results were used to feed into the rest of the questions. Data for question one was collected from the literature available in the form of previous research. Questions two and three were answered through a qualitative analysis in which a purposive survey sampling strategy was used by talking to energy professionals in the industry. Thus, a theory was used leading to a hypothesis. Questions were formulated to then test the hypothesis (Saunders et al., 2007).

3.2 Research Design

The research process involved data collection, analysis, interpretation, and an analysis of results. Techno-economic modelling, a quantitative technique, is used to answer research question number one through Homer Pro. Qualitative analysis is used to answer the exploratory research questions (two and three) which seek to identify what policy pressures can be exerted on the fossil-fuel regime to support the adoption of green hydrogen as a large-scale energy storage technology. Software analysis by CAQDAS (NVivo) was implemented in this analysis.

Information from qualitative research produces data that is more detailed with respect to exploratory, rather than explanatory, research questions. It offers extensive insights into the issues being considered. It has the advantage of allowing a deeper understanding of respondents' experiences and meanings.

A qualitative research process allows the researcher to delve deeper and discover the participants' inner experiences and explore how these are shaped. Participants' alternative views are thus considered.

On the other hand, quantitative research allows us to understand the grades and scores assigned to a particular item. It is designed to have a structure that is flexible and able to be constructed and reconstructed until the margin of error is reduced and accurate results are obtained (Rahman,2016).

Quantitative research attempts to exclude subjective meanings and experiences. Some policymakers may not value studies that use a qualitative approach, preferring quantitative research. In the case of the latter, the sample size is critical for external validity (the extent to which the result can be extrapolated to the whole population). Data analysis and interpretation must be undertaken using interpretive statistics (Rahman,2016).

3.3 Data Collection Methods

For the quantitative techno-economic data modelling of phase 1, secondary data sources were used.

In phase 2 (qualitative study), primary data was collected. A survey strategy was implemented in the form of a questionnaire and online interviews. The survey and interviews were conducted using a sample of participants in the energy sector and projected to the larger population. Purposive sampling was implemented. The questionnaire survey includes an introductory section that explains the research and the reason why it is being conducted. Responses to the questionnaire are anonymous (Robson, 2005).

Surveys seek to answer questions of what, why, and how. A large data set can be obtained when using surveys and they are economical. The data collected is easy to analyse as it is in a standard format (Saunders et al., 2007).

3.4 Population and Sample

3.4.1 *Population*

The target population was primarily professionals in the energy sector in South Africa. Respondents were selected based on industry experience with at least five years' experience in the energy sector. Respondents include post graduate students studying courses in energy studies, industry decision makers, engineers, scientists, and environmentalists. For effective soliciting of insight data on green hydrogen, a survey in the form of an emailed questionnaire and follow-up online interviews were conducted to reach a wider population, including those actively involved in hydrogen research (Silverman, 2010). (Refer Appendix B for consent form).

3.4.2 *Sample and sampling method*

The sample consists of individuals with at least five years' experience in the energy sector as they have the knowledge base and are up to date with trends in the green hydrogen market. For this research, a short text questionnaire and online interviews with eleven respondents was conducted.

Table 4: Research questions, sampling strategy and data collection

Research Question	Data	Targeted Respondents	Data Collection Method
What is the present LCOS of green hydrogen, as a large-scale energy storage technology, relative to competing technologies (such as the lithium-ion battery and pumped hydro)?	Techno-economic analysis/modelling.	Not applicable.	Data recovery from secondary data and archival sources.
What economic, financial, and engineering factors would need to be addressed for the technology to be competitive?	Qualitative.	Energy Professionals with a minimum of five years' experience (engineers, architects, scientists, energy and post graduate engineering students).	Survey questionnaire with 10-15 questions and online video interviews.
Based on the framework of the multi-level perspective (MLP), which policy strategies that can implemented on the fossil fuel regime that will result in the adoption of green hydrogen as a viable energy storage technology?	Qualitative.	Energy professionals with a minimum of five years' experience (engineers, architects, scientists, energy and post graduate engineering students).	Survey questionnaire with 10-15 questions and online video interviews.

3.5 The Research Instruments

Research question one was answered through data analysis modelling (techno-economic analysis) whilst research questions two and three were answered through online interviews and a short text questionnaire distributed by email (refer to Appendix C.) This allowed for the easy collection and sorting of data. Turna-round time for data is fast and it is an economical way of collecting data from respondents. An introductory section was included before the actual questions to address the aims and consent section of the research. A demographics section followed and then questions to address the research questions thereafter (Fox, Hunn & Mathers, 2009).

3.6 Data Analysis and Interpretation

Sequential quantitative (techno-economic analysis) and qualitative analysis were employed. Data was collected from secondary data sources for the quantitative phase and from survey questions/interviews for the qualitative phase. The survey data was transcribed, coded, and presented in the form of text, tables, and figures.

Exploratory descriptions of central variables such as the median, mean, standard deviation and variance was used for research questions two and three. This covered how many and what percentage. Inferential statistics to test the relation-ship between green hydrogen and critical turning points was also used.

The qualitative data was analysed through the deductive approach whereby a structure or predetermined framework is used to analyse data. The researcher took advantage of their own structure or theories on the data and then made use of these to analyse the interview transcripts. This approach is convenient in this study as the researcher was already aware of probable participant responses. The data collected was explored and explained (Burnard, Gill, Stewart, Treasure & Chadwick, 2008).

3.7 Issues of Validity and Relevance

The proposed research approach had an inherent weakness in that the second phase was vulnerable to bias from the respondents, particularly those respondents who have interests in the carbon economy or prefer another storage technology like batteries. This bias could lead to unreliable and unsatisfactory results.

The study was also limited to the research experience level on techno-economic analysis and the design of the survey instrument. Surveys or interviews with time constraints were noted as problematic by Kirby, Delva, Knapper & Birtwhistle (2003) in that respondents with time constraints could be less likely to respond and would rush through the interview to get it done. Moreover, the style and type of questions might force respondents into a particular response category thereby limiting the range of responses although respondents can clarify questions.

To increase the trustworthiness of this study, respondents were selected in the energy sector with a minimum of five years' experience and with an appreciation of the green hydrogen economy. Furthermore, the research supervisor and other research specialists were consulted to assess the trustworthiness of the research instrument (Shenton, 2004).

3.7.1 *Transferability*

The purposive sampling strategy model was applied by extrapolating data from the sample to the general population. The sample is derived from the energy industry. It covers people with common characteristics and the study is relevant to them. Selected participants took part in this study by purposive survey or sampling, hence increasing the chance of every participant taking part in the research. Standard tests of statistical inference were then applied. This passes the test of transferability as applied in qualitative research (Polit & Beck, 2010).

3.7.2 *Credibility*

This research intended to illustrate that a true picture of the occurrence of being studied is being projected to meet the credibility test (Shenton, 2004).The results are presented in the form of charts and graphs in an attempt to validate whether the study precisely measures what it intended to measure as well as how truthful the results are (Bashir, Afzal & Azeem, 2008). Qualified experts used in this study guarantee that the results will be consistent and unbiased, thus validating the content of the research.

3.7.3 *Dependability*

This study is based on a techno-economic analysis and respondents' views. If the study is to be carried out again, the same results might not be achieved as this depends on how each individual views green hydrogen storage and which assumptions they make. To increase the dependability, the questionnaire was pre-tested on selected energy professionals and the feedback was used to improve the types of questions, consistency and structure of the instrument (Bashir et al., 2008).

3.7.4 *Confirmability*

The study is based on views which do not guarantee the independence of attitudes from the individual participants. Therefore, opinions and personal feelings might blur how objectively the respondents answered the questions due to prior knowledge they had regarding green hydrogen storage. To pass the confirmability quality standard, this study implemented a short questionnaire survey with well-structured questions to meet performance standardisation. Data analysis modelling for questions was carried out using Homer Pro software. Descriptive statistics and interpretation was implemented to evaluate the data from the study (Fischer, Boone & Neumann, 2014). Honest interpretation and analysis were employed to ensure the results and findings reflect the true perceptions of the participants (Shenton,2004).

3.8 Ethical Considerations

The research followed the ethical framework and policies of Wits University. An ethical clearance certificate for data collection is attached to Appendix E. Data was obtained from secondary data sources, by means of an e-mail questionnaire and followed by online interviews. Consent was requested from all participants with a clear short description of the objectives of the research. Confidentiality and anonymity of all participants was guaranteed, and they were treated with respect. No data collected will be used for any commercial activities without prior approval. Responses were anonymised.

3.9 Summary and Consistency Matrix

Table 5: Consistency table: research questions and hypothesis

	Stated Research Question	Stated Hypothesis/Proposition	Data Collection and Analysis
1	What is the present levelised cost of storage (LCOS) for green hydrogen, relative to competing technologies such as the lithium-ion (Li-ion) battery and pumped hydro storage?	The present LCOS has to be sufficiently competitive for it to be deployed as a large-scale energy storage technology in the South African energy mix.	Techno-economic modelling using a LCOS approach. This phase of the research is quantitative, and the model is used to identify the turning points for green hydrogen as an energy storage technology.
2	What economic, financial, and engineering factors would need to be addressed for the technology to be competitive?	Green hydrogen could be a competitive storage technology should the cost of storage be reduced to a more competitive level.	Qualitative study with a research questionnaire and purposive sampling. This phase tests and elaborates upon the turning points as identified in the first phase of the project. Results are generated with software for content analysis.
3	Based on the framework of the multi-level perspective (MLP), which policy strategies that can implemented on the fossil fuel regime that will result in the adoption of green hydrogen as a viable energy storage technology?	With a more supportive policy framework, green hydrogen could become a useful storage technology for specific applications.	Qualitative, exploratory study aimed at translating the factors, as previously identified in the second research question, into clear policy interventions which may expedite the adoption of green hydrogen.

CHAPTER 4. PRESENTATION OF RESULTS

4.1 Introduction

Results from the analysis and interviews is presented in this chapter in the form of tables and figures starting with research question number one and including research questions two and three. The discussion of results will be covered in the following chapter.

4.2 Results Pertaining to Hypothesis 1

4.2.1 *System description*

A stand-alone PV powered hydrogen electrolysis system is being proposed for this analysis as shown in Figure 13 below (Hassan, Abdulrahman, Salman, Olapade & Jaszczur, 2023). The LCOS is determined considering historical weather data for the particular chosen location to model the PV system and optimise its size contrasted with the electrolyser. For this project, a detailed calculation of the LCOS has been performed for a standalone PV-driven electrolyser system that is able to be installed with an electricity grid connection. There is always the risk of the considerable expense of a grid connection, delays in both the physical connection and the approval process. To determine LCOS, we used the real world generation of electricity from the PV system based on historical weather data (and potential future trends) for specific locations and optimise the size of the PV installation (compared to the electrolyser) and resultant electrolyser capacity factor (Yates, Daiyan, Patterson, Egan, Amal, Ho-Baille & Chang, 2020).

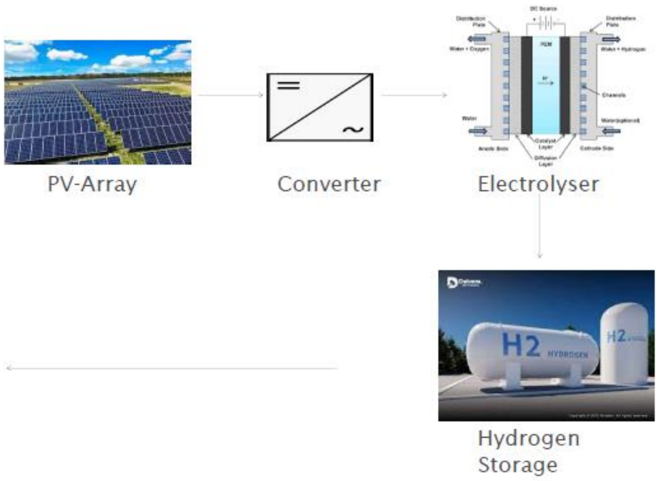

Figure 13: System block diagram (Source: Hassan et al., 2023)

Compressed hydrogen will be stored above ground in steel tanks and a polymer electrolyte membrane (PEM, also called proton exchange membrane) fuel cell will be used to convert the stored hydrogen back into electricity. The PV plant is connected to the grid, and this stabilises power supply to the electrolyser and the various equipment. Production can be carried out with steady-state conditions which as a result reduces the amount of time operators are needed when there is a fluctuation in renewable electricity production (Srettiwat, Safari, Olcay & Malina, 2023).

4.2.2 *Simulation software*

In this study HOMER software was used to perform the economic analysis. Individual components of the system, energy resources and the electrical loads were modelled on an hourly basis. The costs and energy flows were assumed to be constant. Inputs for the system are subsystem component options and performance, capital and replacement costs, fuel and electricity costs, and resource availability. These inputs are used to simulate different system configurations and generate a list of practical configurations sorted by net present cost (NPC). HOMER further reports the cost of energy generated for each feasible system configuration, reported on a $/kWh basis. Because the energy storage systems modelled in this study consistently produce the same amount of electricity, the system configuration with the lowest NPC is also the configuration with the lowest cost of electricity. As such, the system configuration with the lowest cost of energy is the most economical solution (Steward, Saur, Penev & Ramsden, 2009).

HOMER defines LCOS as the average cost per kWh of usable electricity (and hydrogen if produced as a product rather than as a storage medium)produced by the system. To determine the LCOS, HOMER divides the annualised cost of producing electrical energy and/or hydrogen by the total useful electric and hydrogen energy production. For the energy arbitrage system modelled in this study, the cost of electricity is the total annualised cost of the system ($/yr) divided by the total primary AC load served (kWh/yr).

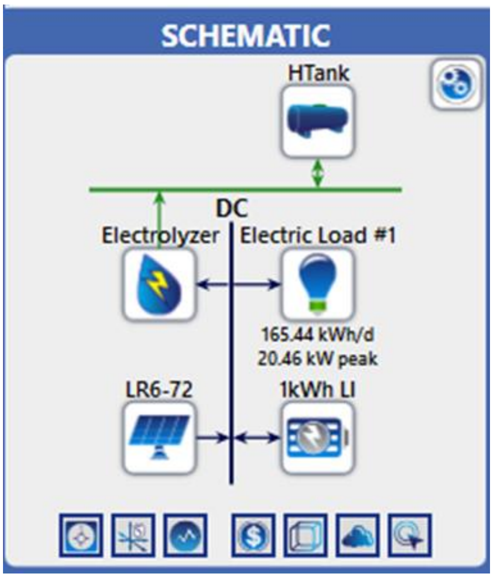

Figure 14: System model in HOMER (Source: HOMER, 2024)

4.2.3 *Economic analysis*

The assessment index LCOS was utilised for the analysis and the unit is USD/kWh. According to IRENA (2021), the LCOS is:

$$LCOS = \frac{\sum_{n=1}^{N}(I_n + M_n + F_n).(1+i)^{-n}}{\sum_{n=1}^{N} E_{n.}(1+i)^{-n}}$$

(2)

Where:I_n=initial investment cost for year n,

M_n=maintenance cost in year n,

F_n=fuel cost in year n,

E_n=energy generation in year n,

i=discount rate,

N=lifetime

The input data for the system model is shown in Tables 6-8 below (Park, Ryu, Kim, Cho, Kim, Lee & Lee, 2023). Values for South Africa were taken from Srettiwat et al (2023) and (Ahmed M. Al-Orabi et al., 2023).

Table 6: Photovoltaics Plant Details (Source: Ahmed M.AI-Orabi et al.,2023)

Photovoltaic Plant,PV(45MW)	
Item	**Description**
Name	Canadian Solar Maxpower CS6U-340M
Module Efficiency	17.50%
Dimensions	2172 x 1303 x 35 mm (A=2.8m^2)
Nominal Module Operating Temperature	42±3 °C
Temperature Coefficient(Pmax)	-34 % /°C
PV Panel Capital Costs	$29,295,000.00
PV Panel Operating Costs	$ 450 000,00/yr
NB:USD($) to Rand (ZAR) exchange rate of the date to be used	

Table 7: Techno-Economic Analysis: Assumptions (Source: Park et al., 2023)

Techno-Economic Analysis:Assumptions	
Item	**Description**
Year of evaluation	2024
System life span	25 years
Yearly hours	8760hours
Bank rate (Debt Interest Rate)	6.86%
Income tax rate	32%
Inflation	4%
Equity risk premium	8.87%
WACC	12.20%
Capital Investment	
Electrolysis system cost	$10 320 000.00
Supplement cost	$2,064M(20% of electrolyser system cost)
Basic material & Utility Cost	
Freshwater	1.2 USD/ton
Electricity	0,00 USD/kWh
Oxygen	110 USD/ton
Operating budget	
Maintenance (Stack)	$1,032M(10% of Capital investment of Stack)
Balance of plant (BOP) Maintenance	$0,516M(5% of Capital investment of BOP)
Operating supplies	$0,0675M(15% of Maintenance cost)
Insurance	$0,206M(2% of Fixed cost investment(FCI))
NB:USD($) to Rand (ZAR) exchange rate of the date to be used	

Table 8: Simulation Input Data (Source: Ahmed M.AI-Orabi et al.,2023)

Simulation input data	
Item	**Description**
PV plant size	45MW
Electrolyser size	20MW
Electrolyser system capital investment	516 USD/kW
Electrolyser BOP cost	$10 320 000
Electrolyser efficiency	72%
Electrolyser operating pressure	30bar
Stack degradation	1%/yr
Electrolyser minimum operating capacity	5%
Others	
Inverter efficiency	97.50%
NB:USD($) to Rand (ZAR) exchange rate of the date to be used	

4.2.4 *Results*

Below are the results from the simulation. The figure below shows the electrolyser output corresponding to the summer months when the PV output is high.

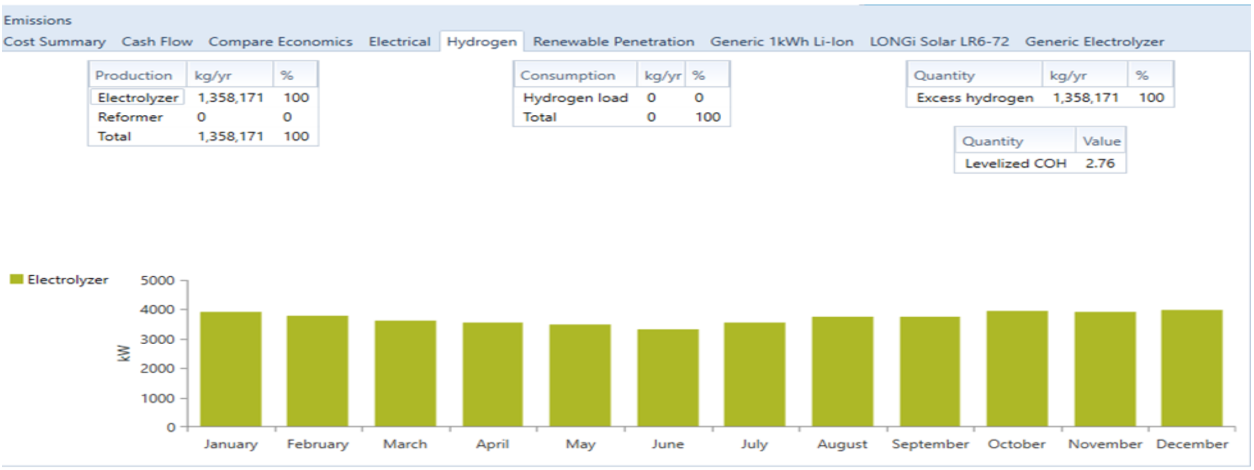

Figure 15 : Levelised Cost of Energy (LCOH) (Source: HOMER, 2024).

The LCOH is estimated to be $2.76/kg which gives LCOS of $0.228/kWh which is fairly acceptable to others that has been found in the literature at $0.032/kWh (Achour, Berrada, Arechkik & El Mrabet, 2023) but acceptable according to according to Lazard's 2024 analysis, which gives the LCOS for GH typically in the range of $0.20 to $0.40 per kWh(Lazard, 2024). The individual cost calculations for each component are shown in the cost summary.

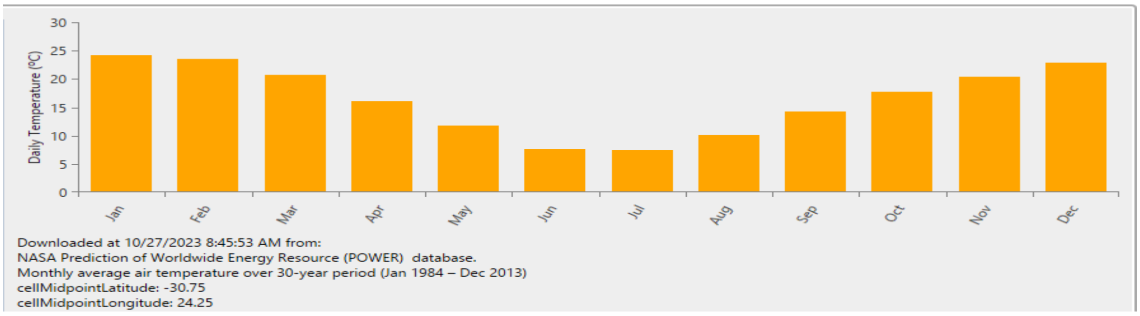

Figure 16 : Photo-Voltaics Monthly Average Ambient Temperature in De Aar (Source: HOMER, 2023).

Figure 16 above shows the amount of solar irradiation experienced at the chosen location. As expected, solar irradiation is lower during winter.

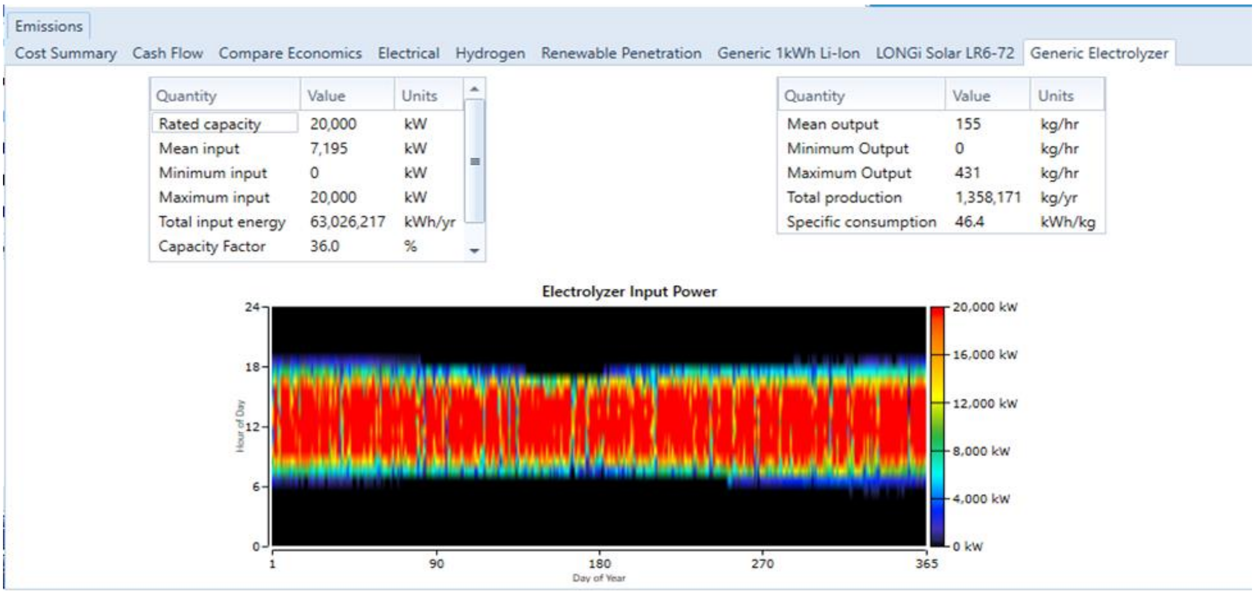

Figure 17 : Electrolyser Output Summary (Source: HOMER, 2024).

The electrolyser output summary from the model is shown in Figure 17 above and PV power output is shown below.

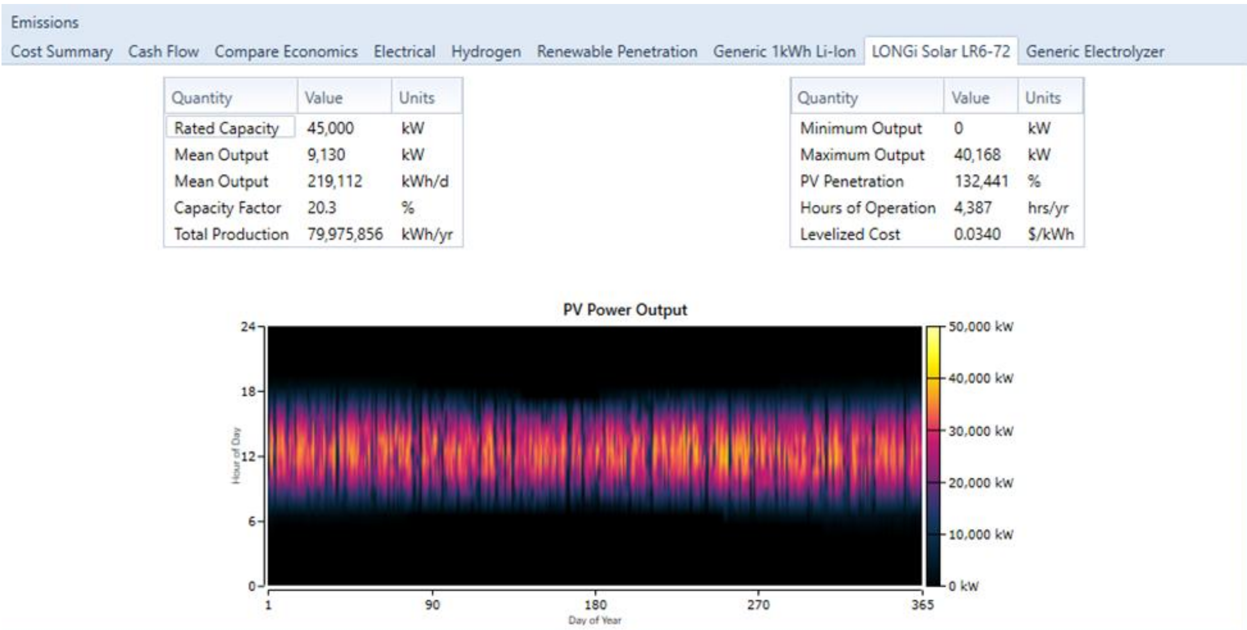

Figure 18: PV Electricity Production (Source: HOMER, 2024).

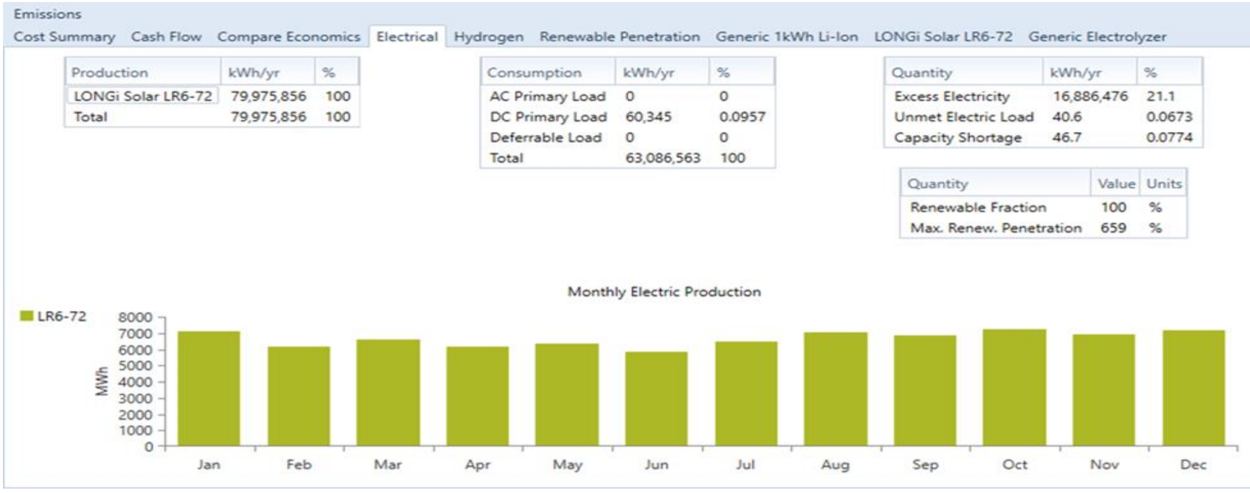

Figure 19: Monthly Electrical Production (Source: HOMER, 2024).

The monthly electricity produced by the model showing the higher PV production supplemented by the grid. The fuel cell is the least component producing electricity for consumption (refer to Figure 19).

4.3 Results Pertaining to Proposition 2 or Hypothesis 2

NVivo qualitative data analysis software was used, and the findings are presented below in Figures 20 to 23. The prominent results from the respondents pertaining to the advantages of deploying green hydrogen technologies are shown in Figure 20. These mainly cover issues relating to its low carbon footprint.

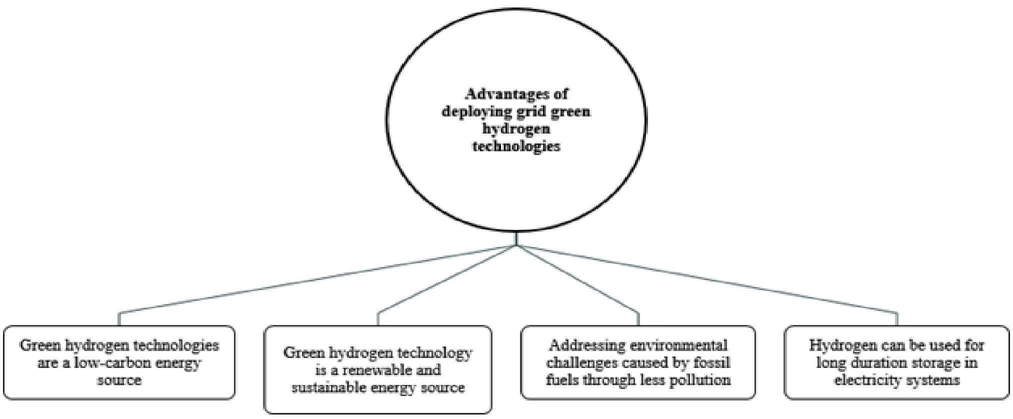

Figure 20: Advantages of Deploying Grid Green Hydrogen Technologies (Source: NVivo, 2023).

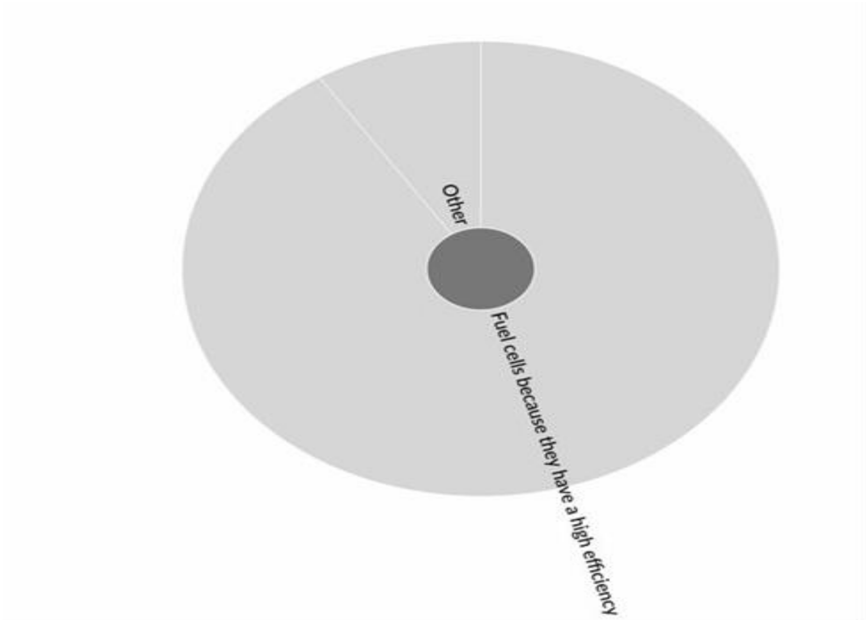

Figure 21: Opinion on Best Technology to Convert Stored Hydrogen to Electricity (Source: NVivo, 2023).

From the figure above, it is certain most respondents are of the opinion that fuel cells are the best technology for hydrogen conversion to electricity. The figure below shows the responses when it comes to challenges in the development of green hydrogen technology in South Africa.

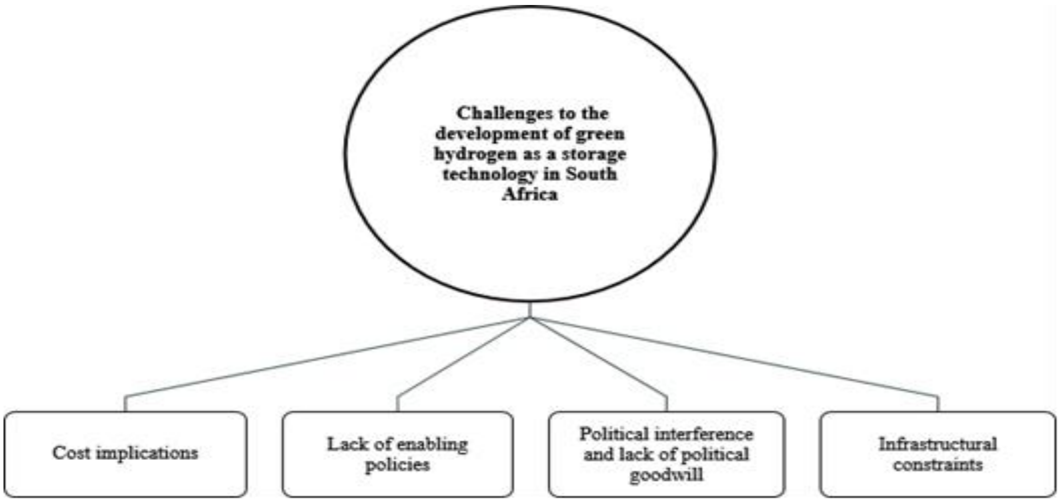

Figure 22: Challenges to the Development of Green Hydrogen as a Storage Technology in South Africa (Source: NVivo, 2023).

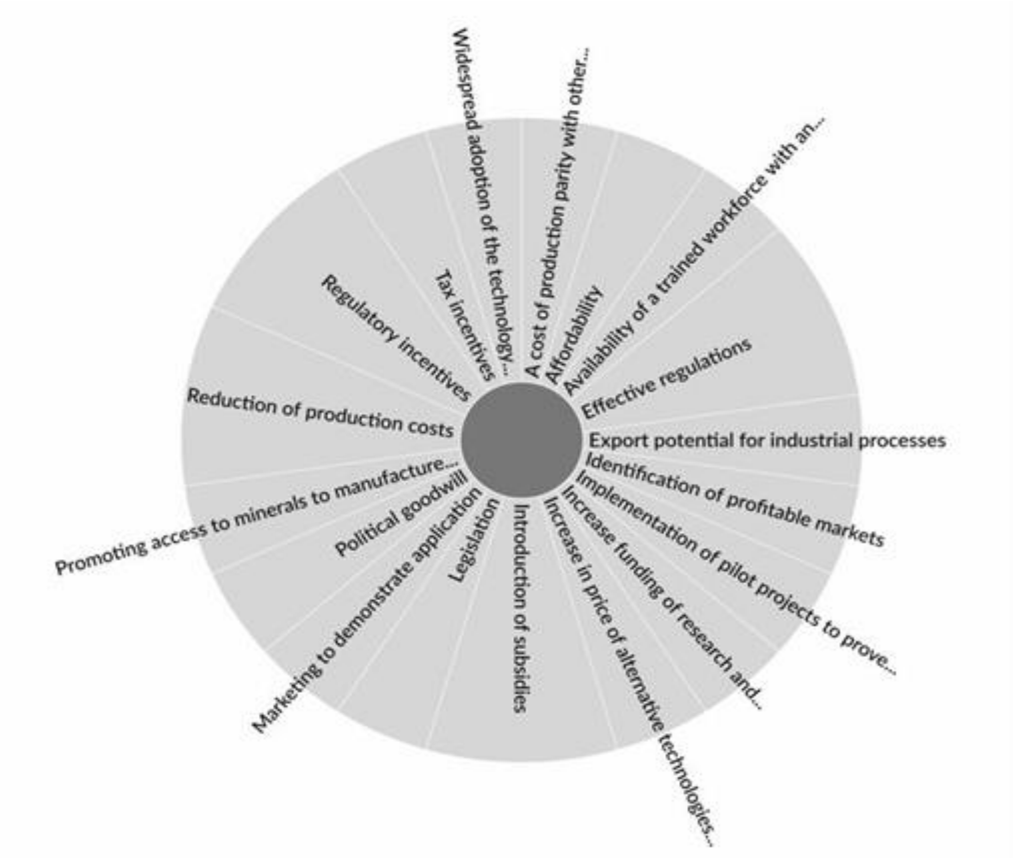

Figure 23: Factors that Could Contribute to the Adoption of Green Hydrogen Technologies in South Africa (Source: NVivo, 2023)

Respondents gave a variety of factors that could contribute to the adoption of green hydrogen technologies in South Africa as shown above. They varied from production costs with the most answers centred around regulations and incentives.

4.4 Results Pertaining to Proposition 3 or Hypothesis 3

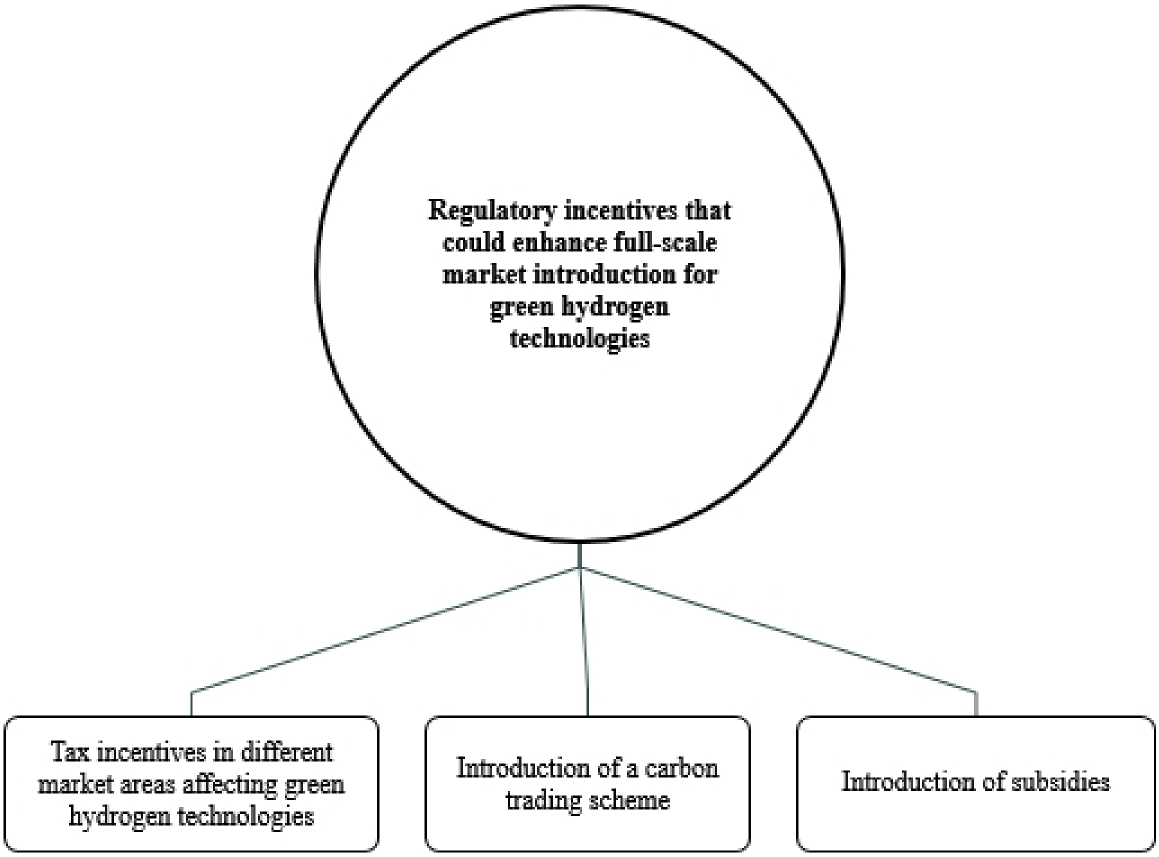

Figure 24: Regulatory Incentives that Could Enhance Full-Scale Market Introduction for Green Hydrogen (Source: NVivo, 2023)

When it comes to regulatory incentives, the most that stood out are the three shown above mainly the tax incentives, subsidies and introduction of a carbon trading scheme. The discussion of the results in chapter 5 gives a further breakdown.

4.5 Summary of the Results/Findings

According to the model, it is comparatively cheap for green hydrogen to be used as a storage technology for power generation as the LCOS from the model falls within the range of some values found in the literature. This could be because of the good solar irradiation found in South Africa which lowers the cost of PV production.

The benefits of green hydrogen as a green technology in reducing the effects of climate change are noted. Most participants feel that fuel cells are the best technology for converting hydrogen into electricity, however, as an energy storage technology to help South Africa in alleviating its energy problems costs, political interference, infrastructure, and lack of enabling policies are noted as the major hindrances to its deployment.

The economic turning point mostly noted for green hydrogen to be competitive is when its costs are equal to or below the current costs for fossil fuels in South Africa. To discourage continuous deployment of fossil fuels, the introduction of significant carbon taxes and less funding could be used. Regulatory incentives such as tax incentives on green hydrogen technologies and carbon tax were mentioned mostly to promote the adoption of green hydrogen technologies.

Table 9. Comparison of Literature Review and Findings

Research Question Number	State Research Question or Objective	Stated Hypothesis/Proposition	Findings From Own Study
1	What is the present levelised cost of storage (LCOS) for green hydrogen, relative to competing technologies such as the lithium-ion (Li-ion) battery and pumped hydro storage?	The LCOS has to be sufficiently competitive for it to be deployed as a large-scale energy storage technology in the South African energy mix.	The LCOS is estimated to be \$0.228/kWh. Lazard's 2024 analysis gives the LCOS for GH typically in the range of \$0.20 to \$0.40 per kWh. Li-ion batteries are at \$0.13/kWh with pumped hydro at \$0.11/kWh.
2	What economic, financial, and engineering factors would need to be addressed for the technology to be competitive?	Green hydrogen could be a competitive storage technology should the cost of storage be reduced to a more competitive level.	The economic turning point mostly noted for green hydrogen to be competitive is when its costs are equal to or below the current costs for fossil fuels in South Africa. As an energy storage technology to help South Africa in alleviating its energy problems, political interference, infrastructure, and lack of enabling policies were noted as the major hindrances to its deployment.
3	Based on the framework of the multi-level perspective (MLP), which policy strategies that can implemented on the fossil fuel regime that will result in the adoption of green hydrogen as a viable energy storage technology?	With a more supportive policy framework, green hydrogen could become a useful storage technology for specific applications.	To discourage continuous deployment of fossil fuels, the introduction of significant carbon taxes and less funding could be used. Regulatory incentives like tax incentives on green hydrogen technologies and carbon tax were mentioned mostly to promote the adoption of green hydrogen technologies.

CHAPTER 5. DISCUSSION OF THE RESULTS

5.1 Introduction

This chapter provides a description and explanation of the research results in relation to the three research questions. The results are referenced and compared to those found in the literature. The demographic profile for the respondents who took part in the research is also indicated (refer to Appendix A).

5.2 Demographic Profile of Respondents

Of the participants who took part in this research, 82% are male and 18% are female. In terms of education, 64% have a Bachelor's degree while 27% have a Master's degree and 9% of the participants have a Doctor of Philosophy (PhD). (refer to Figure 25 and 26).

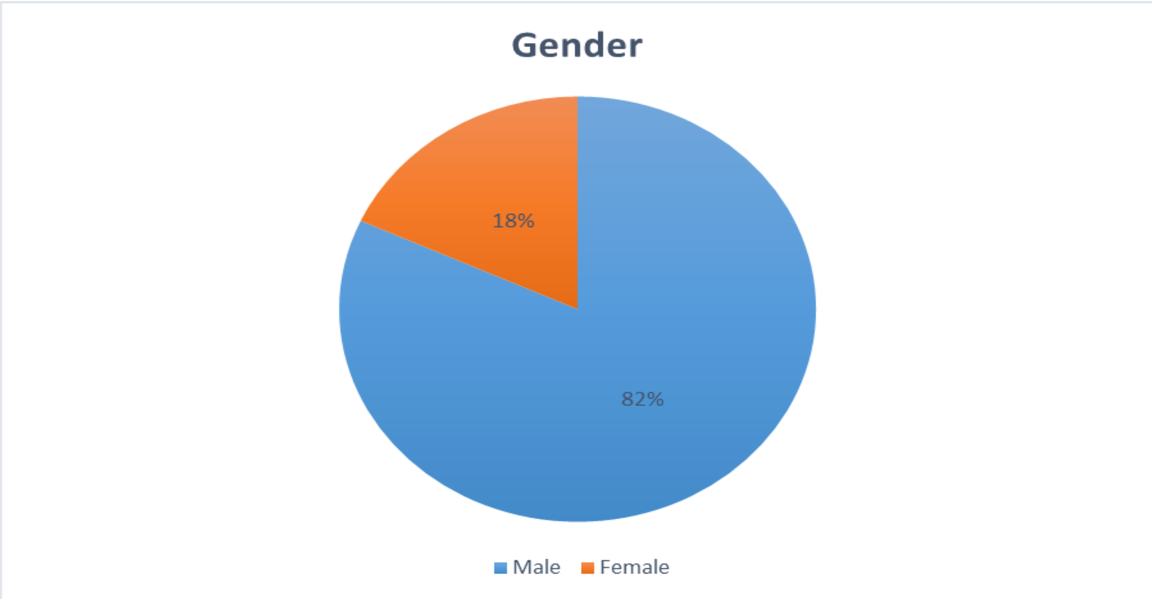

Figure 25: Gender Information (Source: NVivo, 2023)

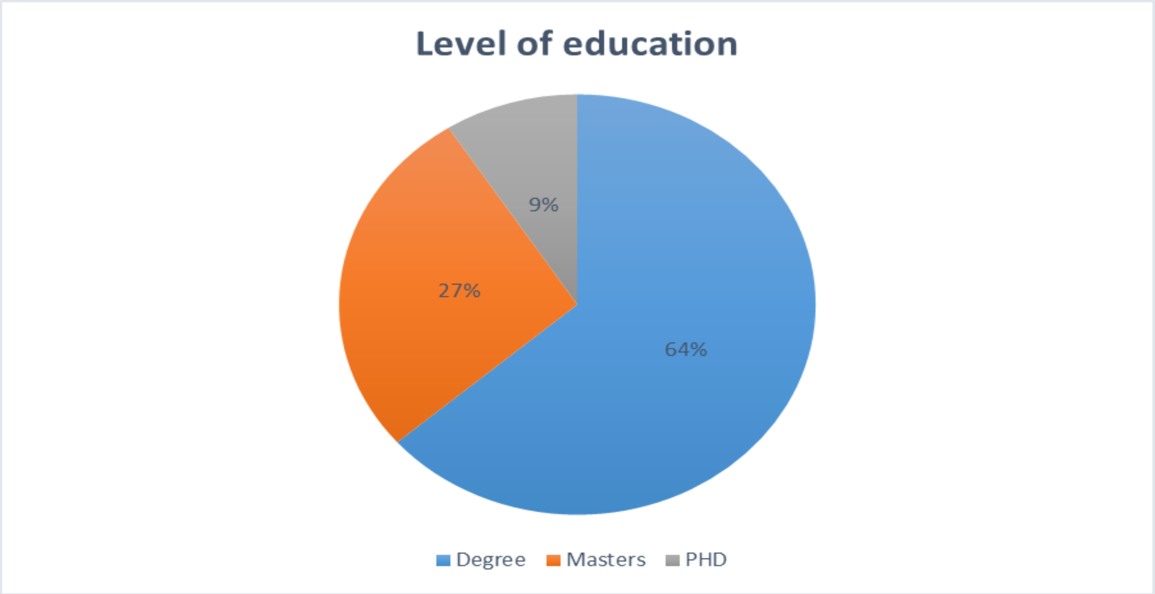

Figure 26: Participant's Level of Education (Source: NVivo, 2023)

37% of the participants have working experience in the energy sector of between 0 to 10 years, 6% have working experience of between 11 to 20 years, 18% have working experience of between 21 to 30 years, and 9% have working experience of between 31 to 40 years (refer to Figure 27).

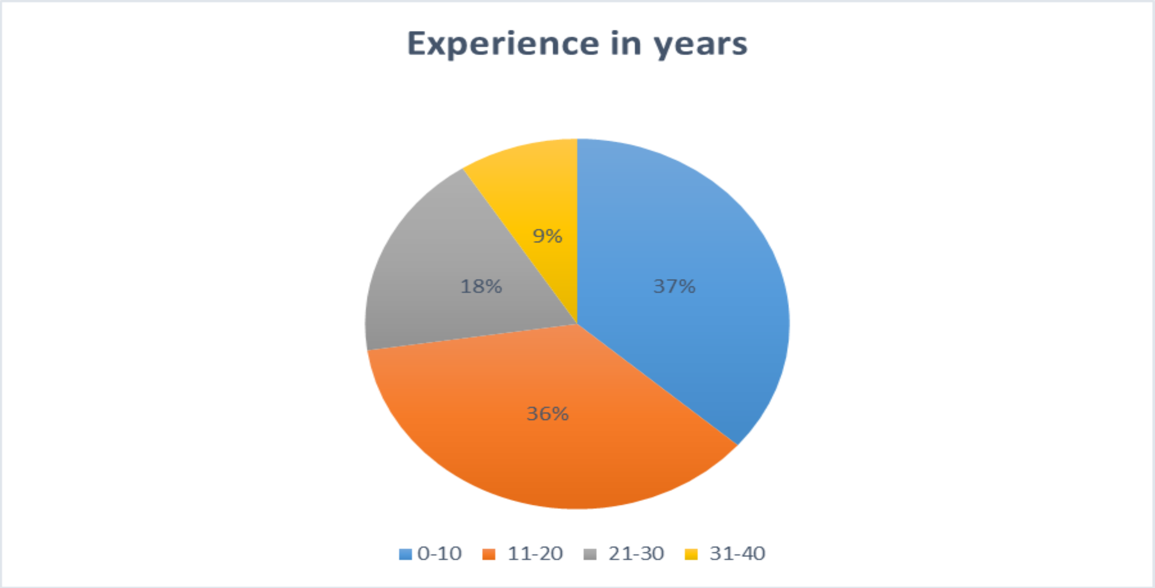

Figure 27: Participant's Experience in Years (Source: NVivo, 2023)

5.3 Discussion Pertaining to Proposition OR Hypothesis 1

The LCOS is estimated to be $0.228/kWh which is fairly a bit higher than what has been found in the literature at $0.32/kWh (Achour et al., 2023). Lazard's 2024 analysis gives the LCOS for GH typically in the range of $0.20 to $0.40 per kWh. Li-ion batteries are very competitive due to their power density, cost, and efficiency (Xu, Pei, Cui, Liu & Ma, 2022). Cost comparisons for LCOS are indicated in Table 10 (Viswanathan, Mongird, Franks, Li, Sprenkle & Baxter, 2022). In practice, South Africa has a higher solar irradiation which makes it suitable to generate excess PV power at a lower cost which then makes the cost of producing green hydrogen low (Chartan et al., 2017).

Table 10: Comparison of Energy Storage Technologies in USD per kWh (Source: Viswanathan et al., 2022; Xu et al., 2022)

Item	Rate in USD $kWh
Li-ion Batteries	0.13
Green Hydrogen	0.35
Lead Acid Batteries	0.33
Pumped Hydro	0.11
Large Scale Compressed Air (CAES)	0.25

5.4 Discussion Pertaining to Proposition 2 or Hypothesis 2

A reflexive thematic analysis process was used (Braun & Clarke, 2019). The themes that emerged are linked to research question two. The emergent themes are shown in Table 11 below. (refer to Appendix D for the NVivo qualitative coding codes).

Table 11: Emergent Themes (Source: NVivo, 2023)

Themes	Participants	Coding References
RQ2. What economic, financial, and engineering factors (referred to as turning points) would need to be addressed for the technology to be competitive	**11**	**123**
Prior Experience	10	12
Green Hydrogen as a Storage Technology	11	54
Future Development of Green Hydrogen	11	44
Economic Turning Points	10	13

5.4.1 *Prior experience*

The participants' answers varied with regards to having any prior experience working directly with hydrogen. Five participants had no direct experience working with hydrogen although they were familiar with hydrogen by virtue of working in the energy sector:

> *P1*
> *No, I have never worked with hydrogen directly.*
>
> *P3*
> *I attended a 5-day course on Green Hydrogen Technology 15-19 May 2023.*
>
> *P6*
> *No. I only know what I have recently read (last 3-4 years). We did an assignment on green vs. grey hydrogen in 2021 when doing the Masters in Energy Leadership (the latter I never finished due to work and other commitments).*
>
> *P7*
> *No. The only exposure is from reading and what I see on the news.*
>
> *P9*
> *No, I have not.*

Three of the participants indicated that their past experience with hydrogen was in research and development:

> *P11*
> *I have not worked with hydrogen as a storage directly. We did some brief research on this at my previous employer.*
>
> *P2*
> *Yes, I have in Research & Development.*
>
> *P8*
> *I haven't worked with it directly at all. I recently started working with it from a research perspective to look at the impact from a decarbonisation perspective.*

Two participants indicated that they had previously worked with hydrogen as consultants:

> *P2*
> *Consulting, project design and delivery, and standards.*
>
> *P5*
> *I have worked with hydrogen as a consultant focusing on its application in transport and heavy industry. My work includes feasibility studies, process modelling and activities such as hydrogen demand mapping.*

One participant indicated that they had previously worked with hydrogen as a by-product:

> *P4*
> *My exposure to hydrogen was primarily managing it as a by-product in bleaching chemical reactions and its interaction in boilers to create acids. My main consideration surrounding elemental hydrogen was its high corrosive damage of steel pressure vessels and reaction towers. Management and safety around hydrogen were the chief concerns.*

On the other hand, one of the participants indicated that they had previously worked with hydrogen in education and training:

> *P2*
> *Education and training.*

5.4.2 *Green Hydrogen as a storage technology*

Different sub-themes emerged from the data analysis that contributed to the major theme of green hydrogen as a storage technology. These sub-themes included: advantages of deploying grid green hydrogen technologies; opinion on best technology to convert stored hydrogen to electricity; views on whether green hydrogen is presently a better technology than batteries; and views on whether green hydrogen could be a better technology than batteries in the future.

Table 12: Green Hydrogen as a Storage Technology (Source: NVivo, 2023)

Theme and sub-themes	Participants	Coding References
Green Hydrogen as a Storage Technology	**11**	**54**
Advantages of deploying grid green hydrogen technologies	10	17
Opinion on best technology to convert stored hydrogen to electricity	11	11
Views on whether green hydrogen is presently a better technology than batteries	11	15
Views on whether green hydrogen could be a better technology than batteries in the future	11	11

5.4.2.1 Advantages of deploying grid green hydrogen technologies

Five participants indicated that one of the main advantages of deploying grid green hydrogen technologies was addressing environmental challenges caused by fossil fuels through less pollution:

> *P1*
> *It addresses environmental challenges.*
>
> *P11*
> *It is less harmful to the environment provided that the initial electrolysis is done with renewable power. Lithium mining can be unsustainable and damaging to the environment and green hydrogen is sourced from water.*
>
> *P2*
> *Improved environmental performance with reduced emissions/kg hydrogen produced compared to Small Modular Reactors , coal gasification and grid connected electrolyser systems.*
>
> *P7*
> *It helps with climate change, reducing the effects of it. It is good for the environment.*
>
> *P9*

Reduction in greenhouse gas emissions which is good for the planet.

Three of the participants also indicated that green hydrogen technologies were a low-carbon energy source as an advantage of deploying grid green hydrogen technologies:

P1
It aids in clean energy production.

P3
Low carbon energy source.

P6
Relatively low-carbon energy source.

Two participants indicated that another advantage of deploying grid green hydrogen technologies was that green hydrogen technology is a renewable and sustainable energy source:

P3
Green hydrogen represents a renewable resource thus a more sustainable energy source.

P6
The obvious advantages are that it would be sustainable.

Other advantages of deploying grid green hydrogen technologies that were highlighted by the participants are:

P1
Addressing energy security challenges.

P6
If produced locally, it could also avoid geopolitical volatility in energy prices and availability.

P8
I think green hydrogen is most feasible for industrial processes and not necessarily grid applications due to loss of efficiencies in the process.

P4
These technologies may be beneficial for energy storage to accommodate the variability inherent in renewable energy as a fuel source. In this way,

the peaks and troughs in electricity supply vs. time can be smoothed to maintain a constant supply to the grid users.

P3
The energy source can be deployed at the point where it will be consumed.

P5
Hydrogen can be used to store potentially curtailed electricity. Further, hydrogen could be useful for long duration storage in the electricity system.

P1
Also helps in job creation.

The literature provides the same advantages as noted by the respondents in terms of the benefits of deploying green hydrogen in relation to climate change and to limiting emissions when compared to fossil fuels (IGEM,2020).

5.4.2.2 Opinion on best technology to convert stored hydrogen to electricity

Participants favoured fuel cells when asked which is the best technology to convert stored hydrogen to electricity. Ten participants indicated that fuel cells were the best technology because of a higher efficiency:

P1
I would say fuel cells as they are modular and have a high efficiency. Also, gas combustion engines.

P10
Fuel cells.

P11
The vehicle industry where hydrogen fuel cells are used to fuel cars.

P2
Depends on the application but generally speaking, fuel cells have a higher efficiency compared to Hydrogen Internal Combustion Engine and hydrogen fired turbines. High temperature Solid Oxide Fuel Cells have the highest efficiency. Polymer electrolyte membrane (PEM) fuel cells are used extensively for mobile applications.

P4

The main technology that I am familiar with is reverse electrolysis through a fuel cell arrangement. My assessment of this technology only is that it entails double losses in energy, i.e. losses in energy by using energy in the electrolysis process to create the hydrogen and to store it, then losses when converting it back to electricity for consumption.

P5
My understanding is that fuel cell technologies would be best suited although there are Internal Combustion Engine (ICE) applications being explored. It is important to note the significant losses involved in producing hydrogen from electricity to then convert that back to electricity.

P6
Alternatively used in fuel cells but for grid scale electricity – I think scale, cost and availability of metals would be a problem.

P7
I think fuel cells are still the best option.

P8
Fuel cells.

P9
I only know fuel cells.

Although most participants chose fuel cells, the literature cites fuel cells as still being prohibitively expensive at USD$3000/kW with a 2030 target of USD$1800/kW (Hernandez & Gençer, 2021).

5.4.2.3 Views on whether green hydrogen is presently a better technology than batteries

Table 13: Green Hydrogen as a Better Technology than Batteries (Source: NVivo, 2023)

Sub-themes and Codes	Participants	Coding References
Views on whether green hydrogen is presently a better technology than batteries	**11**	**15**
Better	**3**	**4**
Green hydrogen technologies can be effective in power grids requiring storage of electricity for longer durations	2	2

Green hydrogen technology might be better than batteries in applications and sectors requiring extended range	2	2
Not better	**10**	**11**
Batteries are better and more efficient for light duty passenger vehicle mobility	1	1
Batteries are better technology than green hydrogen currently	3	3
Batteries are cheaper which makes them a better technology currently	5	5
Batteries are currently better technology because of demonstrated capabilities while green hydrogen has not been effectively tested	2	2

The majority of the participants indicated that green hydrogen was not a better technology than batteries presently with most participants citing cost as a factor:

> *P1*
> *Batteries are cheaper and hydrogen is still costly although the potential for hydrogen is there.*
>
> *P10*
> *It could with time but as of now batteries have an upper hand in terms of cost.*
>
> *P5*
> *The reality at the moment is that batteries would be cheaper and more reliable in terms of prior testing/demonstration.*
>
> *P6*
> *Currently cost and distribution limitations, as well as conversion of hydrogen to useful energy, make batteries a much better option, e.g. for home appliances requirements. Unless hydrogen storage could be used to produce grid-scale electricity when required, e.g. for peaking or mid-merit power requirements, replacing pumped-storage and gas turbines, batteries will probably continue to be required. Otherwise, hydrogen distribution systems and networks would need to be established to load canters (i.e. a hydrogen infrastructure). Even so, applications would remain limited for the end user unless converted to a more useful energy source.*
>
> *P9*
> *At the moment, batteries are still cheaper than hydrogen.*

Of the ten participants who indicated that green hydrogen was not a better technology than batteries presently, two of them stated that batteries are currently a better technology because of demonstrated capabilities while green hydrogen has not been effectively tested:

P5
Battery storage at the grid scale has been demonstrated and as such has a high Technology Readiness Level (TRL). Hydrogen storage, on the other hand, and hydrogen in general for decarbonisation is a more novel concept which will require time to be proven, tested and for the economics to start becoming favorable.

P8
I don't think this is feasible as battery storage makes more sense.

Three participants stated that green hydrogen is presently a better technology than batteries. Two of the three interviewees that stated that green hydrogen is presently a better technology than batteries indicated that green hydrogen technologies can be effective in power grids requiring the storage of electricity for longer durations:

P2
For power grid firming both can be used, hydrogen is better for electricity storage longer than 8 hrs.

P7
Green hydrogen has advantages for long storage duration and helping with load shedding especially in the case of South Africa.

The literature recognises the importance of green hydrogen for long duration storage and batteries for short duration storage to stabilise grid operations (M. Becherif et al., 2015). They both have different applications, and they could all play a different role in energy storage. At the moment, batteries are still cheaper than green hydrogen and have matured on the market.

5.4.2.4 Views on whether green hydrogen could be a better technology than batteries in the future

When asked to express their views on whether green hydrogen could be a better technology than batteries in the future, eight of the interviewees agreed stating:

P3

Yes, definitely, Green Hydrogen is more energy dense per weight than batteries. Green Hydrogen can be transported to places where the energy needs to be consumed, either through piping systems or through long haul trucks.

P1
Batteries are cheaper and hydrogen is still costly although the potential for hydrogen is there.

P10
Yes, in future for long-term storage and electricity generation to reduce load shedding.

P11
Yes, it is lighter than lithium batteries and depending on what happens with the availability of resources, it might become a definite alternative.

P6
It would certainly be better in the longer term if cost, conversion, and distribution challenges could be met. Batteries will not solve energy requirements in the medium-to-longer-term if only because there are insufficient battery materials to meet future requirements.

P4
It could be a better technology from a sustainability perspective. The main resources used in green hydrogen are water and air and these can be sustainably converted using the electrolysis/reverse electrolysis processes. Batteries have a defined cycle life, after which they may be discarded.

P7
With time, and as costs of green hydrogen start to decline, yes it could be a better technology.

P9
Maybe in the future as it becomes cheaper.

One participant indicated that green hydrogen could not be a better technology than batteries in the future:

P8
No. It is expensive.

Two participants indicated that it is significantly dependent on the application:

P2

Depends on the application again but also the technology type, maturation level and cost and performance potential of battery technologies compared to fuel cells over the coming years.

P5
I think in certain applications and business models (e.g. hydrogen production for offtake and electricity storage) hydrogen may emerge as a better solution but I think this will likely be case by case.

5.4.3 Future Development of Green Hydrogen

Table 14: Future Development of Green Hydrogen (Source: NVivo, 2023)

Themes and Sub-themes	**Partici-pants**	**Coding References**
Future Development of Green Hydrogen	**11**	**44**
Challenges to the development of green hydrogen as a storage technology in South Africa	11	14
Factors that could contribute to the adoption of green hydrogen technologies in South Africa	11	22
Views on whether green hydrogen has the potential to solve South Africa's energy storage challenges	8	8

5.4.3.1 Challenges to the development of green hydrogen as a storage technology in South Africa

Participants identified different challenges to the development of green hydrogen as a storage technology in South Africa. Seven participants indicated that one of the main challenges to the development of green hydrogen as a storage technology in South Africa was the high costs:

P10
Its present cost at the moment.

P11
Cost implications.

P2
Affordability based on LCOS which is a function of power cost, electrolyser, hydrogen storage, hydrogen compressor and balance of plant (BOP) item. Capex costs. High retail cost of Fuel Cell Electric Vehicles (FCEVs) and hydrogen refueling stations (HRS).

P6

I was told that Renewable Energy (RE) costs may come down further, electrolysis costs can also come down – but that the other costs in establishing the industrial plant are not coming down. So, production cost looks like it will remain higher than those of other energy sources. Obviously then, if cost comes down, it will require a transport and distribution system, plus an entire "re-tooling" of the energy use landscape.

P7
The costs which are still high.

P8
Costs.

P9
It is expensive and people are not familiar with it.

Other challenges to the development of green hydrogen as a storage technology in South Africa included:

P8
Efficiency losses.

P4
Also finding profitable local and international markets to justify expanding the industry locally.

P1
Infrastructure constraints. The market is not yet mature in the case of South Africa like with gas and fossil fuels.

P4
The biggest challenge is to justify it as a profitable avenue for investment against the backdrop of other cheaper storage and generation technologies. The business case for green hydrogen is often lacking, and subsidisation of this industry will require justification as there are many other developmental areas which require funds in South Africa.

P7
Lack of skills.

P3
South Africa needs to create enabling policies that advocate for Green Hydrogen manufacturing plants and investment. At present no white paper, road map or allocation in the Integrated Resource Plan (IRP) exist for Green Hydrogen.

P5

Frankly, I believe the main hindering factor for most green technologies becoming developed is political will and interference.

5.4.3.2 Factors that could contribute to the adoption of green hydrogen technologies in South Africa

Participants identified factors that could contribute to the adoption of green hydrogen technologies in South Africa.Two participants highlighted that effective regulations could contribute to the adoption of green hydrogen technologies in South Africa:

P1
Another factor is regulatory.

P5
Fleshed out regulation and policies for grid storage.

Another two participants also indicated that the introduction of subsidies could go a long way to contributing to the adoption of green hydrogen technologies in South Africa:

P3
Introduction of subsidies to increase adoption.

P4
Subsidy.

Two participants highlighted that the reduction of production costs could go a long way towards the adoption of green hydrogen technologies in South Africa:

P4
The key factors will be: Reduced cost of production.

P9
Costs, it must be cheap to start with.

Regulatory incentives were also identified by two of the interviewees as factors that could contribute to the adoption of green hydrogen technologies in South Africa:

P2
Regulatory incentives.

P4
Supportive industrial policy.

Other identified factors that could contribute to the adoption of green hydrogen technologies in South Africa included:

P6
Cost must become competitive with Liquefied Natural Gas (LNG) and other energy sources. There may also come a time when the world realises that current technologies will not be able to meet all its energy requirements (e.g. shortage of battery and other metals, logistics and geopolitical constraints) and therefore that all energy options must be utilised, albeit the higher-cost ones.

P7
Affordability of the technology is mainly in relation to costs. Will consumers afford it?

P2
Ability for local manufacture of Solar Photovoltaics modules, fuel cells and electrolysers with relatively low labour costs, a trained workforce of hydrogen engineers, plumbers, electricians, and fitters and turners.

P2
Access to essential minerals at low cost.

P8
Export potential for industrial processes.

P4
Identification of profitable markets.

P5
Pilot projects to show feasibility.

P1
Lots of funding and research is needed.

P11
And the potential rising cost of alternatives due to future scarcity of resources.

P3
Demonstration of application (marketing benefits)

P1
Political willingness to drive green hydrogen.

P1
Pricing and tax incentives.

P10
Large scale deployment of the technology which reduces costs.

Similar to the participants in this research study, the literature recognises the high costs of green hydrogen amongst other factors as a challenge to the full scale deployment of green hydrogen technologies (Wanner, 2021).

5.4.3.3 Views on whether green hydrogen has the potential to solve South Africa's energy storage challenges

The participants presented diverse views on whether green hydrogen has the potential to solve South Africa's energy storage challenges. Two participants stated that green hydrogen has the potential to solve South Africa's energy storage challenges because of the availability of natural resources which can make it economically viable:

P5
I think hydrogen is no silver bullet but can play a crucial part of the picture. South Africa is well-endowed with renewables meaning the economics can be favorable for hydrogen production under the right circumstances (once again the business model is essential).

P6
Yes, we have the best solar resources to potentially produce cheaper renewable energy for conversion of water to hydrogen. Once the technology has matured, this would give South Africa a competitive advantage for hydrogen production, albeit that it would be produced in an area which is remote from load requirements. But if the government changed and enabled investment in infrastructure, export potential would also exist.

Another two of the participants also stated that a reduction in the cost of green hydrogen technology in the future could make it a viable solution to South Africa's energy storage challenge:

> *P11*
> *If it becomes cheaper and more efficient than the current storage systems, yes.*
>
> *P7*
> *With time, and as costs of green hydrogen start to decline, yes it can solve them as it is good for long-term storage duration.*

Other views expressed by the interviewees on whether green hydrogen has the potential to solve South Africa's energy storage challenges included:

> *P1*
> *Not in the short term. I would give it 10-15 years for green hydrogen to be competitive. In the future, maybe, because of infrastructure constraints.*
>
> *P4*
> *Green hydrogen may find use if greater renewable electricity generation takes place, but my opinion on renewable energy is that decentralised systems will be more effective. This brings into question the scalability of green hydrogen storage systems and at what level of energy intensity they are most efficient. I do not envision that green hydrogen would be efficient for use in residential and commercial buildings. Its usage within industry may bring benefit in terms of reducing the carbon costs associated with production and thus assist industry in reducing emissions to improve profitability and competitiveness internationally, bearing in mind that the Carbon Border Adjustment Mechanism (CBAM) will come into play in 2026.*
>
> *P2*
> *Potential to solve some of them, yes, but not all. The immense capacity scale and hence cost of hydrogen-based infrastructure to accommodate all thermal storage requirements would be prohibitive.*
>
> *P3*
> *Over time Green Hydrogen can become part of the energy mix, given its feedstock abundance especially in the coastal areas.*

5.4.4 Economic Turning Points (Source: NVivo, 2023)

Table 15: Economic Turning Points

Sub-themes and Codes	Partici-pants	Coding References
Views on when the cost of green hydrogen would be sufficiently attractive to warrant investments in green hydrogen as an energy storage technology	**10**	**13**
After the elimination of current supply chain issues	1	1
After the widespread adoption of the technology	1	1
Consideration of the case-to-case basis of the cost to benefit application of green hydrogen as energy storage technology	2	2
Establishment of long-term power purchase agreements with developers	1	1
When all-up costs become competitive to within perhaps 10%-20% of LNG at scale	1	1
When the costs are comparable to those of conventional energy storage	4	4
When the costs are competitive to gas and other fossil fuels per kWh produced	3	3

Four of the participants indicated that the cost of green hydrogen would be sufficiently attractive to warrant investment in green hydrogen as an energy storage technology when the costs are comparable to those of fossil fuels and conventional energy storage:

> *P1*
> *I would say when it becomes competitive to the cost of gas and batteries.*
>
> *P5*
> *I would say that hydrogen needs to reach cost parity with conventional fuels prior to it being an economically feasible option.*
>
> *P7*
> *The overall costs must match or even be below fossil fuels.*
>
> *P9*
> *I think when it is cheap enough to match the current sources of energy storage.*

On the other hand, three of the participants stated that the cost of green hydrogen would be sufficiently attractive to warrant investment in green hydrogen as an energy storage technology when the costs are competitive to gas and other fossil fuels per kWh produced:

> *P1*
> *Gas peakers are used a lot in South Africa to balance demand so when it matches the LCOS of gas peakers and when its competitive to gas/kWh.*
>
> *P10*
> *When its cost matches fossil fuels.*
>
> *P2*
> *Depends on the use of hydrogen, load factors of solar PV and wind, capex of electrolysers, cost of gas, diesel, and power generation via fossil fuels. As an example, in Australia renewable power LCOS needs to drop to less than $19.52USD/MWh to enable green ammonia production to be cheaper than natural gas derived ammonia production. For remote areas and isolated communities hydrogen is viable now, particularly if the local gas and diesel costs are high. Approximately by 2030 for other locations including major cities Joburg, Cape Town, Durban, Soweto etc. that are grid connected and with access to reticulated gas.*

Two participants indicated that there was a need for consideration of the case-to-case basis of the cost to benefit application of green hydrogen as energy storage technology:

> *P11*
> *I'm not sure about the actual cost but a cost benefit analysis should be done on a case-by-case basis to determine the IRR and yield.*
>
> *P4*
> *The point at which it would be sufficiently attractive would be contextual, it lends itself towards application in situations with excess renewable electricity and may find specialised use. This may not be primarily on a cost basis, but on a utility basis in terms of suitability to the application in the special circumstance of a renewable electricity plant. A cost exercise surrounding the application of green hydrogen can be done on a case-by-case basis - it may be the most cost-efficient technology on a solar farm in the middle of the Northern Cape so that Independent Power Producers (IPPs) can guarantee a certain base load. Or it may be cost effective for the national grid operator to use instead of hydro and other schemes, all of which will have a cost attached to which it can be compared.*

Other views expressed by the participants on when the cost of green hydrogen would be sufficiently attractive to warrant investments in green hydrogen as an energy storage technology included:

P3
Once the supply chain blockages have been eliminated.

P3
Once adoption of technology occurs, once the technology maturity has been established.

P3
Sign long-term PPA (Power Purchase Agreements) with developers and over takers.

P6
When all-up costs become competitive to within perhaps 10%-20% of LNG at scale.

The literature recognises that the costs of production, conversion and storage of green hydrogen has to be competitive enough for it to be economically viable (IRENA,2021).

5.5 Discussion Pertaining to Proposition 3 or Hypothesis 3

After the reflexive thematic analysis process, different themes emerged that are connected to research question two. The emergent themes are shown in Table 16 below.

Table 16: Policy Framework (Source: NVivo, 2023)

Theme	Participants	Coding References
RQ2. Based on the framework of the multi-level perspective (MLP), what policy pressure can be exerted on the fossil-fuel regime that will result in the adoption of green hydrogen as a viable energy storage technology?	**11**	**28**

Regulatory Incentives	11	28

Nine of the interviewees indicated that tax incentives in different market areas affecting green hydrogen technologies would be one of the regulatory incentives that could enhance full scale market introduction for green hydrogen technologies:

P10
Tax deductions of the manufacturing and production of the technology.

P11
If the incentives introduced can lower the cost of green hydrogen technologies to similar or just less than "normal alternatives" then the market will start to purchase green hydrogen technologies. Price/demand will then start to determine the prices and hopefully in time incentives won't be required to make hydrogen alternatives more attractive and affordable.

P2
Hydrogen R&D and innovation tax concessions, no fuel tax on hydrogen, no road tax on Fuell Cell Electric Vehicles (FCEVs), no commodity tax on hydrogen exports, and no import tax on imported hydrogen goods.

P3
Tax breaks for developers.

P5
Tax breaks or grants could also act as incentives for the market to move in a certain direction.

P6
Incentivising business to continue developments in this area through tax and other incentives.

P7
Tax rebates or cuts in importing the components.

P8
Carbon border adjustment mechanisms, carbon tax.

P9
Introduction of tax credits on hydrogen equipment.

Three participants indicated that the introduction of a carbon trading scheme was a regulatory incentive that could enhance full scale market introduction for green hydrogen technologies:

P1
Carbon pricing makes green hydrogen more attractive.

P2
A carbon tax or carbon trading scheme.

P4
Firstly, the assumption would be that green hydrogen adoption is to be encouraged due to its lower overall emissions. This means that conventional carbon tax schemes can influence its competitiveness.

The introduction of subsidies was also identified as a regulatory incentive that could enhance full scale market introduction for green hydrogen technologies:

P1
Production subsidies that would help the market to grow.

P3
Introduction of tax subsidies.

P8
Subsidies.

Other highlighted regulatory incentives that could enhance full scale market introduction for green hydrogen technologies included:

P3
Create special economic zones.

P1
Setting of mandates in specific sectors like transport.

P4
Emissions regulations can also influence this.

P2
Grants and seed funding for developers.

P1
Infrastructure development support.

P2
Implement national hydrogen Codes of Best Practice.

P5
Funding is a major issue for projects so funding bodies and mechanisms need to be established (the IRA in the US is a fine policy to consider).

P5
A more robust and better implemented IRP could also help.

P6
Facilitating the entry of skilled enterprises and their staff e.g. by enabling visas, making the destination attractive for foreign investment, etc. Obviously current conditions in the country do not favour this.

P5
Greater liberalisation of the electricity value chain could stimulate innovation and competition, of course, under regulation which could accelerate the adoption of hydrogen.

P1
Setting minimum targets for introduction of green hydrogen.

P2
Streamline hydrogen project planning and approvals process.

P7
Government intervention by training people to get the necessary skills.

5.6 Conclusion

The levelised costs of storage has been found to be fairly acceptable although a bit higher than what is in the literature for it to be economically viable as a storage technology in South Africa just like all technologies when they are still being introduced. The main costs are from producing, storing, and converting the hydrogen back into electricity. Other factors such as the cost of electrical power for electrolysis, costs for production equipment, and the efficiency of the electrolysers have to be considered as well. As more research is carried out, this allows the technology to be mass produced on a higher economy of scale making it cheaper with time.

Batteries are still cheaper as it is a mature technology with pumped hydro still the cheapest form of energy storage. The most viable and common option for the conversion of green hydrogen to electricity is through a fuel cell although research is ongoing to design and produce gas turbines that will only use hydrogen gas as a fuel without mixing with other fuels. Hydrogen has the potential in future to assist South Africa with its energy problems as the country has an abundance of renewable power mostly solar PV. The economic turning point would be when the cost of green hydrogen is fairly cheap enough to compete with other fuels and storage technologies.

For the adoption of green hydrogen technologies, regulatory incentives and political goodwill could assist in the widespread adoption of the technology. To discourage the continuous deployment of fossil fuels, the introduction of significant carbon taxes and less funding could be used. To encourage the deployment of green hydrogen, the following could be considered: tax incentives such as the introduction of subsidies, increased funding for research and development, the training and development of a skilled workforce and widescale marketing to promote the adoption of the technology. The creation of standards and regulations for the establishment of the green hydrogen industry and simplifying licensing requirements with the DMRE and the energy regulator are also key to the adoption of this technology.

CHAPTER 6. CONCLUSIONS & RECOMMENDATIONS

6.1 Introduction

This chapter concludes the report by summarising the research findings in terms of each research question. Comparisons between the research and the literature are noted.

6.2 Conclusions Regarding Research Question 1

The LCOS is estimated to be $0.228/kWh which is still fairly higher than the literature value of $0.13/kWh for lithium-ion (Li-ion) batteries and $0.11/kWh for pumped hydro storage. Lazard's 2024 analysis gives the LCOS for green hydrogen to be around the range $0.20 to $0.40 per kWh. This makes Li-ion batteries and pumped hydro very competitive due to their cost, power density and efficiency. In practice, South Africa has a higher solar irradiation which makes it suitable to generate excess PV power at a lower cost which then makes the cost of producing green hydrogen low.

The cost of production for green hydrogen is still fairly high for it to be economically viable as a storage technology just like all technologies when they are still being introduced. The main costs are from producing, storing, and converting the hydrogen back into electricity. Other factors such as the cost of electrical power for electrolysis, costs for production equipment, and the efficiency of the electrolysers have to be considered as well. As more research is carried out ,this will allow the technology to be mass-produced on a higher economy of scale making it fairly cheaper with time as compared to other technologies.

6.3 Conclusions Regarding Research Question 2

For green hydrogen to be competitive, the total costs have to be fairly competitive or match the current costs of fossil fuels and other storage technologies. The round-trip efficiency has to improve, and the technology be mass-produced. The literature recognises batteries and pumped hydro as cheaper as they are mature technologies. It also points out that the costs of production, conversion and storage of green hydrogen has to be competitive enough for it to be economically viable.

6.4 Conclusions Regarding Research Question 3

To discourage the continuous deployment of fossil fuels, the introduction of significant carbon taxes and less funding could be used. For adoption of green hydrogen technologies, the introduction of regulatory incentives and the fostering of political goodwill could assist in the widespread adoption of the technology. To encourage the deployment of green hydrogen, the following could be considered: tax incentives such as the introduction of subsidies, increased funding for research and development, the training and development of a skilled workforce and widescale marketing to promote the adoption of the technology. The introduction of standards and regulations for the establishment of the green hydrogen industry and simplifying licensing requirements with the DMRE and the energy regulator are also key to the adoption of this technology.

Table 17: Consistency Table: Research Questions, Conclusions, and Contribution to Knowledge

Research Question	Research question or objective	Literature-based proposition or hypothesis	Conclusion or answer based on own research	Highlight key differences between initial propositions / hypotheses and findings – contribution to knowledge
1	What is the present LCOS for green hydrogen, relative to competing technologies such as the lithium-ion battery and pumped hydro storage?	The present LCOS is sufficiently competitive for it to be deployed as a large-scale energy storage technology in the South African energy mix.	The levelised costs of green hydrogen are still too high for it to be economically viable as a storage technology in South Africa.	The LCOS is estimated to be $0.228/kWh. Lazard's 2024 analysis gives the LCOS for GH typically in the range of $0.20 to $0.40 per kWh. Li-ion batteries are at $0.13/kWh with pumped hydro at $0.11/kWh.
2	What economic, financial, and engineering factors would need to be addressed for the technology to be competitive?	Green hydrogen could be a competitive storage technology should the cost of storage be reduced to a more competitive level.	For green hydrogen to be competitive, the total costs have to match the current costs of fossil fuels. The round-trip efficiency has to improve, and the technology be mass produced.	The total costs of green hydrogen are still higher than fossil fuels in South Africa for it to be competitive enough. There is a need for mass deployment of the technology and for that to happen, further research and development must be carried out to lower production costs.
3	Based on the framework of the multi-level perspective (MLP), which policy strategies that can implemented on the fossil fuel regime that will result in the adoption of green hydrogen as a viable energy storage technology?	With a more supportive policy framework, green hydrogen could become a useful storage technology for specific applications.	Regulatory incentives and political goodwill could assist in widespread adoption of the technology. This includes tax incentives like the introduction of subsidies, funding research and development, and training of a skilled workforce.	To discourage the continuous deployment of fossil fuels, the introduction of significant carbon taxes and less funding could be used to encourage deployment of the technology. Investment in skills and tax incentives are also major contributing factors on top of a strong political will.

6.5 Recommendations

For the policy makers and energy stakeholders in South Africa, because they are decision makers and their perspectives will determine the future of the technology, they need to publicly discourage the continuous deployment of fossil fuels by promoting the introduction of significant carbon taxes and discouraging the financing of fossil fuel projects. To encourage the deployment of green hydrogen, tax incentives such as the introduction of subsidies, increased funding of research and development, the training and development of a skilled workforce and widescale marketing should be embarked on to promote adoption of the technology. The introduction of standards and regulations for the establishment of the green hydrogen industry, and simplifying licensing requirements with the DMRE and the energy regulator are also key to the adoption of this technology.

The capacity for the local manufacturing of solar PV, fuel cells and electrolysers with relatively low labour costs should also be promoted.

6.6 Suggestions for Further Research

Further research and development is needed in making the technology cheap enough for it to be deployed on a large scale to assist in alleviating the energy crisis in South Africa.The round trip efficiency is still very low for green hydrogen production and its re-use in electricity generation. More research also needs to be carried out in making the development of green hydrogen more efficient to match or even surpass that of fossil fuels.

Research into the safe storage of green hydrogen is another area that needs attention. Advanced process control tools should keep developing for efficient monitoring of the whole production and consumption chain for green hydrogen.

The overall factor that determines the deployment of the technology is cost. Costs need to be sufficiently low to be able to achieve a return on investment as well as addressing energy poverty and the climate change initiative.

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APPENDIX A: Participant Information Sheet

Identity	Gender	Qualifications	Experience in years
P1	Male	PHD	5
P2	Male	Degree	33
P3	Male	Masters	23
P4	Female	Degree	11
P5	Male	Masters	5
P6	Male	Degree	25
P7	Male	Degree	15
P8	Male	Masters	10
P9	Male	Degree	15
P10	Male	Degree	12
P11	Female	Degree	14

APPENDIX B: Consent Form

Title of project: Critical Turning Points for Green Hydrogen in Energy Storage: Insights from Techno-Economics and Transitions Theory in South Africa

Name of researcher: Allen Manyere

I ……………………………………….. agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree that my participation will remain anonymous YES NO (please circle)

I agree that the researcher may use anonymous quotes

in his research report YES NO

I agree that the interview may be audio recorded YES NO

I agree that the researcher may take photos of me YES NO

(but not my face)

I agree that the information I provide may be used YES NO

anonymously by other researchers following this study

…………………………………… (signature)

…………………………………… (name of participant)

…………………………………… (date)

APPENDIX C: Research Instrument

Cover Letter

Dear Participant

I am undertaking a Master of Management in Energy Leadership at the Wits Business School, and, as part of the programme, I am required to undertake a research project, and I am under the supervision of Professor David Walwyn.

The topic of my research is " Critical Turning Points for Green Hydrogen in Energy Storage: Insights from Techno-Economics and Transitions Theory in South Africa".

I kindly request your consent and assistance in this project by inviting you to take part in this survey questionnaire followed by an online interview by completing a few questions that will take around 10 minutes as attached in the e-mail.

The survey questionnaire is anonymous, and confidentiality is guaranteed. Information submitted will be stored securely and used for research and academic purposes only. Participation in this research is voluntary and you are allowed to withdraw from the process at any stage.

For any further questions, do not hesitate to contact the undersigned.

Allen Manyere

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Research Questions

Prior Experience

How long have you been working in the energy sector?

Have you worked directly with hydrogen as either a fuel, or for energy storage, or as a chemical feedstock? Please elaborate on your experience with hydrogen.

Green Hydrogen as a Storage Technology

What do you think are the advantages of deploying grid green hydrogen technologies?

In your opinion, please indicate which technology is better suited to convert stored hydrogen back to electricity.

Do you think green hydrogen is presently a better technology than batteries? Please elaborate on your answer.

If not already a better technology, do you think green hydrogen could be a better technology than batteries? Please elaborate on your answer.

Future Development of Green Hydrogen

Do you think green hydrogen has the potential to solve South Africa's energy storage challenges?

In your own view, what do you see as the biggest challenge to the development of green hydrogen as a storage technology in South Africa?

In your view, what could be the key factors that can drive the adoption of green hydrogen technologies in South Africa?

Economic Turning Points

In your own opinion at what point would the cost of green hydrogen be sufficiently attractive to warrant investments in green hydrogen as an energy storage technology?

Regulatory Incentives

In your view, what regulatory incentives can be introduced to encourage a full-scale market introduction for green hydrogen technologies?

APPENDIX D: NVivo Qualitative Coding Codes

Name	Description	Files	References
RQ1. What economic, financial, and engineering factors (referred to as turning points) would need to be addressed for the technology to be competitive?		11	123
1.1 Prior Experience	Interviewees' past experiences working with hydrogen	10	12
1.1.1 Experiences working with hydrogen	Interviewees' past experiences working with hydrogen	10	12
No past experience working with hydrogen		5	5
Previously worked with hydrogen as a by-product		1	1
Work with hydrogen in education and training		1	1
Worked with hydrogen as a consultant		2	2
Worked with hydrogen in research and development		3	3
1.2 Green Hydrogen as a Storage Technology	Different views related to green hydrogen as a storage technology	11	54
1.2.1 Advantages of deploying grid green hydrogen technologies	Interviewees' thoughts on the advantages of deploying grid green hydrogen technologies	10	17

Name	Description	Files	References
Addressing environmental challenges caused by fossil fuels through less pollution		5	5
Addressing security challenges		1	1
Can help address volatility in energy prices if produced locally		1	1
Feasible for industrial processes		1	1
Green hydrogen technologies are a low-carbon energy source		3	3
Green hydrogen technologies can help in storing energy to smooth the swings in energy supply		1	1
Green hydrogen technology energy can be utilised at point of generation		1	1
Green hydrogen technology is a renewable and sustainable energy source		2	2
Hydrogen can be used for long duration storage in electricity systems		1	1

Name	Description	Files	References
Job creation		1	1
1.2.2 Opinion on best technology to convert stored hydrogen to electricity	Participants' opinion on which technology is better suited to convert stored hydrogen back to electricity.	11	11
Fuel cells because they have a high efficiency		10	10
Steam Methane Reforming		1	1
1.2.3 Views on whether green hydrogen is presently a better technology than batteries	Interviewees' views on whether green hydrogen is presently a better technology than batteries	11	15
Better		3	4
Green hydrogen technologies can be effective in power grids requiring storage of electricity for longer durations		2	2
Green hydrogen technology might be better than batteries in applications and sectors requiring extended range		2	2
Not better		10	11
Batteries are better and more efficient for light		1	1

Name	Description	Files	References
duty passenger vehicle mobility			
Batteries are better technology than green hydrogen currently		3	3
Batteries are cheaper which makes them a better technology currently		5	5
Batteries are currently better technology be-cause of demonstrated capabilities while green hydrogen has not been effectively tested		2	2
1.2.4 Views on whether green hydrogen could be a better technology than batteries in the future	Interviewees’ views on whether green hydrogen could be a better technology than batteries in the future.	11	11
Better		8	8
Green hydrogen can be a better technology than batteries because it is more energy dense per weight and can be easier to transport		1	1

Name	Description	Files	References
Green hydrogen has a high potential as technology		1	1
Green hydrogen technology can be a better technology in the future because of allowing long-term storage of electricity which can reduce load shedding		1	1
Green hydrogen technology can be a better technology than batteries depending on the ease of the availability of resources for the technology in the future		1	1
Green hydrogen technology would be a better technology than batteries in the long term if conversion, cost, and distribution challenges were met		1	1
Green hydrogen technology would be more sustainable than batteries		1	1

Name	Description	Files	References
making it a better technology			
Reduction in the cost of green hydrogen technology in the future will make it a better technology than batteries		2	2
Not better		3	3
Green hydrogen cannot be a better technology than batteries because it is expensive		1	1
Significantly dependent on application of such technology		2	2
1.3 Future Development of Green Hydrogen	Views expressed by the participants related to the future development of green hydrogen	11	44
1.3.1 Challenges to the development of green hydrogen as a storage technology in South Africa	The biggest challenge to the development of green hydrogen as a storage technology in South Af-rica	11	14
Cost implications		7	7
Efficiency losses associated with the technology		1	1
Finding local and international markets		1	1

Name	Description	Files	References
to justify industry expansion			
Infrastructural constraints		1	1
Justifying the profitability of green hydrogen technology compared to other cheaper storage and generation technologies		1	1
Lack of a sufficient number of skilled individuals to work with green hydrogen technology in South Africa		1	1
Lack of enabling policies		1	1
Political interference and lack of political goodwill		1	1
1.3.2 Factors that could contribute to the adoption of green hydrogen technologies in South Africa	Key factors that can drive the adoption of green hydrogen technologies in South Africa	11	22
A cost of production parity with other common energy sources		1	1
Affordability		1	1

Name	Description	Files	References
Availability of a trained workforce with the ability to manufacture green hydrogen technologies locally		1	1
Effective regulations		2	2
Export potential for industrial processes		1	1
Identification of profitable markets		1	1
Implementation of pilot projects to prove feasibility		1	1
Increase funding of research and development		1	1
Increase in price of alternative technologies which can make green hydrogen technology more viable		1	1
Introduction of subsidies		2	2
Legislation		1	1
Marketing to demonstrate application		1	1
Political goodwill		1	1
Promoting access to minerals to		1	1

Name	Description	Files	References
manufacture green hydrogen technology			
Reduction of production costs		2	2
Regulatory incentives		2	2
Tax incentives		1	1
Widespread adoption of the technology which can contribute to cost reduction		1	1
1.3.3 Views on whether green hydrogen has the potential to solve South Africa’s energy storage challenges	Whether green hydrogen has the potential to solve South Africa’s energy storage challenges?	8	8
Green hydrogen cannot solve South Africa's energy storage crisis in the short-term because of infrastructural constraints		1	1
Green hydrogen has potential to solve South Africa’s energy storage challenges because of the availability of natural resources which can make it economically viable		2	2
Green hydrogen technology can help resolve South Africa's		1	1

Name	Description	Files	References
energy storage challenges through the implementation of centralised renewable energy systems			
Green hydrogen technology can solve some of South Africa's energy storage challenges, but the cost of hydrogen-based infrastructure would be prohibitive		1	1
In the long run, green hydrogen can help solve South Africa's energy storage challenges because of high availability of hydrogen in the country's coastal areas		1	1
Reduction in the cost of green hydrogen technology in the future can make it a viable solution to South Africa's energy storage challenge		2	2
1.4 Economic Turning Points	Interviewees' views on the point at which the cost of green hydrogen is sufficiently attractive to warrant investments in green hydrogen as an energy storage technology	10	13
1.4.1 Views on when the cost of green hydrogen would be sufficiently		10	13

Name	Description	Files	References
attractive to warrant investments in green hydrogen as an energy storage technology			
After the elimination of current supply chain issues		1	1
After the widespread adoption of the technology		1	1
Consideration of a case-to-case basis of the cost to benefit application of green hydrogen as energy storage technology		2	2
Establishment of long-term power purchase agreements with developers		1	1
When all-up costs become competitive to within perhaps 10%-20% of LNG at scale		1	1
When the costs are comparable to those of conventional energy storage		4	4
When the costs are competitive to gas and other fossil fuels per kWh produced		3	3

Name	Description	Files	References
RQ2. Based on the framework of the multi-level perspective (MLP), what policy pressure can be exerted on the fossil-fuel regime that will result in the adoption of green hydrogen as a viable energy storage technology		11	28
2.1 Regulatory Incentives	Regulatory incentives that could enhance full-scale market introduction for green hydrogen technologies.	11	28
2.1.1 Regulatory incentives that could enhance full-scale market introduction for green hydrogen technologies		11	28
Creation of special economic zones focusing on green hydrogen technologies		1	1
Developing mandates to introduce green hydrogen technologies in sectors such as transport		1	1
Emission regulations		1	1
Grants and seed funding		1	1
Infrastructural support and development		1	1
Introducing a national practice code for		1	1

Name	Description	Files	References
professionals involved in green hydrogen technology			
Introduction of a carbon trading scheme		3	3
Introduction of funding mechanisms and bodies		1	1
Introduction of more robust policies affecting green hydrogen technologies		1	1
Introduction of subsidies		3	3
Making the country more attractive to foreign investments in green hydrogen technologies		1	1
More liberalisation of the electricity value chain		1	1
Setting targets to encourage introduction of green hydrogen technologies		1	1
Streamline hydrogen project planning and approvals process		1	1
Tax incentives in different market areas		9	9

Name	Description	Files	References
affecting green hydrogen technologies			
Training opportunities for workers working with green hydrogen technologies		1	1

APPENDIX E: Ethics Approval Notification.

Graduate School of Business Administration
University of the Witwatersrand, Johannesburg

Wits Business School

Wits Business School Ethics Committee
Constituted under the University Human Research Ethics Committee (Non-Medical)

Ethics Clearance Certificate

Ethics protocol number: WBS/EL2029471/972

This certificate is only valid with a legitimate ethics protocol number and signed by the Researcher (below).

Project title	Turning points for green hydrogen in energy storage: insights from techno-economics and transition theory
Investigator / Researcher	Mr Allen Manyere
Nature of Project	MM (Energy Leadership)
Decision of the Committee	Approved, provided stakeholders and participants are guaranteed confidentialty.
Issue Date of Certificate	2023/09/18
Expiry date	Date of submission of the project / research report
Chairperson	Dr Pius Oba ☎ +27 11 717 3976 +27 82 733 6587 pius.oba@wits.ac.za

Declaration by Researcher

One copy must be signed by the Researcher and returned to the Chairperson of the Wits Business School Ethics Committee.

I fully understand the conditions under which I am authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I undertake to resubmit the protocol to the Committee.

AManyere

Signature

22 September 2023

Date: