Opportunities for a green hydrogen market: The case of South Africa and the European Union

Khanyiselo Kumalo

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Master's Thesis

STUDENT REPORT

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Department of Development and Planning
Sustainable Energy Planning and Management
Rendsburggade 14
9000 Aalborg
en.plan.aau.dk

Title

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Author:

Khanyiselo Kumalo

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Abstract:

The narrative of this project argued that South Africa is a prominent coal exporter, however, the country finds itself in a predicament as coal demand dwindles due to global energy transitions. The project outlined South Africa's comparative advantages and asserted these can be leveraged to unlock an alternative low carbon trade market in the form of green hydrogen. As such, the following research problem was identified: *"Using green H_2 as an enabler for decarbonisation between 2030 and 2050 in the industrial sector, how will the projected increase in the EU's H_2 demand influence SA's ability to export carbon-free energy?"*. Altogether, the viability of hydrogen from South Africa to Europe was analysed as a case study. This lead to an extensive review of the economics of producing, storing, and transporting hydrogen. Literature review and stakeholder interviews were among the methods utilised for collecting and validating information. While the Inductive, Carbon Lock-in and Multilevel Perspective theories were adopted as the worldview of the project. Finally, recognising that it takes time for emerging technologies to reach commercial viability, the project proposed policy recommendations to foster the development of a scaled green hydrogen market in South Africa.

Summary

Hydrogen (H_2) is receiving increasing global attention thanks to its decarbonisation potential. Therefore, this research aimed to evaluate the extent to which green H_2 and other hydrogen-based energy carriers could be an alternative route for South Africa (SA) to maintain its role as a prominent energy exporter.

The project opened with an introduction to SA as one of the signatories to the Paris Agreement. This agreement signifies SA's obligation to efforts that should see the country transition towards low carbon pathways. The export of coal was identified as an important foreign trade earner for the region. However, due to global energy transitions, this market will put SA and the communities that depend on the continued existence of the coal sector in a precarious position.

A strong renewable energy offering coupled with years of engineering and technological know-how with the Fischer-Tropsch (FT) process was among a suite of options that were cited as comparative advantages the country could leverage to unlock a green H_2 export market. Further analysis showed that trading energy across borders will prove to be a challenge if the energy cannot be stored and transported cost competitively. Criteria for selecting a suitable trade partner ensued, where the European Union, for its current and projected H_2 demand in the industrial sector, its preference for green H_2 and its ambitious climate targets, was selected. As a result, the following research problem was posed: *"Using green H_2 as an enabler for decarbonisation between 2030 and 2050 in the industrial sector, how will the projected increase in the EU's H_2 demand influence SA's ability to export carbon-free energy?"*

Altogether, the practicality of H_2 from SA to Europe was analysed as a representative case study, where a comprehensive review of the technical and financial elements that affect the H_2 supply chain from production, storage, and transportation was carried out.

The research problem was addressed using a suite of methods which included:

- Literature review
- The Levelised Cost of Energy (LCOE) metric
- Stakeholder analysis
- Interviews
- Email correspondence

The data analysis from the aforementioned methods revealed the following insights:

1. It has been argued that there is a relationship between electricity prices and the levelised cost of H_2 (LCOH). The findings have been shown that the higher the price of electricity, the higher the H_2 production cost. While other economical and technical factors influence H_2 production cost, it is asserted that the cost of electricity will be one of the key drivers.
2. The project asserted that storing H_2 as a chemical was more cost-effective than storing H2 in its pure form. Moreover, the project found shipping was the more

financially viable mode for carrying H_2 over long distances.

3. Drawing from stakeholder engagements, it became apparent that there is a likelihood that SA's dependence on coal will lead to technical, social and institutional tendencies that foster carbon lock-in.

Finally, research from reputable institutions has shown that emerging energy technologies take time before they can compete with longstanding technologies. As such, the project concluded with policy recommendations to stimulate the growth of SA's green H_2 export market.

Preface

The basis for this research project stems from my passion and inquisitive nature about solutions to decarbonise global economies. This education has shown me that electricity and hydrogen are essential to making the world sustainable. But for as long as that electricity and hydrogen come from fossil fuels, this vision may not be realised.

Writing this thesis alone, under lockdown was incredibly difficult. The entire experience has reaffirmed the notion that no man is an island. To that, my gratitude goes to my friends and family for their invaluable support.

The project has been written at Aalborg University on the fourth semester of the Master programme Sustainable Energy Planning and Management. The project addresses the semester's theme: "Master's Thesis". In no particular order, I would like to thank the following individuals for sharing their expert knowledge and insight:

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Moreover, I wish to thank my supervisor, Peter Sorknæs, for his guidance throughout the project.

The citations used in the report follow the APA referencing style. This means that the author's last name and year of publication are in brackets. In situations with more than two authors, the last name of the first author, followed by "et al" and the publication year is used in brackets. "n.d." is used to denote sources with no publication date. Finally, the spread of sources used throughout the project is shown in alphabetical order in the bibliography.

Below is a list of appendix attached to the report:

- Appendix 1 - Overview of engaged stakeholder
- Appendix 2 - Email correspondence
- Appendix 3 - Interview transcripts

“Water will be the coal of the future” - Jules Verne, 1874

Acronyms

Acronym	Abbreviation:
AAU	Aalborg University
AE	Alkaline electrolyser
AEM	Anion exchange membrane
CAPEX	Capital expenditure
CCS	Carbon Capture Storage
CCUS	Carbon Capture Use and Storage
CGH_2	Compressed gaseous hydrogen
CO	Carbon monoxide
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
CTL	Coal-to-liquid
DAC	Direct Air Capture
DEA	Department of Environmental Affairs
DSI	Department of Science and Innovation
EU	European Union
FLH	Full Load Hours
FT	Fischer–Tropsch
GJ	Gigajoules
GTL	Gas-to-liquid
H_2	Hydrogen
H_2O	Water
HySA	Hydrogen South Africa
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRP	Integrated Resource Plan
kg	kilogram
LCOE	Levelised Cost of Energy
LCOH	Levelised Cost of Hydrogen
LCOS	Levelised Cost of Storage
LCOT	Levelised Cost of Transport
LH_2	Liquid Hydrogen
LOHC	Liquid Organic Hydrogen Carrier
MeOH	Methanol
MLP	Multilevel Perspective
MW	Mega watts
MWh	Mega watts hours
NDP	National Development Plans
NH_3	Ammonia
O&M	Operations and maintenance
O_2	Oxygen
PEM	Polymer electrolyte membrane
PGM	Platinum Group Metals
PV	Photovoltaics
R&D	Research and development
RE	Renewable Energy
SA	South Africa
SAT PV	Single Axis Tracking Photovoltaics
SMR	Steam methane reforming

SOEC	Solid oxide electrolyser cell
SSA	Sub-Saharan Africa
tpd	tonnes per day
USD	United States Dollar
VRES	Variable renewable energy source
WACC	Weighted Average Cost of Capital

Contents

Problem Analysis 1

This chapter reveals how SA's dependence on the coal industry puts the country in a precarious position. The chapter further speaks to comparative advantages that the country could leverage to offset its reliance on coal exports. Lastly, the chapter draws to a close by establishing the project's research problem.

1.1 South Africa's obligation to the Paris Agreement

South Africa (SA) is one of many countries that signed the Paris Agreement [Department of Environmental Affairs, 2019]. In so doing, the country committed itself to make efforts that would decarbonise the economy by shifting to sustainable and carbon-free pathways. According to Amusan og Olutola [2016], South Africa's (SA's) economy is largely coal dependant. This view is echoed in a newly published report by the Department of Environment, Forestry and Fisheries [2020], where energy industries such as liquid fuel production and electricity generation are highlighted as primary carbon-intensive industrial activities, owing to their dependence on coal. As depicted in Figure 1.1, SA's reliance on extractive activities comes with negative environmental implications.

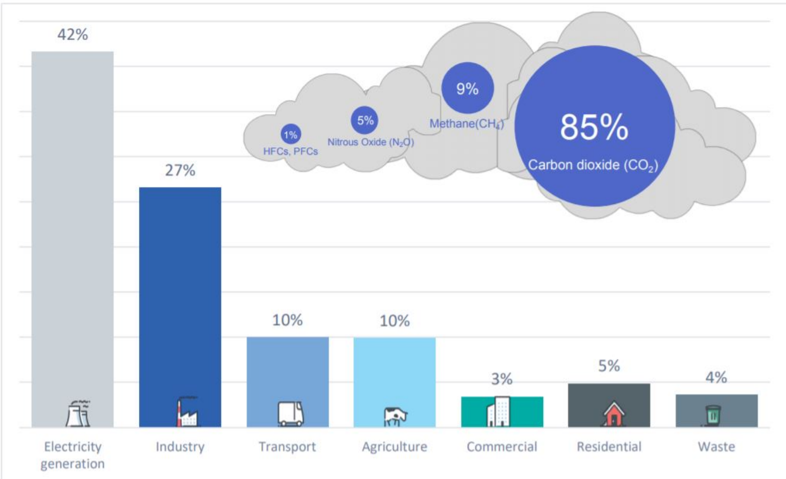

Figure 1.1. Image illustrating SA's emissions by economic sector [Department of Environment, Forestry and Fisheries, 2020].

Also worth mentioning is SA's crucial role as a global exporter of coal. Findings in the Department of Energy [2019] reveal that with the 5th largest coal reserves globally, about 30% of the country's coal production is for the export market. This makes the coal economy an important trade earner for the national fiscal [McSweeney og Timperley, 2018]. All things considered, the demand for coal is expected to dwindle as more countries strive to meet their decarbonisation targets in line with the Paris Agreement. Consequently, this poses a treat for workers and communities that depend on the continued existence of the coal sector in SA [Upadhyaya og Naudé, 2018]. Fortunately, SA is endowed with good wind and solar resource potential, giving it a slightly better adaptive capacity to respond to climate change. With this context, Section 1.2 elaborates on (i) SA's comparative advantages, and (ii) the possibility to leverage these advantages to unlock new and sustainable export commodities.

1.2 Why South Africa?

This section identifies drivers that highlight SA's comparative advantage with unlocking opportunities for exporting clean energy.

1.2.1 A strong renewable energy offering

A study by Metcalfe et al. [2020] reported figures that indicated some 30% of the planet's energy was traded across borders in 2017. The study continues to infer that this number is likely to increase as regions with the best RE resources export their energy to those less enriched [Metcalfe et al., 2020]. On this point, research by Roos og Wright [2021] contends Southern Africa's solar resource is among the best in the world. While the wind resource potential is competitive with Europe's onshore wind potential. For illustrative purposes, Figure 1.2 and Figure 1.3 provide a depiction of this potential.

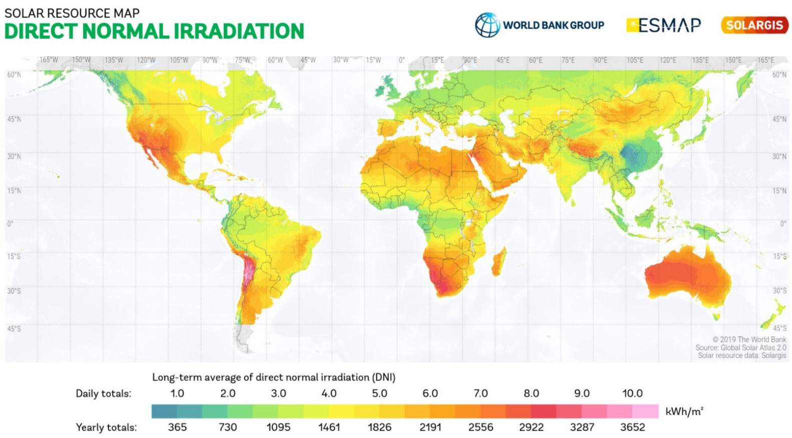

Figure 1.2. Image illustrating SA's long-term average of direct normal radiation (DNR) relative to the rest of the world [Global Solar Atlas, 2019].

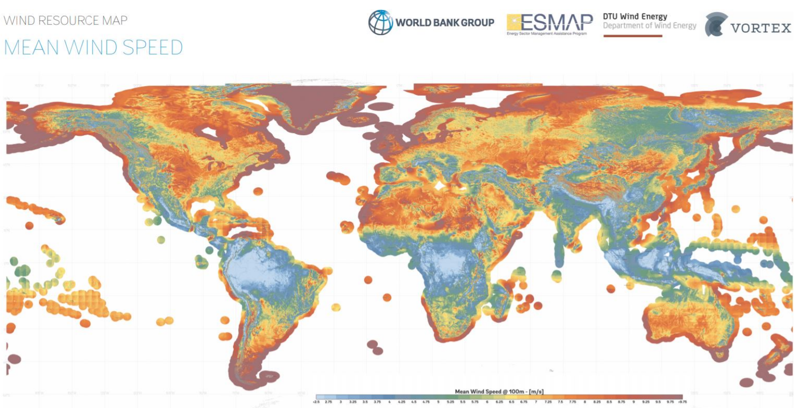

Figure 1.3. Image illustrating SA's mean wind speed relative to the rest of the world at 100m above surface [Global Wind Atlas, 2019].

For countries that rely on fossil-based energy exports to meet their energy needs, SA's RE potential presents an opportunity to unlock a new trade commodity. One that will transition the country from its current role as an exporter of coal, to a clean energy exporter. And while the prospect of SA leveraging its resource potential to supply clean energy to other countries appears attractive, it is equally important to recognise that energy trading will become increasingly difficult if it cannot be stored and transported in a cost-effective manner [Metcalfe et al., 2020]. With that, the question of what type of storage and transport is necessary to facilitate the trading of clean energy cost-effectively is an important one to understand. Section 1.5 speaks to this narrative. But before that, subsection 1.2.2 elaborates on SA's comparative advantage.

1.2.2 The Fischer-Tropsch advantage

The history of the Fischer-Tropsch (FT) process extends as far back as the 1920s in Germany [Hubbard, 2015]. It was used in the coal-to-liquid (CTL) industry to make petroleum products by converting the main constituents of H_2, carbon monoxide (CO) and gas [EPA, 2009]. The report by van de Venter [2005] argues that Sasol, which is situated at Secunda in SA has over 55 years of experience with FT. Moreover, van de Venter [2005] maintains Sasol is the only company in the world to operate large scale, commercial, and integrated CTL plants viably. This view is corroborated in recent research findings by Metcalfe et al. [2020] and Patel [2020].

The ability to be applied to a variety of feedstocks is, according to EPA [2009] and van de Venter [2005], one of the favourable attributes of Sasol's FT technology. Aside from coal and crude oil, low carbon alternative feedstocks include biomass, natural gas, and H_2 [van de Venter, 2005]. Similarly, PetroSA, situated in the Western Cape province of SA, operates a gas-to-liquid (GTL) facility that uses a variation of the FT technology process [EPA, 2009].

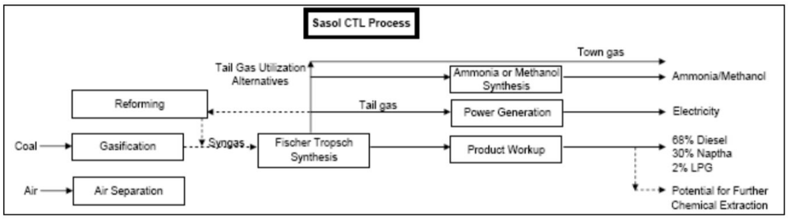

Figure 1.4. Image illustrating Sasol's coal-to-liquid process [EPA, 2009].

As shown in Figure 1.4, the FT synthesis process can be used to produce synthetic fuels that include ammonia and methanol. The H_2, which is mainly produced from natural gas via reforming and from coal via gasification, is used as a feedstock for many industrial processes, including ammonia and methanol production [IEA, 2019] and [Metcalfe et al., 2020]. However, IEA [2019] further argues when the H_2 is derived from renewable resources such as wind and solar, ammonia and methanol become attractive candidates for achieving decarbonisation in hard-to-abate sectors.

Considering everything, Sasol's 50+ years of engineering experience with constructing, maintaining and operating CTL related plants and technologies, the competent pool of skills and resources coupled with SA's RE potential, all provide unparalleled comparative advantages that the country could leverage to locally produce and supply H_2-based, carbon-neutral energy across borders.

1.2.3 Unmatched platinum footprint and government buy-in

Platinum is a precious metal that belongs to a group of six metals that are collectively called platinum group metals (PGMs). Other metals in this group include palladium, rhodium, iridium, osmium, and ruthenium [Shah, 2021]. In a report by Clifford Chance [2021], the author states that PGMs are not only used in fuel cells but also play a crucial role in platinum-based electrolysers that produce renewable H_2.

As of 2020, estimated at 69,000 metric tons globally, approximately 95% of the world's platinum reserves are found in SA [Garside, 2021]. In the words of Clifford Chance [2021], this unparalleled platinum footprint makes "*South Africa a potentially indispensable player in the growth of a green hydrogen economy in Africa.*"

In a bid to explore the prospects of utilising clean H_2 in different sectors, the SA government established Hydrogen South Africa (HySA) in 2008 as a dedicated national competency. More recently, the government has been evaluating potential avenues to supply renewable H_2 to countries like Germany and Japan [Clifford Chance, 2021].

Given the aforementioned advantages, it is apparent that SA has capabilities that could be leverage to produce H_2 and other H_2-based chemicals such as ammonia and methanol. In drawing this section on SA's advantages to a close, section 1.3 will shed light on the (i) different types of H_2, (ii) various ways of producing the molecule and, (iii) the type of H_2 and production pathway that this project limits itself to.

1.3 Hydrogen types and production pathways

DNV GL [2018] writes there are different ways of producing H_2. And while the different production pathways all produce chemically identical product in the end, they differ in the carbon-intensive nature of the H_2 production process [Metcalfe et al., 2020]. According to Metcalfe et al. [2020], there are three methods of producing H_2. These are:

1. a fossil-based method.
2. a fossil-based method paired with carbon capture use and storage (CCUS).
3. a renewable energy based method that uses electrolysis.

For illustrative purposes, Figure 1.5 depicts the various hydrogen production option alongside its decarbonisation measures. Though H_2 is a colourless, tasteless and odorless gas, the colours in the image are a reflection of the H_2 colour code.

According to the H_2 colour code, when electricity from clean sources such as wind and solar are used to split water into H_2 and O_2, that H_2 is considered green H_2 because the production process does not have emissions. H_2 is considered blue H_2 when SMR is used to produce the molecule from natural gas. The emissions associated with this process are then captured and stored [McKie, 2020].

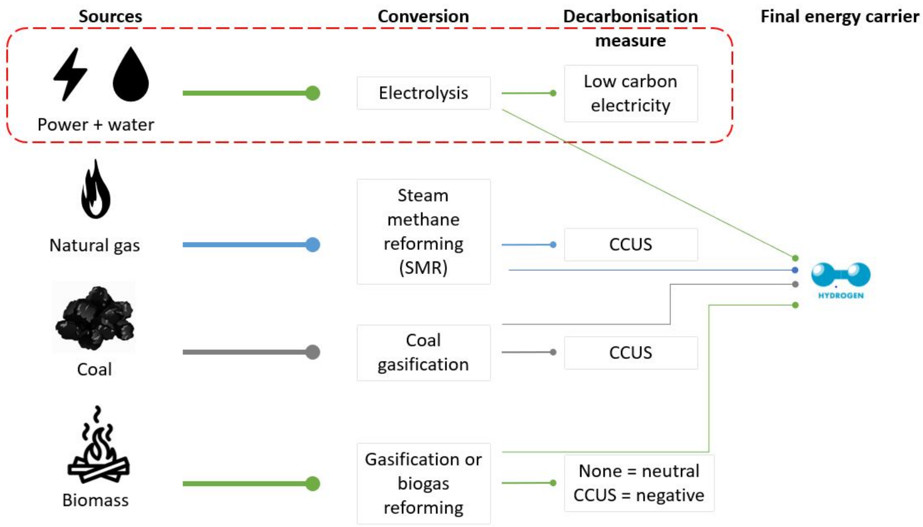

Figure 1.5. Image illustrating H_2 production options and decarbonisation measures. Own image adapted from [DNV GL, 2018] and [Shell, 2017].

McKie [2020] writes that grey H_2 is the cheapest way to produce H_2. Consequently, this is the prevalent H_2 production method globally. In this method, gasification is used to converts solids into a gas. Feedstocks could be coal, biomass, or heavy oil residues [Weeda og Segers, 2020]. By numbers, grey H_2 accounts for 18kg - 20kg of carbon emissions for every kg of H_2 produced [Metcalfe et al., 2020]. However, the process can be decarbonised with the use of CCS [DNV GL, 2018]. Finally, H_2 can be produced from biomass via reforming or gasification. The process is carbon neutral and can be carbon negative when CCUS is used [DNV GL, 2018].

According to DNV GL [2018] and IRENA [2019], H_2 is receiving international and cross-sectoral attention because of its decarbonisation potential. This implies that emphasis should be placed on low-carbon H_2 production pathways. In addition, many countries have released H_2 strategies that highlight a preference for green H_2 in the future. With that context in mind, and for the purpose of this research, the project limits itself to investigating the prospects of green H_2. This approach is denoted by the dotted red line in Figure 1.5.

Given this understanding, section 1.4 will thus delve into the economics of green H_2 production.

1.4 The economics of producing green hydrogen

As alluded to in section 1.3, green H_2 is derived by splitting water (H_2O) into H_2 and oxygen (O_2) with the use of an electrolyser and renewable electricity [IRENA, 2019]. According to IEA [2019], the decreasing costs of electricity from wind and solar PV has sparked a growing interest in green H_2. Roos og Wright [2021] outline three key cost drivers that influence cost-competitive green H_2 production. These include: (i) electricity costs from renewable energy, (ii) electrolyser costs, and (iii) costs of water supply.

1.4.1 Electricity costs from renewable energy

Electricity costs account for approximately 50% - 70% of the levelised cost of H_2 (LCOH)[PwC, 2020]. Moreover, PwC [2020] argues it is worthwhile to invest in electrolysers that are situated in regions with abandant RE as that approach would go a long way to achieving cost parity with H_2 from fossil fuels.

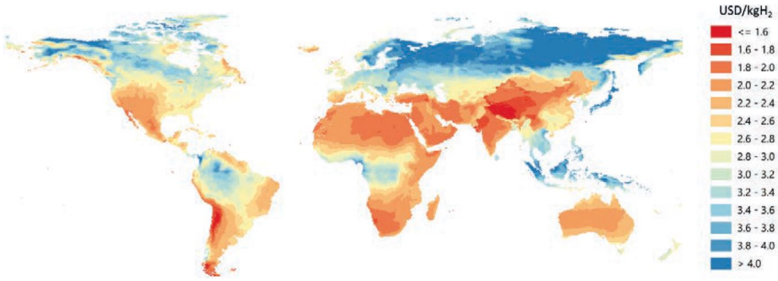

Figure 1.6. Image illustrating the long-term costs of hydrogen production from hybrid solar and onshore wind [IEA, 2019].

Figure 1.6 shows the long-term costs of green H_2 across the globe. As a country with rich RE potential, the figure suggests that SA can produce H_2 at a cost of between 1.8 - 2.0 USD/kgH_2. This view is echoed by ESMAP [2020] with findings that state that SA is one of the resource-enriched countries that could provide green H_2 at a cost below 2 USD/kg by 2030. Considering such prices, producing green H_2 could be equivalent, and in some cases, cheaper than dedicated on-site production of H_2 from natural gas via SMR [ESMAP, 2020]. To this, IEA [2019] contends that combining wind and solar in a hybrid plant in regions with excellent RE resources has a high likelihood to lower costs even further. Additional details on the relationship between H_2 and renewable electricity are unpacked in Chapter 5, section 5.1 of the report.

1.4.2 Electrolyser costs

Zhang et al. [2016] identified three main types of electrolyser technologies. First is the alkaline electrolyser (AE), which Zhang et al. [2016] suggests, relative to the others, is the more mature and predominantly used at large scale. Then there is the Proton-exchange membrane (PEM) electrolyser. According to Zhang et al. [2016] and Roos og Wright [2021], unlike the AE, the PEM uses a solid electrolyte instead of the corrosive liquid electrolyte in AE. Both authors also agree that PEM typically has high manufacturing costs than AE. Zhang et al. [2016] continues to state that the PEM is more fitting for systems with fluctuating power supply.

Lastly, is the Solid oxide electrolyser (SOE). Zhang et al. [2016] and Roos og Wright [2021] both agree the SOE operates at a high temperature than the AE and PEM, giving it higher efficiency. Roos og Wright [2021] further states that SOE is at the demonstration level but still have a lower technology readiness level. Additionally, because SOE can be operated in reverse mode as a fuel cell, IEA [2019] argues this will not only make it possible for H_2 to be converted back to electricity, but it will also increase the utilisation rate of the technology. As with the previous section, more details on important elements that influence electrolyser costs are explained in Chapter 5, section 5.2 of the report.

1.4.3 Costs of water supply

Research by IEA [2019] speaks to the water-intensive nature of green H_2 production. The author states that producing 1kg of H_2 requires some 9liters of water. Comparatively, IEA [2019] explains SMR without carbon-capture use and storage (CCUS) needs about 7litres of water per kg of H_2. To this point, Roos og Wright [2021] argues it is important to ensure that the use of water for H_2 production should not negatively affect other equally important, water dependant sectors such as agriculture etc. For water-stressed coastal regions, IEA [2019] suggests the utilisation of seawater as a potential alternative. The relationship between water costs and H_2 production is further explained in Chapter 5, section 5.3 of the report.

In section 1.2, Metcalfe et al. [2020] reported the world is likely to see an increasing need for clean energy trading as climate change restrictions become more stringent. This section also mentioned for this demand to be met, the energy will need to be stored and delivered efficiently. It is therefore against this backdrop that 1.5 evaluates the various storage and transport options.

1.5 Storage and transport of clean energy

There are multiple ways to store and transport energy across borders. The subsections that follow will discuss the various options and limitations associated with each.

1.5.1 Regional power trading via interconnection lines

Eberhard et al. [2011] argues many benefits can be derived from regional power trading in Sub-Saharan Africa (SSA). Despite this, trade between countries in this region is still minimal, with most trade happening largely between SA and Mozambique [Eberhard et al., 2011]. Niyimbona [2005] writes there are factors that contribute to the issue minimal trading. These include:

- the issue of underdeveloped interconnection networks
- a non-existent legal framework for trading resulting in challenges operationalising power pools in SSA.
- Eberhard et al. [2011] identifies the challenge of forging political consensus as another limiting factor.

Without these key elements in place, this project, therefore, disqualifies regional trading via interconnection lines as a viable means for exporting clean energy cost-effectively.

1.5.2 Chemical and electrical energy storage

According to DNV GL [2019], the intermittent nature of variable renewable energy sources (VRES) like wind turbines and photovoltaics (PV) is a major difficulty. Similarly, Christensen et al. [2013] contends systems with VRES at scale have limited adaptive capacity for system regulation and balancing. This explains the increasing attention and importance of system balancing technologies such as energy storage today and in the future [Christensen et al., 2013].

Scott [2018] argues electrical storage, particularly lithium-ion batteries, are ahead of the rest both in market adoption and technology readiness level. In contrast, Metcalfe et al. [2020] states electrical energy is both challenging and expensive to store at scale for extended periods without incurring energy losses and creating inefficiencies. Metcalfe et al. [2020] goes on to list additional factors that count against the extensive use of electrical storage. These include the

- rarity of battery material,
- production costs, and
- power to weight ratio.

As an alternative, Metcalfe et al. [2020] speaks highly of chemical storage as a more viable and suitable option for trading green H_2 cost-effectively.

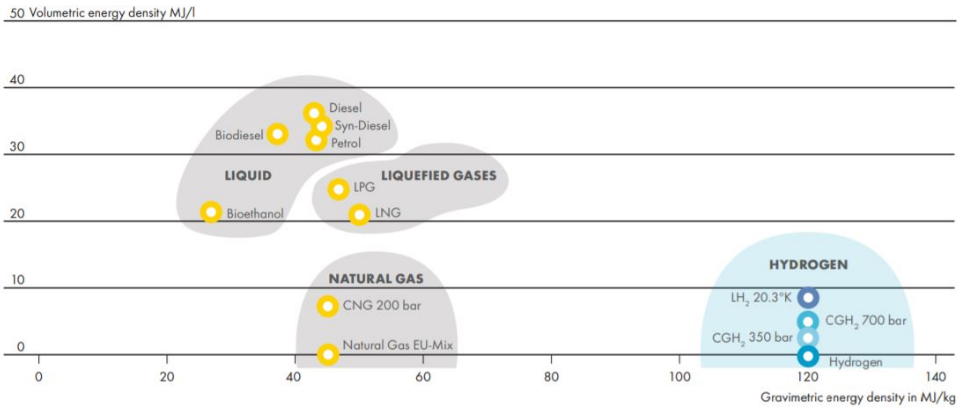

Figure 1.7. Image illustrating the gravimetric and volumetric energy density of H_2 and other types of fuels and energy carriers [Shell, 2017].

As shown in Figure 1.7, H_2 has an exceptionally higher gravimetric energy density. In contrast, the volumetric energy density is relatively low. Nevertheless, unlike electrical storage, DNV GL [2019] and Shell [2017] maintain the ability to be stored at scale, over long periods of times without incurring significant losses is one of the appealing attributes of chemical energy storage. However, prior to transporting the energy to relevant markets, it must be stored in an appropriate form [Roos og Wright, 2021]. Detailed information on the various pathways of storing H_2 can be found in Chapter 6, section 6.1 of the report.

With the possibility of green H_2 as a new tradable commodity for SA sufficiently explored, Section 1.6 reveals the criteria followed for identifying a likely importer of green H_2 from SA.

1.6 Selecting a suitable trade region

The following criteria was used for identifying and selecting a suitable trade region:

1. The size of the H_2 market in both regions today and in the future. Closely linked to this was understanding the importing region's reliance on energy exports and its long-term ability to sufficiently meet its H_2 demand.

2. The region must have long-term green H_2 targets with policies in place for meeting set targets.
3. Alongside the defined climate change goals, the region must have existing relations with SA.
4. Most importantly, SA's comparative advantage with low-cost hydrogen production and delivery compared to other potential countries.

Following the above criteria, the EU was identified to be a potential importer of green H_2 from SA.

1.7 The European Union as a strategic partner

Europe is one of the continents with ambitious climate goals. More specifically, the European Green Deal speaks to the continent's commitment to be climate neutral by 2050 [European Commission, 2020a]. Owing to its deep decarbonisation potential, the European Green Deal identifies H_2 as an integral part of meeting the mid-century target [European Commission, 2020b]. The European Union's (EU's) H_2 strategy recognises that there are economic sectors where emission reduction is both urgent and difficult to achieve [European Commission, 2020a]. As such, in a communication in Brussels to the European Parliament, European Commission [2020b] clarified the EU's preference for green H_2 by making the following statement: "*The priority for the EU is to develop renewable hydrogen, produced using mainly wind and solar energy.*"

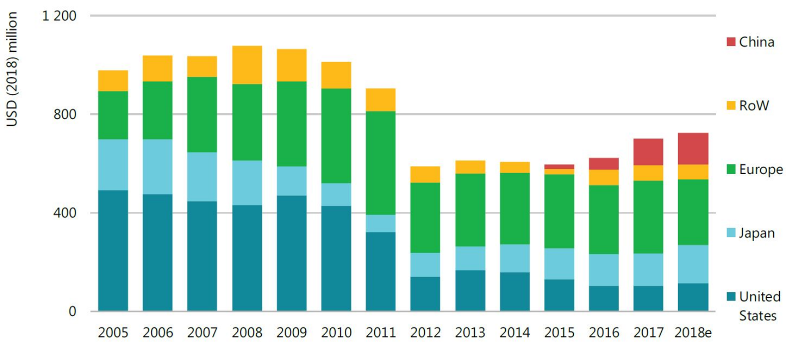

Figure 1.8. Image illustrating governments allocated spending on research development and demonstration for fuel cells and H_2. RoW = rest of world [IEA, 2019].

Evidently from Figure 1.8, Europe is one of the continents that has allocated considerable spending, relative to other regions, geared towards research development and demonstration in the H_2 and fuel cell space. In addition, it is also important to recognise that the EU and SA have a longstanding strategic partnership that extends as far back as 2006 [European Commission, 2020d]. Though the partnership is broad and comprehensive, it includes mutual interests such as climate change and sustainable energy, resulting in both parties working cooperatively to carry out the Paris Agreement [European Commission, 2020d].

In drawing this section to a close, section 1.8 will clarify the role H_2 currently plays in Europe's hard-to-abate sectors, while also considering projected future demand and the nature of that demand.

1.8 The role of hydrogen in Europe's hard-to-abate sectors

With a focus on the industrial sector, this section describes where most of the H_2 is being used at present, as well as demand projections for the future.

1.8.1 Hydrogen in the chemicals sector today

Figure 1.9 provides a general overview of the role H_2 plays in Europe at present. From the image, it can be seen that H_2 use is concentrated in the chemicals and petrochemicals industry [FCH, 2019]. By numbers, according to Figure 1.9, a total of 325 TWh of H_2 is used as a feedstock on a yearly basis.

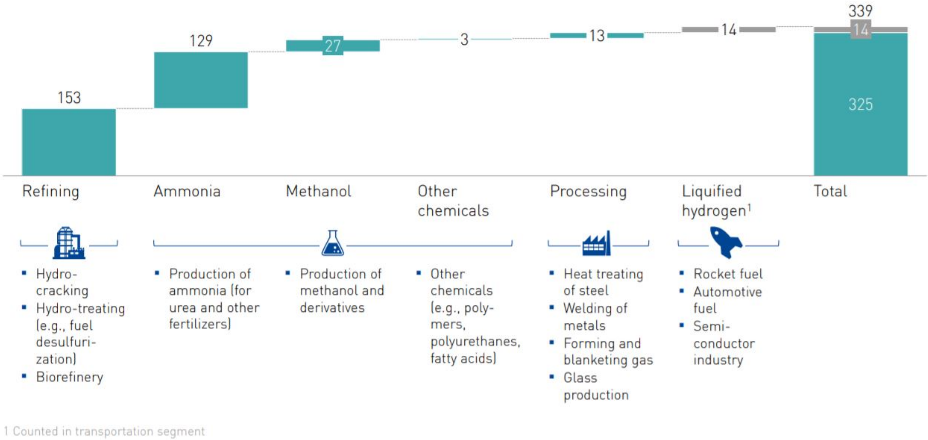

Figure 1.9. Image illustrating the EU's current total H_2 use in Terawatt-hour (TWh) [FCH, 2019].

A study by the IEA [2019] argues that while H_2 is commonly found in the molecular structure of nearly all industrial chemicals, it is ammonia and methanol, as shown in Figure 1.10, that is primarily responsible for the large amounts of dedicated H_2 production in Europe. To that end, FCH [2019] maintains that some 95% of the H_2 used in the making of these chemicals and the broader industry comes from natural gas via SMR without carbon capture storage (CCS). To put this into perspective, Figure 1.10 reveals Europe's extensive use of natural gas for the production of ammonia and methanol.

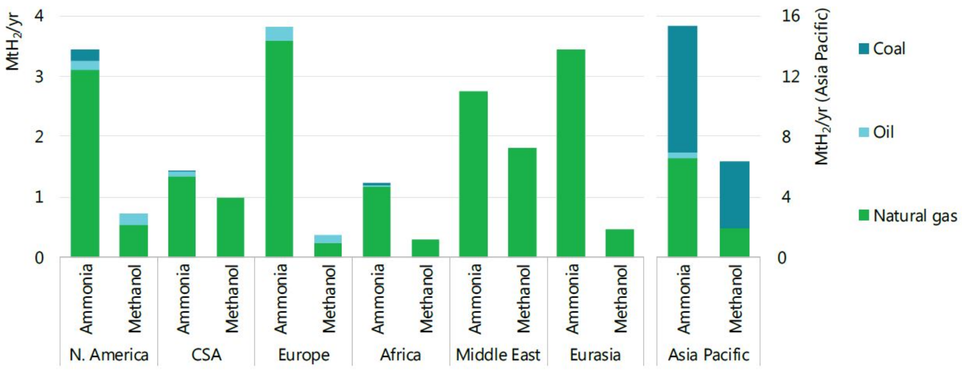

Figure 1.10. Image illustrating the large quantities of hydrogen demand in the production of ammonia and methanol [IEA, 2019].

1.8.2 Projected future demand

In terms of projected future growth for H_2 demand, the report by IEA [2019] states that driven by demand for ammonia and methanol, global demand for H_2 is expected to grow from today's 44 million tonnes per year (Mt/yr) to 57 Mt/yr by 2030. More specifically for Europe, FCH [2019] contends demand for H_2 as a feedstock in the industrial sector is anticipated to continue increasing by between 1% to 3% annually. IEA [2019] also notes that demand for ammonia and methanol is likely to further increase as the value in utilising these chemicals as carriers for the transmission, distribution and storage of H_2 ramps up.

1.8.3 Hydrogen in the oil refinery sector today

Referencing back to Figure 1.9, it can be seen that H_2 plays a prominent role in the oil refining sector. By numbers, approximately 47% of the total H_2 usage in the EU is consumed in oil refining. It is used for essential processes such as hydrotreating and hydrocracking to mention a few [FCH, 2019]. Both these processes are necessary for removing impurities such as sulphur in refined products and upgrading residual oils into higher-value products [IEA, 2019].

Figure 1.11. Image illustrating the different sources of meeting hydrogen demand for refineries [IEA, 2019].

In Figure 1.11, Europe is identified as one of the major consumers of H_2 in the sector, with a substantial amount of that H_2 supplied through dedicated on-site production using SMR [IEA, 2019].

1.8.4 Projected future demand

Current use for H_2 in the sector aside, IEA [2019] contends refinery H_2 demand is likely to grow due to the rising need for hydrocracking and hydrotreating. To this, Catalá et al. [2013] argues additional H_2 supply will be necessary to satisfy the increasing demand for sulphur removal. Catalá et al. [2013] further argues that the EU's ability to reduce sulphur content in refined products will be severely hampered without additional H_2 production capacity. By numbers, a 7% growth in overall refinery H_2 demand is expected, bringing the number to 41 MtH_2/yr in 2030 [IEA, 2019]. Beyond 2030, the rate for refinery H_2 demand is anticipated to gradually decline. The decline is said to be driven by reduced oil demand in the transport sector due to electrification and energy efficiency improvements, among other things [IEA, 2019].

1.9 Problem formulation

In the problem analysis, section 1.1 revealed that SA is one of the many countries that signed the Paris Agreement and therefore has to make efforts to transition from its emission-intensive economy. Additionally, as a prominent coal exporter, SA finds itself in a predicament as demand for coal dwindles driven by global energy transitions. Section 1.2 highlights the country's competitive advantages. Namely a strong RE offering, the FT advantage, unmatched platinum reserves and government buy-in. The section ends with a recognition that given the aforementioned advantages, SA is well-positioned to unlock export opportunities for a green H_2 market. The economics of producing green H_2 are briefly touched on in section 1.4. From this section, it becomes evident that renewable electricity costs, electrolyser costs and water supply costs are key economic factors that have an impact on the cost per kg of H_2.

Storage and transport are necessary elements to consider in energy trade discussions. As such, section 1.5 segues into an assessment of various energy storage and transmission options. The section concludes on chemical storage as better suited for exporting clean energy cost-effectively. At this point, green H_2 has been identified as a new potentially tradable commodity for the country. Section 1.6 describes the criteria followed for identifying the EU as a potential importer of H_2 from SA. While section 1.7 speaks to the EU's preference for green H_2.

The problem analysis draws to a close in section 1.8, where it becomes evident that H_2 plays an extensive role in the EU's industry sector, particularly in the chemicals and oil refinery sector. The H_2 is used as a feedstock, it is largely produced from natural gas via SMR and demand is expected to increase in the future. To that end, the need for cleaner hydrogen production pathways is also then realised.

Consider all of the aforementioned, green H_2 in the context of climate change and trade is the focus of this research. Against this backdrop, the project sets out the following research problem:

"Using green H_2 as an enabler for decarbonisation between 2030 and 2050 in the industrial sector, how will the projected increase in the EU's H_2 demand influence SA's ability to export carbon-free energy?"

The research problem is underpinned by the following research questions:

- What is the long-term cost of producing hydrogen-based energy in SA?
- What type of storage and transport is necessary to facilitate the trading of hydrogen-based energy to the EU in a cost-effective manner?
- What type of policy and regulatory regime is needed to encourage the development of SA's green H_2 market at scale?

1.9.1 Delimitation

The subsection outlines aspects of the research that are considered out of scope.

1. The project does not concern itself with other H_2 producing countries and regions that could potentially supply H_2 to the EU.
2. SA's domestic use of hydrogen for energy purposes is not considered in the scope of this project. Put in another way, the H_2 production is designated to supply an international market without the obligation to meet internal demand first.

Research Design 2

The chapter details the choice behind the research framework of the project. It reflects the priority given to the research process to ensure the findings are valid, reliable and replicable.

2.1 Case study design

In the words of Bryman [2012], a case study approach is about "the detailed and intensive analysis of a single case." Bryman [2012] goes on to state that a case study is often associated with a particular location. This could be an organisation or a community, where the focus is on the nature and the complexities of the case in question [Bryman, 2012].

Yin [2009] is well known for his publication on case studies. In his 2009 publication, Yin [2009] writes about the five types of case studies and the differences between them. These include:

- The **critical case**: in this case, the researcher begins with a theory and sets out to prove or dispel it.
- The **extreme or unique case**: popular in clinical studies, this case is used for investigating instances where outliers exist.
- The **representative or typical case**: this type of case study is said to be used in instances where the case is representative of a broader group or category of which it is a member.
- The **revelatory case**: this case is useful when investigating phenomenons that were previously out of reach in scientific research.
- The **longitudinal case**: this final case is said to be useful for research that can be studied over a long period.

Given the nature of the project's research problem, the representative case was considered an easy pairing and thus the adopted case study approach. The representative case was chosen for two reasons:

1. it provides an appropriate context for the research questions to be answered.
2. the case is a representation of many other similar cases.

The selection of SA and the EU as a representative case for the project's research design was made using the criteria outlined in section 1.6.

2.1.1 Limitations of case study in research

Yin [2009] openly acknowledges that there are advantages and limitations to using case studies in one's research. Similarly, Flyvbjerg [2006] published a paper on the "*Five Misunderstandings About Case-Study Research*". In essence, the paper is a discussion of the five commonly mentioned disadvantages of case study research. In the words of

Flyvbjerg [2006], the limitations of case studies in research can be summed up to the following:

1. One cannot generalize on the basis of an individual case.
2. The case study contains a bias toward verification.
3. The case study is most useful for generating hypotheses; that is, in the first stage of a total research process, whereas other methods are more suitable for hypotheses testing and theory building.
4. It is often difficult to summarize and develop general propositions and theories on the basis of specific case studies.
5. General, theoretical (context-independent) knowledge is more valuable than concrete, practical (context-dependent) knowledge

Despite the above limitations, case studies have been and continue to be used by researchers with success [Krusenvik, 2016]. In a very short essay, Siggelkow [2007] provides thought-provoking viewpoints on the justification of case studies and what makes them persuasive. To the first point, Siggelkow [2007] argues that a single case or a small sample need not be seen as a disadvantage. According to Siggelkow [2007], a single case can be a powerful example. On the matter of bias towards verification, Siggelkow [2007] argues representative case studies are not chosen randomly for good reason. This implies that the case study is often known ahead of time and chosen on the basis that it allows the researcher to gain insight that other cases may not provide. In line with Siggelkow [2007], Flyvbjerg [2006] states that "the case study contains no greater bias toward verification of the researcher's preconceived notions than other methods of inquiry." Flyvbjerg [2006] defends the third point by stating "The case study is useful for both generating and testing of hypotheses but is not limited to these research activities alone." In addressing the final two points, Flyvbjerg [2006] draws the conclusion that training researchers on context-independent knowledge alone limits one to the beginner stage of the learning process. Siggelkow [2007] echoes this view. In his own words, Siggelkow [2007] writes that "it is much harder to make a paper interesting whose findings or conclusions only address theory. A paper should allow a reader to see the world, and not just the literature, in a new way."

It is evident that the use of case studies in research, much like other research methods, has its advantages and limitations. The key point of departure from this evaluation is that case studies should be used by the researcher if he/she determines the approach to be appropriate for addressing the research problem [Krusenvik, 2016].

In conclusion, and considering all the above factors, this project recognises that there are energy trade regions that exemplify the conditions in SA and the EU where green H_2 is concerned. Nevertheless, it is not the aim of this project to generalise the results of this case study beyond the EU-SA context.

An illustrative representation of how the research design ties into the rest of the project is shown in Figure 2.1.

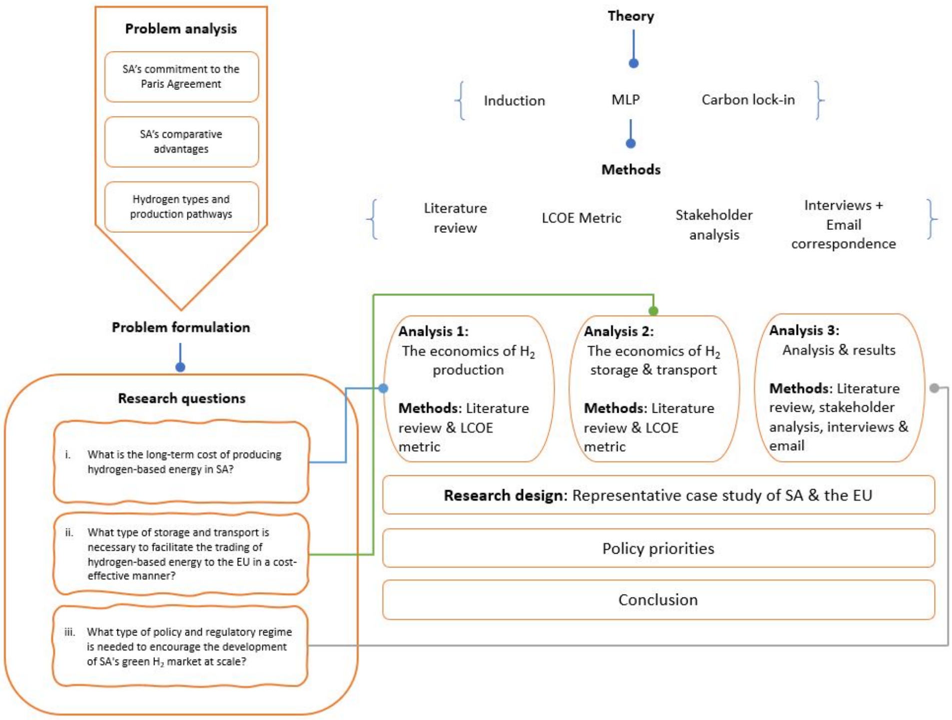

Figure 2.1. The research design of the project. Own image.

Theory 3

Chapter 3 addresses the theoretical framework adopted in this project. It assesses three main theories, namely the induction theory, the multilevel perspective theory, and the carbon lock-in theory in relation to how they contribute to addressing the research problem.

3.1 Induction theory

According to Bryman [2012], an inductive research approach is one that draws generalised inferences based on observations. Unlike the deductive approach that begins with a theory and a hypothesis, and then uses that to drive the research process, an inductive approach takes the opposite perspective [Bryman, 2012]. To this point, Burney og Saleem [2008] states that the induction theory is sometimes referred to as the "bottom-up" approach. Put differently, the theory works by noting specific observations to broad observations and theories [Burney og Saleem, 2008].

According to Bryman [2012], inductive research is exploratory in nature and the theory is the outcome of the research. Figure 3.1 is a depiction of the bottom-up approach of inductive research.

Figure 3.1. Image illustrating the inductive research approach. Own image. Adapted from [Burney og Saleem, 2008].

The exploratory nature of the induction theory is what made it an easy pairing and fitting theoretical approach for this research project. The project is characterised by a research problem that is underpinned by open research questions. Following an inductive stance, the project seeks to find possible explanations that address the research problem. To that effect, it is important to reiterate that this project will not generalise its conclusions beyond the scope of this research.

3.1.1 Limitations of the induction theory

According to Raths [1967], the most obvious limitation of an inductive research approach is that it cannot be used to prove anything. Instead, the generated data may only be used to support, fail to support, and in certain instances, discredit a certain generalisation [Raths, 1967]. In a more recent study, Streefkerk [2019] shares a similar view.

Consider an example where an individual observes that a low-cost bus is delayed. The individual notices that another five low-cost buses are also delayed. Naturally, the individual concludes that low-cost buses are always delayed. In line with [Raths, 1967], Streefkerk [2019] states that decisions drawn based on an inductive approach can never be proven. Instead, they can be invalidated.

3.2 Multilevel Perspective

In the words of Aslam [2016], the multilevel perspective (MLP) as a theoretical framework is "a tool for analysing and understanding transitions, not just from a technical, but a socio-technical perspective." Aslam [2016] further reveals that Frank Geels is the individual behind the development of the MLP as a transition framework.

The MLP is essentially a theory about the dynamics of societal changes and developments. Geels [2006] maintains that when system innovations come about, they do not simply affect technical products, instead, they also have an impact on policy, infrastructure, end-users, industry structures etc. The MLP theory by Geels [2006] considers the following traits to be characteristic of system innovations:

- involves the co-evolution of several elements
- involves changes on both the supply (e.g. knowledge and technology) and demand-side (e.g. infrastructure and user preferences)
- a wide range of actors is involved
- the process evolves over decades, making it a long-term transition process. This in turn may pose challenges for effective policy interventions.

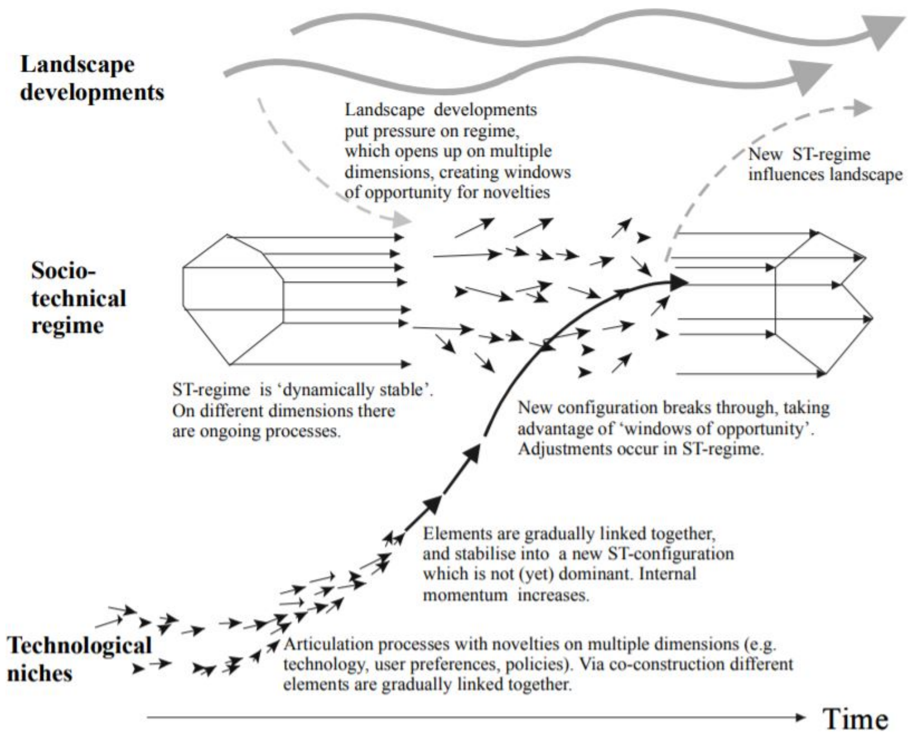

Figure 3.2. Image illustrating the MLP on system innovations [Geels, 2006].

On the basis of Figure 3.2, the MLP theory makes a distinction between three transition dynamics:

1. The **landscape**: changes and trends in society locally or globally.
2. The **regime**: social norms and technical structures that influence peoples behaviour in society.
3. The **niche**: novel products, ideas and processes that sit outside the mainstream activities.

The MLP is therefore a useful theory for understanding how transitions to novel systems and process happen [Geels, 2006].

3.2.1 MLP in relation to the project

The MLP has been applied to the project as a theoretical framework and approach that speaks to how gradual shifts to new socio-technical systems come about. In the context of this project, SA has the opportunity to explore the long-term possibility of transitioning from a prominent fossil fuel exporter to a clean energy trader by investing in the production of green H_2.

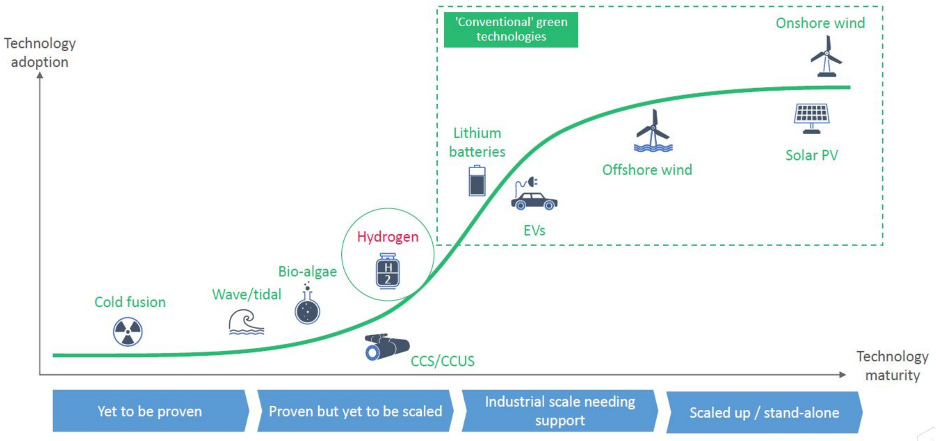

Figure 3.3. Image illustrating the technological maturity and adoption level of H_2 in relation to other technologies [Hydrogen Council, 2020].

According to Figure 3.3, it is apparent that H_2 despite being proven but not yet scaled commercially like technologies such as wind and solar, is on the verge of a breakthrough. Using the H_2 economy as a case in point, the MLP approach will be used to illustrate how transitions happen. But before that, it is interesting to point out that the transition to H_2 in Figure 3.3 follows an s-curve pattern similar to the one observed in Figure 3.2.

In this project, the change in **landscape** (i.e. the growing interest in green H_2) is influenced by a number of reinforcing factors. These include stringent climate change targets, the falling costs of RE technologies and a rapid need to decarbonise hard-to-abate sectors. These factors apply pressure on the regime, while also creating opportunities for the development of new interventions. In response to the change in the landscape, the **regime** can either adapt or be taken over by new interventions. In this case, the use of fossil fuels with CCUS (i.e. blue H_2) for H_2 production can be viewed as the regime's way of adapting. At this point, green H_2 at a global scale is still a niche opportunity. Over time, however, the **niche** develops and evolves into a new regime. In some instances, the niche is assimilated by the existing regime. In this context, cheaper RE prices plus increasing capacity factors, economies of scale and increasing electrolyser capacities are some of the elements that result in green H_2 evolving into a new regime.

3.2.2 Limitations of the MLP theory

Overall, the MLP is an interesting theory for making sense of system innovations. However, it too has drawbacks associated with it. For one, the MLP has been criticised for being imprecise and using metaphors [Geels, 2006]. Other scholars argue that the MLP is not straightforward, thus requiring attention to the changing dynamics at many levels. Finally, Geels [2006] mentions that currently, the MLP gives the impression that system innovation is about the success of a single niche. However, in reality, system innovation can be about the breakthrough of multiple niches that compete and/or reinforce each other [Geels, 2006].

3.3 Carbon lock-in theory

Unruh [2000] published a paper that describes that habitude of carbon-intensive technological systems to carry on longer than they should due to a combination of technological, institutional and social forces. Unruh [2000] refers to this condition as "*carbon lock-in*". Unruh [2000] goes on to state that this tendency comes about "through a combination of systematic forces that perpetuate fossil fuel-based infrastructures in spite of their known environmental externalities and the apparent existence of cost-neutral, or even cost-effective, remedies."

Similar to the MLP theory in section 3.2, the carbon lock-in narrative recognises that large technological systems like electricity generation do not exist in isolation. Instead, they are immersed in a social context of powerful and longstanding private and public institutions [Unruh, 2000]. According to Seto et al. [2016], there are three types of carbon lock-in:

1. **Infrastructural and technological lock-in**: this refers to lock-in associates with the long lifespan of the physical infrastructure and technologies that not only shape the energy system, but also directly and indirectly contribute to the emission of CO_2.
2. **Institutional lock-in**: this refers to lock-in associated with decision-making by government, private sector and other relevant institutions that shape the demand and supply patterns of the energy system.
3. **Behavioral lock-in**: this refers to lock-in associated with the norms, activities, habits linked to the demand of energy-related services and goods.

The concept behind the carbon lock-in theory suggests that the above-mentioned carbon lock-in types are mutually reinforcing and they create collective resistance and inertia [Seto et al., 2016].

Figure 3.4 is a visual representation of the supposed value of an energy asset over its lifetime. Energy assets are typically characterised by long lifespans and long lead times. This means that the costs of investment are incurred in the present while the returns are in the future [Seto et al., 2016]. It is this very nature that makes carbon lock-in a difficult and costly change. This rational is captured in Figure 3.4, where the solid black line represents the net present value (NPV) of an energy asset. Initially, the investment costs outweigh the returns of operating the asset resulting in a negative NPV. Over time, the returns from running the asset start paying the investment costs, resulting in a increasing NPV.

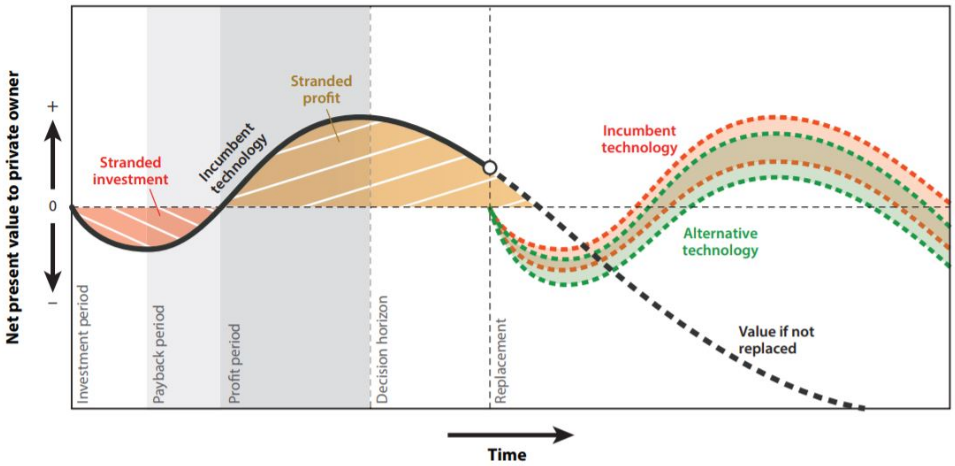

Figure 3.4. Image illustrating the theoretical value of an energy asset over its lifespan [Seto et al., 2016].

After a long while and due to the aging of the infrastructure among other things, the cost of operating and maintaining the asset start to chip away at the returns. According to Seto et al. [2016], in preparation for costs, risks and policy changes in the future, it is at this point that a decision must be made on whether to replace or retrofit the energy asset. If the asset is replaced sooner than originally anticipated, value is lost resulting in "stranded investments" and "stranded profit". Finally, the dotted black line represents the NPV trajectory should the asset owner decide against replacing the asset.

3.3.1 Carbon lock-in in relation to the project

With regard to this project, the risk of carbon lock-in refers to the inertia created by SA's longstanding use and reliance on fossil fuels such as coal, natural gas and oil. This reliance is foreseen to inhibit public and private efforts to introduce low-carbon alternatives such as the investment in the production of green H_2. The application and understanding of the carbon lock-in theory is exercised during stakeholder interviews, where interviewees are questioned on SA's predisposition to carbon-intensive pathways. More details on the discourse regarding the extent to which SA is predisposed to carbon lock-in is unpacked in Chapter 7, section 7.2.

The project recognises that there are additional factors at play that also enable carbon lock-in. These are fossil fuel-supporting infrastructures such as gasoline stations and refineries whose value is dependent on the continued extraction and use of coal, natural gas and oil in SA. The project foresees the risk of such fossil fuel-supporting infrastructures being stranded assets. In turn, this will likely create self-reinforcing motives to resist technological change despite known environmental implications.

This chapter gave a detailed explanation of the theories adopted in this project. The following chapter segues into the applied methods as well as the justification and noted limitations, where relevant.

Methodology 4

The different methods that were used to evaluate the project will be explained in this chapter. These include an extensive literature review that covered hydrogen demand, cost and price projections, stakeholder analysis, interviews and lastly, email correspondence.

4.1 Literature review

There are many reasons the review of existing literature continues to be an essential part of the research process for many scholars. In the words of Bryman [2012], the most evident use for the prominent use of literature reviews is to help the researcher know what is known about his/her area of investigation.

Specific to this project, the process of reviewing existing literature was particularly helpful in identifying and understanding key aspects of the research problem. These include:

1. having a grasp of theories and research design concepts that have been used in the past.
2. having an overview of methodological approaches that other researchers have used.
3. identifying thought leaders and organisations who have contributed to the knowledge base of the hydrogen landscape.
4. identifying knowledge gaps and validate the importance of the research topic.
5. framing the research such that it does not reinvent the wheel, but instead contributes additional information to the growing knowledge base of the hydrogen economy.

It is important to recognise that there are different types of literature. As such, this project made use of an extensive range that included government publications, peer-reviewed journals and articles, published presentations, and related scholarly books. Online newspaper articles from reputable journalists in the RE and hydrogen landscape were also periodically used. However, these were used as secondary information to supplement findings in published sources such as books and journals. Figure 4.1 is a representation of the literature review search process that was employed for the project.

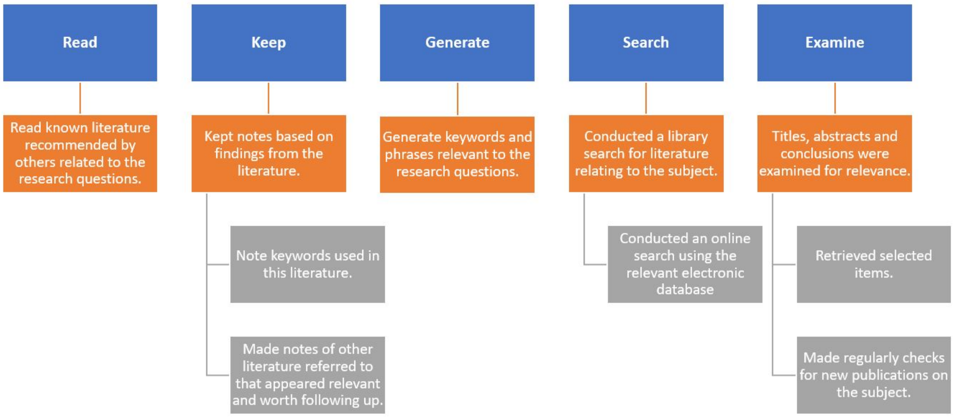

Figure 4.1. Image illustrating the literature review process followed for the project. Own image adapted from [Bryman, 2012].

Bryman [2012] states that while the internet is a convenient platform for finding useful material for one's research, it does not evaluate the information people post. The onus then falls on the researcher to have checks and balances in place to critically evaluate the usefulness and validity of the information one finds. While an effort was made to limit the research to reputable sources and websites, there were a few checks and balances that were employed to ensure rigour.

- The literature process paid attention to when sites were last updated as this indicates how up to date the information is.
- Special attention was also given to where the website is located. According to Bryman [2012], the Uniform Resource Locator (URL) points to a unique source on the web. Paying attention to the URL made it possible to determine whether the website was an academic site, governmental etc.
- In some instances, looking at the journalist or author of the website, as well as his/her intention for making the publication, was also helpful.

4.2 Levelised cost of energy as a metric

The Levelised cost of energy (LCOE) is an economic assessment that is used to determine the required price per unit of energy for an energy project to be considered profitable [CFI, 2021]. This assessment is typically used to compare and contrast different energy production technologies such as wind, solar, geothermal etc [CFI, 2021].

U.S. DOE [2015] argues that the upfront costs of RE technologies do not reflect the complete picture. As such, the LCOE is important because [U.S. DOE, 2015]:

- it allows for a comparison of different technologies that have different lifespans, different operation scales, varying costs of capital, risk and returns. Consider an example where the cost of generated energy from a fossil fuel plant is compared to that of a RE technology.
- it measures value over the lifetime of the energy project, thereby showing expected lifetime costs.

- it provides an economic basis that project developers can use to make informed decisions on whether to proceed with a commercial project.

In the context of theories used in the project, the LCOE as a method of economic assessment pairs well with the carbon lock-in and MLP theories described in section 3.3 and 3.2 respectively. Both these theories speak to the evolutionary nature of energy transitions, where the costs of low-carbon alternatives are a key driver. Similarly, the LCOE as a metric evaluates energy generation technologies to determine financial viability.

4.2.1 Calculating the LCOE

In theoretical terms, the LCOE can be calculated by taking the present value of the total cost of building and operating an energy generating asset over its assumed lifetime. This number is then divided by the total energy generation over the lifespan of the technology [CFI, 2021]. A representation of this formula can be seen in equation 4.1.

The formula is expressed as:

$$LCOE = \frac{Total\,cost\,over\,lifetime}{Energy\,produced\,over\,lifetime} \tag{4.1}$$

Where total costs over lifetime include: Capital investment, operation and maintenance (O&M) costs, fuel costs (if applicable) and financing costs. While the total output of the generation technology will include the sum of all generated energy [CFI, 2021]. The discount rate and the lifespan of the generation asset are also important elements of the equation [U.S. DOE, 2015] and [CFI, 2021].

4.2.2 The LCOE in relation to the project

The levelised cost is used as an evaluation metric throughout the report. Put differently, it is used to assess the cost of energy production, storage and transport. It makes its first appearance in Chapter 5, where the economics of H_2 production are discussed. In addition to the LCOE, Chapter 5 also write about the levelised cost of H_2 (LCOH). Here, the LCOH represents the lowest price H_2 must be produced for it to be cost-competitive. The LCOH is expressed in units of currency per kilogram of H_2 (i.e. USD/kgH_2).

In Chapter 6, the economics of H_2 storage and transport are discussed. It is in this chapter that the levelised cost of storage (LCOS) is introduced as a metric for the first time. Similar to the LCOH, the LCOS is a comparison of different storage options to identify the cheapest price and state H_2 can be stored. It too is expressed in USD/kgH_2.

In this same chapter, the reader is introduced to the levelised cost of transport (LCOT) as a metric of assessment. As with the previous levelised assessment, the LCOT is expressed in USD/kgH_2 and it compares various H_2 modes to arrive at the cheapest cost of transport. There are also instances where it is expressed as USD/GJ and USD/kg.

In drawing this section to a close, it is important to note that the LCOE results used in the report are taken from recently published literature from reputable sources. To ensure comparability, and to the extent that was possible, the assumptions assumed by the authors in the calculations have been shared in the relevant sections. In instances where authors used different assumptions in the calculations, thus making comparability difficult, a second source was used that could corroborate the results.

4.3 Stakeholder analysis

Coghlan og Brydon-Miller [2014] define stakeholder analysis as a research methodological approach that is used to explore the various opinions that interested and affected groups or individuals may have on potential outcomes and their relative influence. According to NREL [1994], stakeholder analysis processes are necessary for many instances. Broadly speaking, the objective of stakeholder analysis is:

- to identify positive and negative impacts of a proposed action
- to identify those groups and individuals who are or may be affected
- to determine the extent to which they could be affected
- to help identify possible solutions and adjustments that could be made to mitigate or reduce negative impacts.

In this project, stakeholder analysis was primarily used as an approach that would feed into answering the third research question. That said, the analysis aimed to (i) identify which stakeholders were relevant to interview, (ii) to determine how much power and influence they have in the context, and (iii) to determine where else in the project their knowledge and input could be useful.

Identifying relevant stakeholders was achieved through a combination of literature review and brainstorming. The literature review process helped identify authors, groups and individuals that were active in the H_2 landscape, while the brainstorming exercise encouraged more out-of-the-box thinking on who might be relevant to the matter at hand. In addition, interviews, which are discussed in section 4.4, also contributed to the stakeholder analysis process. This approach was helpful as it reduced likelihood of overlooking certain entities or individuals. An overview of all the engaged stakeholders is shown in Appendix 1.

About the research design and applied theories, the stakeholder analysis is seen playing a complementary role with the representative case study design and the induction theory. Concerning the case study, the stakeholder analysis method facilities the process of identifying interested and affected parties within the context of the case study. This information then feeds into the exploratory nature of the inductive theoretical approach, where stakeholders, as part of the data collection process, will be interviewed, their inputs will then be analysed and ultimately used to address the research problem.

4.4 Interviews

Where interviews are concerned, Mathers et al. [2002] writes that an interview is a method used for collecting data that involves verbal communication between the researcher and the subject. Mathers et al. [2002] writes it is useful to think of three main types of interviews. These are structured, unstructured and semi-structured interviews.

In structured interviews, interviewees are asked the same question in the same way. They are similar to questionnaires and the questions are framed in a manner that elicits specific and short responses [Mathers et al., 2002]. On the other hand, unstructured interviews are exactly as the name suggests. Typically, according to Mathers et al. [2002], the interviewer has no set plan on how the interview will unfold and the interview questions tend to be framed based on the interviewees' response to the previous question. Finally, semi-structured interviews, unlike unstructured interviews required careful planning and consideration ahead of time. The questions in semi-structured interviews are open-ended in nature, giving the interviewer the flexibility to probe beyond what was asked and to discuss certain points in more detail than others [Mathers et al., 2002].

For this research project, semi-structured interviews were used. This interview style was chosen for the following reasons:

1. The questions could be prepared and sent to interviewees ahead of time, making the interviewer appear competent and prepared. It also made it easier for interviewees to commit their time.
2. The flexibility to not adhere to a script and change questions depending on the direction of the interview [Kajornboon, 2005].
3. Because the questions were open-ended in nature, there was room to gain knowledge and insight on more than just what was asked.
4. To encourage a two-way communication engagement process and to establish rapport.

A total of 4 interviews were conducted with stakeholders in SA and Europe using virtual platforms. With the help of the stakeholder analysis process, the range of stakeholders included representatives from The International Renewable Energy Agency (IRENA), the Department of Environmental Affairs (DEA), DNV, and the Department of Science & Technology (DST). Annexure 1 provides an overview of the interviewed stakeholders. It is important to mention that the views of the interviewees are treated as their personal views and not the views of the organisation they represent. Lastly, the knowledge and insight gathered from the interviews is used in Chapter 7 and 8 of the report.

4.4.1 Limitations

While the use of semi-structured interviews made sense for the project, the project also recognises that there are limitations associated with this approach. One of the main limitations of semi-structured interviews is that the interview is directed by the questions that the interviewer asks. This implies that the quality and the depth of the information collected during the interview is dependant on the skills of the interviewer and the quality of the questions put forward [Kajornboon, 2005]. The second limitation is the issue of comparability. Because questions sometimes vary in each interview, this makes the process of analysing and comparing results difficult [Byrne, 2016].

4.5 Data collection by correspondence

According to Parris [2008], generating data by correspondence is a method in which communication between respondents is enabled by the use of written letters or emails. More specifically, email correspondence is "written communication between the researcher and each respondent" [Parris, 2008]. Parris [2008] further writes that the use of emails as a research method has typically been limited to electronic surveys. However, this has since changed.

4.5.1 Email correspondence in relation to the project

In this project, email correspondence was adopted as a method for soliciting expert opinions and knowledge from key stakeholders within the H_2 landscape. This approach was chosen because:

- Not all stakeholders could commit to a verbal interview due to time limitations. As such, emails were considered to be more convenient for busy people.
- One interviewee sent an email at 21:30. This implies that emails gave interviewees the flexibility to decide when they would engage with the questions.
- Other stakeholders felt more confident in their ability to convey written responses.
- It gave interviewees time to think and reflect on the response they give.

The process began with an introductory email to each of the potential interviewees. The email outlined who the researcher is, the purpose of the email, and how the correspondence would be conducted. To help manage respondents expectations and build good rapport, the email included information on the researcher's frequency of response, particularly in instances where a lengthy response was received.

On average, 5-6 questions related to the research topic were included in each email. Depending on the quality of the responses, follow up questions were sent in subsequent emails. Evidence of the email correspondence is shown in Appendix 2.

4.5.2 Limitations

As with other research methods popular among researchers, this approach had its drawbacks that the project needed to be mindful of. For starters, it is difficult to build rapport over email. This is because one cannot "put a face to the name" which tends to be helpful [Parris, 2008]. This drawback was however managed by outlining the researcher's response frequency and sticking to it.

Another limitation of email correspondence is with follow-up questions. In comparison to verbal interviews, follow up questions take longer, and in some instances, they are not easily done or even possible due to the busy nature of the respondents. This limitation was managed by paying attention to the quality of the questions. This was done so that interviewees were forced to providing answers that had depth, thus reducing the need for follow-ups. In addition, the questions were also ranked in order of importance.

Finally, concerning the project's theoretical framework, both the interview method described in section 4.4 and the email correspondence approach outline in this section complement the induction theory adopted in Chapter 3, section 3.1 of the report. The second step of the induction theory is "data generation", where the combined use of interviews and email correspondence was particularly effective in aiding that process.

The MLP and carbon lock-in theory are also supplemented by the interview and email correspondence. This was done through the insight that was gained from questions about

SA's predisposition to carbon lock-in and the development trajectory of H_2 production technologies.

4.6 Sub-Conclusion

In summation, this chapter outlined the five methods that were applied to ensure the research in this project was rigorous and reliable. The chapter also discussed limitations to the methods and how they were managed. Finally, the chapter spoke to the relevance of the applied research methods in relation to the theoretical framework adopted in Chapter 3.

The subsequent chapters will be a deep dive into the economics of H_2 production, storage and transport.

The economics of hydrogen production 5

Various sources suggest that the key determining factor behind SA's ability to control a sizeable portion of the global market for H_2 exports will be the price at which it can provide the H_2 to potential importers such as the EU. Consequently, this chapter provides an overview of the economic and technical factors that have an impact on the H_2 price.

5.1 Renewable electricity and capacity factor

This section builds on the H_2 production cost drivers described in section 1.4. According to research by PwC [2020], the cost of electricity is roughly calculated to account for about 50% - 70% of the LCOH. If green H_2 is to achieve cost parity with grey and blue H_2, low-cost renewable electricity will be an essential prerequisite. This line of thinking is corroborated by ACIL Allen [2018] where the author contends there is a linear relationship between renewable electricity prices and H_2 production costs.

Capacity factor is a key component of renewable electricity prices [ACIL Allen, 2018]. By definition, capacity factor is the ratio between the maximum output a generation unit is capable of against its average generation output over a certain period of time [NMPP Energy, 2017]. Due to the intermittent nature of energy sources such as wind and solar, ACIL Allen [2018] maintains they tend to have a relatively low capacity factor.

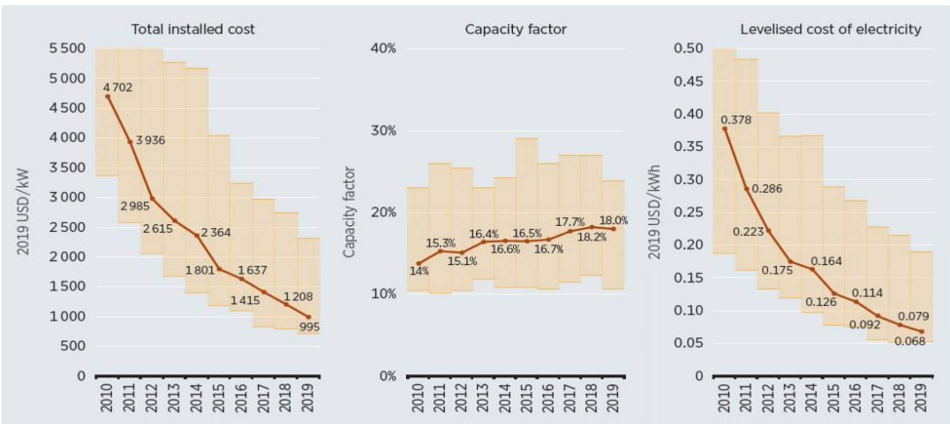

Figure 5.1. Image illustrating global weighted average total installed costs, capacity factors and LCOE for solar, 2010 - 2019 [IRENA, 2020a].

Nevertheless, a recent publication by IRENA [2020a] revealed how on average, global wind and solar have seen noticeable capacity factor improvements between 2010 and 2019. The global capacity factor and LCOE for both these resources can be seen in Figure 5.1 and Figure 5.2.

In Figure 5.1, one can see utility-scale solar PV capacity factor rose from 13.8% in 2010 to 18% in 2019, while the LCOE saw a decline over the same period. Similarly, the onshore wind capacity factor and LCOE recorded a similar trend as shown in Figure 5.2. By numbers, the capacity factor climbed from 27.1% in 2010 to 35.6% in 2019. In tandem, the LCOE observed a downward trend in the same period. With respect to drivers for improvements in capacity factor, IRENA [2020b] states technological improvements resulting in more efficient and higher turbines, the increased use of tracking devices in solar projects, and an increasing shift in deploying projects in regions with higher irradiation and high-quality wind resource are among the contributing factors.

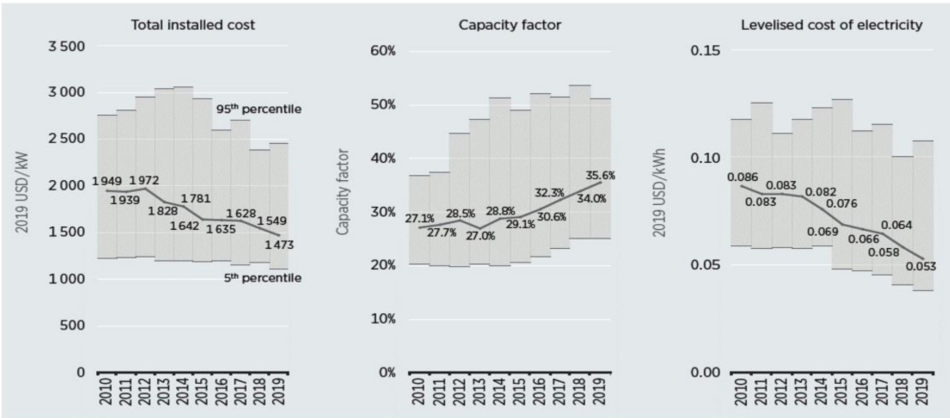

Figure 5.2. Image illustrating global weighted average total installed costs, capacity factors and LCOE for onshore wind, 2010 - 2019 [IRENA, 2020a].

Comparatively speaking, research has revealed that SA's renewable energy capacity factor is higher than that of the EU. In 2017, the average capacity factor for solar PV and wind was 25% and 36% respectively [Bischof-Niemz, 2018]. In comparison to the EU over the same period, the capacity factor for onshore wind was an average of 21.7% [IEA, 2017], while the PV capacity factor was undiscovered for that period.

With average annual sunshine of more than 2500 hours for most regions in the country, an average yearly 24-hour global solar irradiation at about 220 watts per square metre (W/m2) and plentiful land [DMRE, n.d], there is considerable potential for large-scale renewable projects in SA. Comparatively, Europe's annual 24-hour global solar irradiation average is a modest 100 W/m2 [DMRE, n.d].

Delimitation

According to Wind Europe [2020], Europe is home to one of the world's best offshore wind resources. Be that as it may, the resource has challenges that have derailed its widespread adoption.

1. Most of the sea zones are reserved for environmental protection and other users, thus making it impossible to develop wind farms in at least 60% of the Northern Seas [Wind Europe, 2020].
2. There is a high likelihood large-scale deployment of offshore wind will invoke cross-border implications. This presents a barrier as international coordination on the use

of the seas is not in alignment [Wind Europe, 2020].

The emergence of floating offshore wind is seen as yet another promising opportunity space for the EU. All things considered, the project delimits from both these types of wind because predicting the future outlook of these relatively novel technologies is not only difficult but it cannot be achieved without introducing high levels of uncertainty to the report findings.

5.2 Electrolyser and renewable electricity

Section 1.4 provided an overview of the three types of electrolyser technologies that are currently available. This section builds on that knowledge by highlighting additional, and equally important components that influence electrolyser costs.

In the context of electrolysers, the capital expenditure of electrolysers (capex), efficiency, and annual full load hours (FLH) are considered key cost drivers of the LCOH [Roos og Wright, 2021].

5.2.1 Capital expenditure of electrolysers

Ross [2021] defines capex as a major financial expense that a company takes on with a long-term horizon in mind. In the context of H_2 production, the cost of producing H_2 from water electrolysis is affected by the capex of the electrolyser [IEA, 2019] and [Roos og Wright, 2021]. From Figure 5.3, the different electrolyser technologies can be seen. It is also evident they offer varying economic and technical features. Though the capital cost is relatively high at present, the figure shows that this cost is projected to decline in the long term.

According to IEA [2019] and ACIL Allen [2018], the decline in costs will be driven by technology innovations, project scales increasing, improvements in capacity factor, economies of scale and supply chain improvements.

	Alkaline electrolyser	Proton Exchange Membrane (PEM) electrolyser	Solid oxide electrolysis cells (SOEC) electrolyser
Description	A mature technology with relatively low capital costs	Relatively small size, offering flexible operation but greater reliance on previous electrode materials	Least mature option, expected to have lower materials costs (using ceramics), rely on steam electrolysis requiring higher heat source
Electrical efficiency (% LHV)	Current: 63% Long-term: 80%	Current: 56% Long-term: 74%	Current: 74% Long-term: 90%
Capex (AUD/kW)	Current: 740-2,080 Long-term: 300-1,040	Current: 1,640-2,700 Long-term: 300-1,340	Current: 4,200-8,340 Long-term: 750-1,640

Figure 5.3. Image illustrating the range of CAPEX requirements for AEC, PEM AND SOEC electrolysers currently and in the long-term. LHV = low heating value; long-term = 2030-2050 [PwC, 2020].

Another financial indicator that influences the capex is the weighted average cost of capital (WACC). Ellerman [2019] explains WACC as a general rule used in financial institutions to determine whether the return on investment meets or exceeds the project's cost of invested capital. Concerning the economics of H_2 production, a high WACC is a signal of high risk. Put differently, a high WACC means high annual financial charges, thereby resulting in high H_2 production costs [Roos og Wright, 2021]. Because the WACC of a project is determined by its perceived risk, Roos og Wright [2021] argues this risk factor is minimised by two things: (i) an off-taker agreement with a sovereign entity and (ii) seeking project finance from development institutions instead of commercial banks.

5.2.2 Efficiency

Efficiency losses are inevitably incurred when electricity is used to split H_2 from water. And while the losses will vary depending on the electrolyser technology utilised, it is necessary that they are taken into consideration and accounted for [Verkehrswende og Energiewende, 2018].

From Figure 5.3, one can also see the present and anticipated efficiency of the respective electrolysers. It is also clear to see that electrolyser efficiencies are expected to improve as capital costs come down the cost curve. The point of departure from this image is that the cost of green H_2 production is dependent on the rate of efficiency at which electricity can be transformed to a unit of H_2 [PwC, 2020]. As such, to achieve low-cost H_2, (i) the electrolyser conversion efficiency is essential, and (ii) the number of hours the electrolyser can use the renewable electricity is just as important [PwC, 2020], [IEA, 2019] and [Roos og Wright, 2021]. More details on the latter point can be found in the following subsection.

5.2.3 Annual Full Load Hours

By way of definition, the IEA [2019] describes FLH as the annual utilisation rate of the electrolyser. Put simply, it is an indication of the number of hours in a year the electrolyser would operate at its design capacity to meet a predetermined yearly output. According to Roos og Wright [2021], to produce H_2 cost-effectively, and because electrolyser infrastructure incurs high CAPEX costs, high FLH are a necessity.

To put things into perspective, and to demonstrate the relationship between electricity prices and H_2 production costs in relation to FLH, the project turns to an analysis by IEA [2019].

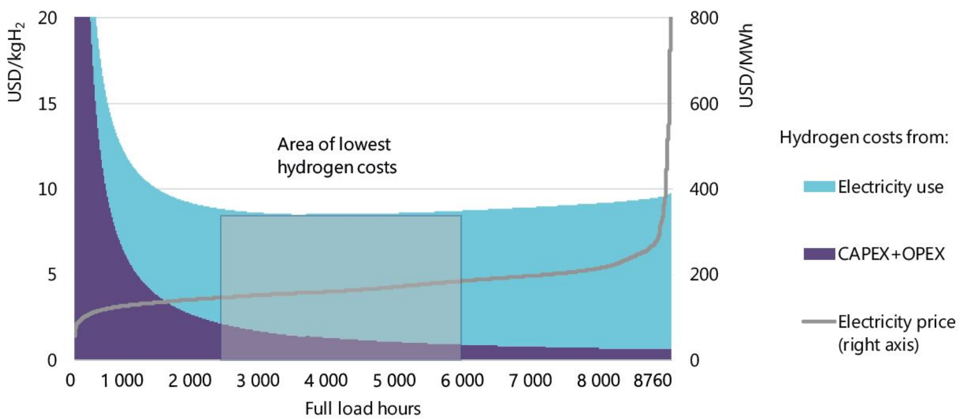

Figure 5.4. Image illustrating the ideal range of FLH required for producing H_2 at a low cost. *Assumptions include: CAPEX = USD800/kWe; efficiency (LHV) = 64%; discount rate = 8%* [IEA, 2019].

Figure 5.4 shows the optimal load where the cost of H_2 production is most favourable. The electricity prices in this figure are based on the Japanese electricity spot market prices observed in 2018. It is also important to mention that the analysis used grid-tied electricity prices to produce the H_2.

From Figure 5.4, it becomes evident that a range of about 3000 to 6000 FLH is ideal for low-cost H_2. Running beyond this range means the electrolyser is working at peak hours, resulting in higher electricity prices. Put in another way, the higher the electricity prices, the higher the H_2 production costs.

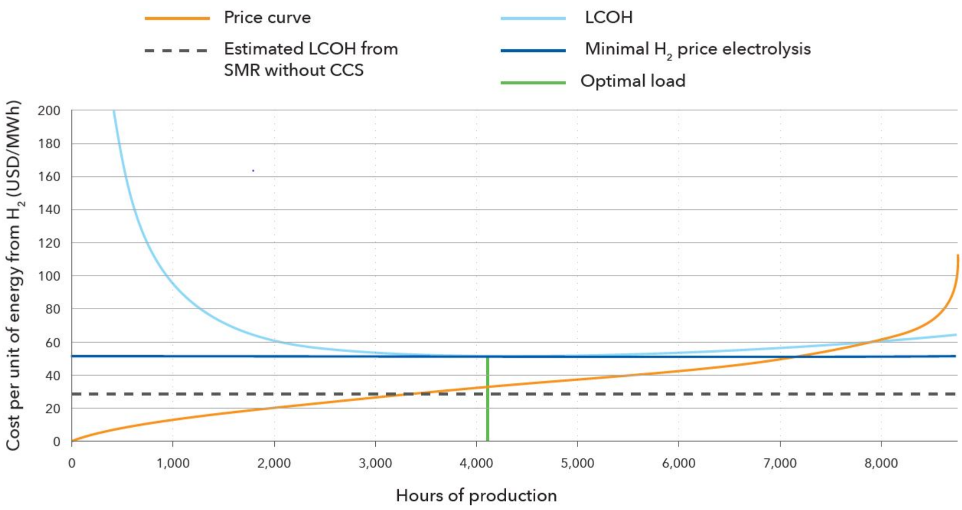

Figure 5.5. Image illustrating a cost analysis of H_2 production by electrolysis in California in 2016 [DNV GL, 2018].

DNV GL [2018] performed a similar analysis based on electricity prices in California in 2016. Unlike the analysis in Figure 5.4 by IEA [2019], this analysis used electricity from wind and PV. The cost analysis in Figure 5.5 assumes that the H_2 is produced only in hours with low electricity prices. Moreover, the analysis assumed zero marginal costs for the electricity generation since PV and wind have no fuel costs associated with them [DNV GL, 2018].

Based on the results shown in Figure 5.5, it becomes apparent that at 2000 hours electricity prices are at about USD20. If one assumes that H_2 is produced during these hours, the LCOH falls to about USD60/MWh. The LCOH continues to drop until just over 4000 hours, which is considered the optimal load. Beyond these hours, electricity prices gradually increase and this effect results in an LCOH that is higher than the minimal H_2 price denoted by the solid blue line.

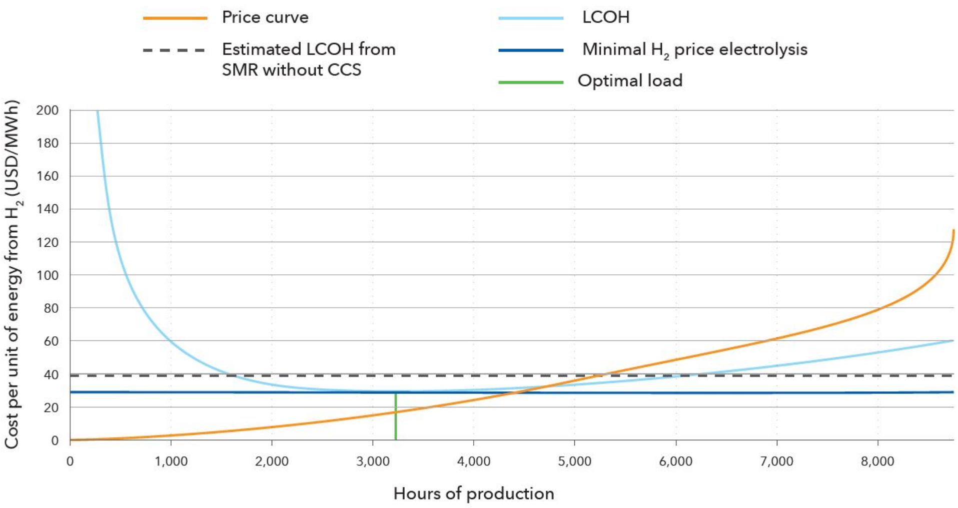

Figure 5.6. Image illustrating a cost analysis of H_2 production by electrolysis in California in 2030 [DNV GL, 2018].

Similar to the cost analysis carried out in Figure 5.5, Figure 5.6 evaluates the cost of H_2 production in California in 2030. According to DNV GL [2018], the LCOH is estimated to drop significantly because

1. In comparison to 2016, electricity prices are noticeably lower.
2. Electrolyser Capex is anticipated to fall by more than 30%. In turn, this reduces the minimal H_2 price and the optimal load hours.

In summary, while the assumptions in Figure 5.4, 5.5 and 5.6 are different, the point of departure from the respective cost analysis' is that there is an undeniable relationship between electricity prices and the LCOH. This implies that emphasis must be on producing H_2 from renewable electricity and optimising the electrolyser for optimal FLH.

5.3 Cost of water supply

The electrolysis process requires 9 litres of water to produce 1kg of H_2 [IEA, 2019]. With this perspective, it is apparent that H_2 production is a water-intensive exercise. With SA ranked as the 30th driest country Mpofu og Botha [2021], this raises considerations that will need to be employed to ensure that H_2 production does not put pressure on freshwater supplies in the country.

According to Mpofu og Botha [2021], SA is a water-stressed country that is characterised by uneven rainfall distribution and evaporation rates that exceed precipitation. In terms of water sources, surface water and groundwater are responsible for the majority of the country's water supply. While agriculture and municipalities account for most of the water usage [Mpofu og Botha, 2021]. A visual perspective of water sources and uses in the country is shown in Figure 5.7.

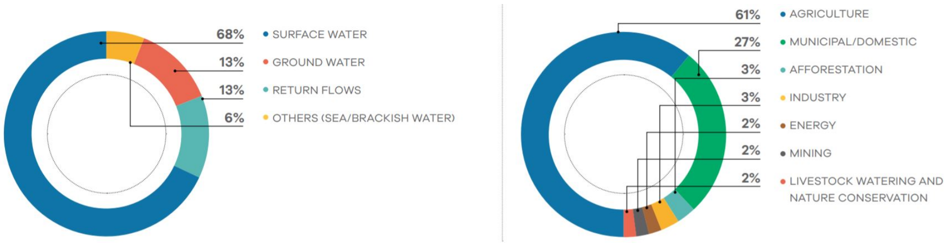

Figure 5.7. Image illustrating the sources and use of water in SA [Mpofu og Botha, 2021].

In the context of H_2 production by electrolysis, though the process is water-intensive, the cost of the water appears to be negligible. Water access, the purity and the cost thereof all influence water costs [ACIL Allen, 2018]. However, according to Verkehrswende og Energiewende [2018] and ACIL Allen [2018], water costs are a small portion of the H_2 production costs. Verkehrswende og Energiewende [2018] argues this is true even in regions where the water is supplied by desalination plants.

Delimitation

In analysing the water supply costs, it is important to clarify that the project only considers direct water consumption. Put in a different way, the project does not consider the life cycle assessment of H_2 production in relation to its water footprint.

5.3.1 Water-energy nexus

The is no universally accepted definition for the water-energy nexus. Nonetheless, the concept points out the relationship between the use of water in the production of energy [Aster, 2012]. Verkehrswende og Energiewende [2018] states that regions endowed with solar and wind potential tend to have limited access to freshwater. In such instances, the use of seawater offers a possible solution for coastal regions [IEA, 2019].

In the case of SA as a water-stressed region, it would be unjust for freshwater to be displaced from water reliant sectors because of H_2 production. With that understanding, there is a need for desalination plants to be built. The availability of seawater desalination plants will ensure that (i) H_2 production does not add pressure to already water-stressed regions in the country, and (ii) it does not divert water away from sectors and communities that are water-reliant [Roos og Wright, 2021]. By so doing, the key concern becomes less about the cost of the water and more about the sustainable supply of the water.

By numbers, IEA [2019] states that 3-4 kWh of electricity demand per m3 of water would be needed for desalination by reverse osmosis. 1 m3 of water is equivalent to 1000kg. This would result in a cost of approximately USD 0.7–2.5 per m3 of water [IEA, 2019]. For clarification, desalination is the process removing salt from seawater. While reverse osmosis is one of the processes that make water purification possible [Kershner, 2008]. Desalination is a energy-intensive activity. However, the use of RE suggests that energy costs associated with the process of desalination are negligible [Patel, 2020]. This is especially apparent when the energy costs of desalination are compared to electrolysis energy costs [Creamer, 2019].

In light of this, Roos og Wright [2021] encourages the use of treated non-portable water as a feedstock for bulk production of H_2 in SA. In addition, to keep H_2 production costs low, Roos og Wright [2021] recommends reducing the need for road-based transport by producing H_2 for the export market close to or at the shipment ports.

In terms of a suitable port in SA, the Port of Saldanha is considered ideal [Roos og Wright, 2021]. The port is situated in the Western Cape, a region endowed with good wind and solar potential. The total land and water area covered by the port is 18 000ha [AfricaPorts, n.d]. According to AfricaPorts [n.d], it is also the deepest port in the country, it has a 365m long tanker for bulk liquid cargo, thus making it an ideal port for H_2 export to Europe [Roos og Wright, 2021].

5.4 Sub-Conclusion

This chapter highlighted the economic and technical factors that influence H_2 production costs. As the chapter draws to a close, the following initial sub-conclusions can be drawn:

1. There appears to be a linear relationship between the price of renewable electricity and the price of producing H_2. The higher the price of electricity, the higher the cost of H_2 production.
2. SA, as a country with good RE potential and high capacity factor for onshore wind and solar PV, is well positioned to produce clean H_2 cost-competitively.
3. Producing green H_2 is a water-intensive process. In line with the water-energy nexus approach, the use of seawater desalination or treated non-portable water as a feedstock will be necessary to ensure that H_2 production does not divert water away from essential water-reliant sectors.

The next chapter will delve into the economical and technical factors involved in storing and transporting green H_2.

The economics of hydrogen storage and transport 6

Storage and transport are the other cost components associated with the H_2 supply chain. Therefore, this chapter discusses the storage and transport requirements necessary to economically store and transport H_2 for export.

6.1 Hydrogen storage pathways and costs

According to Shell [2017], the energy content of an energy carrier has a great impact on how it will be stored. In turn, the calorific or heating value has an influence on the energy content [Shell, 2017]. One may recall that Figure 1.7 identified H_2 as a fuel and energy carrier with a considerably high gravimetric energy density but a comparatively low volumetric energy density. Put simply, for storage purposes, this means that the density of H_2 must be increased substantially and liquefaction can be used to achieve the required higher density for storage purposes [Shell, 2017].

SA is a long way from a suitable H_2 export location in Europe. This means the need for large scale storage over long periods is amplified. ACIL Allen [2018] argues there are many ways to store H_2 before it needs to be used or traded and that each option has different costs associated with it.

H_2 must be compressed, liquefied or converted chemically to ensure that it is stored economically [KPMG, 2019]. There are also factors that need to considered when choosing the appropriate storage method. According to KPMG [2019], these are (i) form/type of H_2 needed for end-use and (ii) the storage period required.

6.1.1 Compression

Gaseous H_2 stored under pressure is colloquially known as compressed gaseous hydrogen (CGH_2). According to Shell [2017], much like it has been the case for many years with natural gas and crude oil storage, underground geological stores such as salt caverns, depleted oil and gas fields or aquifers can also be used as storage for H_2 at industrial scale. To this point, KPMG [2019] contends that it is worth noting that underground storage needs specific geological locations with geological conditions that are capable of containing the H_2. All things considered, space availability and the comparatively cheaper cost make this type of storage a viable option for stationary storage needs [KPMG, 2019].

6.1.2 Liquefaction

H_2 in a liquid state is formally known as liquid H_2 (LH_2). Unlike compression that stores H_2 in a gaseous state, this type of storage makes it possible for H_2 to be stored in a liquid form [Shell, 2017]. DNV GL [2018] and Shell [2017] state that LH_2 has a greater energy density than compressed hydrogen. In addition, both authors argue there is more energy needed to liquefy hydrogen than there is for compressing it to relevant pressures. This is because it needs liquefaction at –253°C. In turn, this makes liquefaction a capital and energy intensive form of H_2 storage [KPMG, 2019], [DNV GL, 2018] and [Shell, 2017]. Nonetheless, LH_2 with its higher energy density is ideal in situations where storage space is limited [KPMG, 2019]. Moreover, ACIL Allen [2018] states that while liquefaction of H_2, similarly to Liquefied natural gas (LNG), increases H_2 production costs, it significantly reduces the cost of transportation.

6.1.3 Material-based or chemical storage

Ammonia and liquid organic hydrogen carrier (LOHC) represent yet another way of chemically binding H_2 [Shell, 2017]. According to Shell [2017] LOHC and ammonia have more H_2 per molecule than H_2 itself. This implies that they can be transported cheaply by bulk modes such as ships, trucks and pipelines [DNV GL, 2018]. Be that as it may, KPMG [2019] argues there is a cost and an energy penalty incurred when the ammonia is converted back to H_2 for use.

In addition to ammonia, methanol (MeOH) is yet another way of storing H_2 chemically. The cost of storing H_2 as methanol is determined by the cost of the CO_2 feedstock [Roos og Wright, 2021]. The cost varies based on the source of the CO_2. Research by Roos og Wright [2021] identifies the following potential sources:

- The CO_2 is costly when it is sourced from direct air capture (DAC) or when it comes from the flue gas of coal-fired boilers. By definition, DAC is a technological method that extracts CO_2 from the atmosphere with the use of chemical reactions. The CO_2 can either be stored in underground geological formation or used immediately for making fuels, chemicals etc [IEA, 2020]. The novelty of DAC technologies coupled with the energy-intensive nature of the extraction and storage process are the drivers for the high CO_2 cost [IEA, 2020].
- The cost appears to be moderately priced when the CO_2 comes from the concentrated flue gas of steel and cement plants. And while the technologies for the CO_2 separation process are mature, they are expensive, complex and energy-intensive [Mustafa et al., 2016]. Thus driving CO_2 feedstock costs up.
- Finally, the CO_2 cost is at its lowest when the source is highly concentrated steam. An example of a process that produces such steam is the water-gas shift reactor of a FT synthesis plant.

As stated by ACIL Allen [2018], each storage pathways has different costs associated with it. And because H_2 has a low volumetric energy density, its density must be increased and this comes as a cost [Shell, 2017]. Put differently, the greater the storage density, the higher the energy required for compression [Shell, 2017]. To this point, both IEA [2019] and ACIL Allen [2018] maintain it is likely that the nature of the demand, scale, and distance will determine the type of storage ultimately utilised.

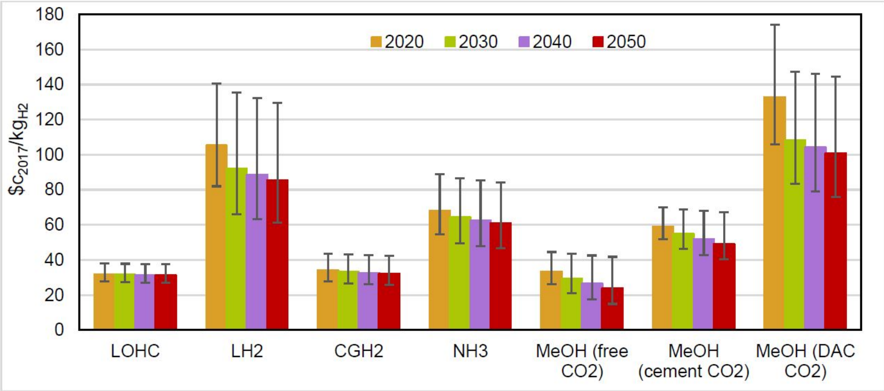

Figure 6.1. Image illustrating the cost of H_2 storage from wind and single axis tracking (SAT) PV generated electricity from 2020 - 2050 [Roos og Wright, 2021].

Figure 6.1 compares the cost of storing H_2. The image looks at the comparison across seven storage methods. These include LOHC, LH_2, CGH_2, NH_3, MeOH from free CO_2, MeOH from cement CO_2 and lastly, MeOH from DAC CO_2. For these comparisons, the H_2 is produced from equal capacities of SAT PV and onshore wind. The bars indicate the most likely costs under the reference scenario. The ambitious scenario is indicated by the lowest point of the whisker. It assumes the lowest WACC and capex for the electrolyser and the RE infrastructure. On the other hand, the least ambitious scenario is denoted by the highest point of the whisker. This scenario assumes the highest WACC and capex for the technologies [Roos og Wright, 2021].

Based on this understanding, for the years 2030 and 2050, the cheapest levelised cost of storage (LCOS) for SA is possible when LOHC, CGH_2 and MeOH from free carbon dioxide (CO_2) are used as storage mediums. According to IEA [2019] and IRENA [2019], because the H_2 is embedded in the LOHC, a further step is needed to release the H_2 before it is ready for final consumption. It is also worth noting that this step and the costs associated with it are avoided if conversion is not needed.

6.2 Transportation

Green H_2, much like RE, will require infrastructure that is affordable, safe, and efficient to transport and deliver it from its production site to end-users [PwC, 2020]. Key factors to consider that will have an impact on the overall cost of delivering H_2 include [IEA, 2019]:

- the infrastructure available in the exporting and importing country
- proximity to import market *(i.e. distance)* [ACIL Allen, 2018]
- the type of transport mode used
- the nature of end-use demand

6.2.1 Transporting hydrogen in different modes

The main modes for transporting H_2 include trucks, pipelines, rail and shipping [KPMG, 2019]. More specifically, KPMG [2019] states that

- Trucks are used to transport liquid or compressed gaseous H_2.

- Existing pipeline infrastructure can be used to transport compressed gaseous H_2.
- In the instance of long distances, rail and shipping are ideal for transporting material-based H_2 or liquid H_2.

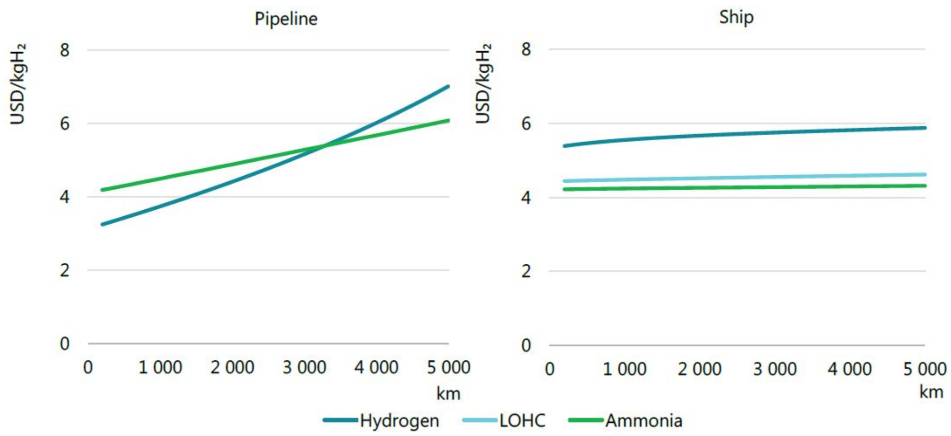

Figure 6.2. Image illustrating a cost comparison of transporting H_2 by ship or pipeline in 2030 [IEA, 2019].

For illustrative purposes, Figure 6.2 compares the full cost of delivering hydrogen-based energy to industry by ship and pipeline in 2030 over varying distances. The analysis assumes that the H_2 is produced at USD3/kgH_2. It also assumes the end-user site is 50km from the receiving terminal and that there is 100 tonnes per day (tpd) distributed through the pipeline [IEA, 2019]. Based on both comparisons, H_2 in its pure form is expensive to transport over long distances. The greater the distance, the greater the cost. Comparatively, transporting ammonia and LOHC by ship is cheaper and the costs between the two energy carriers are similar, making them the more suitable options for long distances.

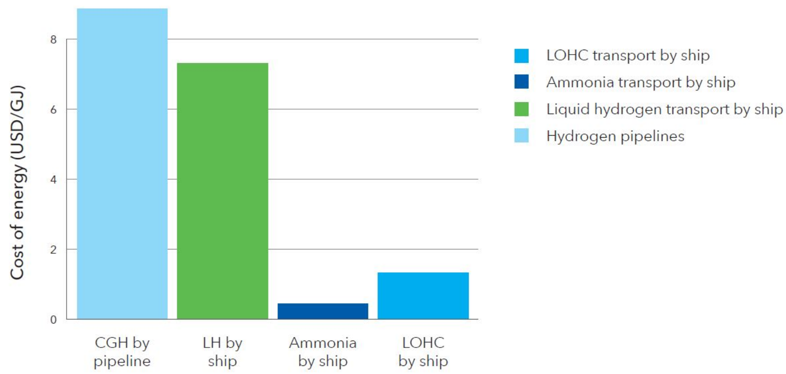

Figure 6.3. Image illustrating a cost comparison of transporting H_2 in different states by shipping or pipeline [DNV GL, 2018].

Figure 6.3 is taken from an analysis by DNV GL [2018]. While the assumptions in this example are different from those noted for Figure 6.2, there are some noticeable parallels than can be drawn. For one, the image echos the view by IEA [2019] that transporting pure H_2 is expensive. According to DNV GL [2018], this is largely because of the high capex required. Similarly, Figure 6.3 also identifies the transportation of ammonia and LOHC by ship as the more cost-effective alternative.

6.2.2 Storage, transport and conversion

From the analysis in the above subsection, it became evident that ammonia and LOHC are the more attractive options. However, according to IEA [2019], there is an energy penalty and cost involved in converting and reconverting these chemicals. To this point, DNV GL [2018] states that conversion is a large part of the storage and transport of ammonia, LH_2 and LOHC.

To illustrate this point, DNV GL [2018] considers value chains that involve the storage, transport and conversion of these chemicals. The assumptions behind the value chains are outlined below:

- **CGH_2**: 1,000 km by submarine pipeline => compression to 350 bar => 50 km by truck => storage.
- **LH_2**: Liquefaction => 1,000 km by ship => 50 km by truck => storage.
- **Ammonia**: ammonia synthesis => 1,000 km by ship => 50 km by truck => storage => reformation.
- **LOHC**: Hydrogenation => 1,000 km by ship => 50 km by truck => storage => dehydrogenation.

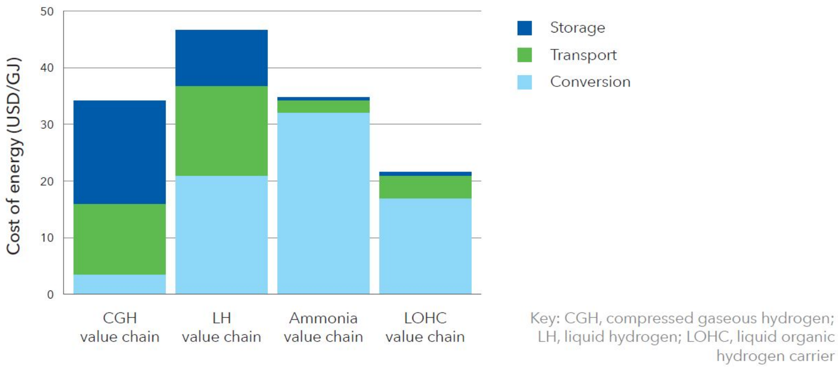

Figure 6.4. Image illustrating a cost comparison of storage, transport and conversion for CGH_2, LH_2, ammonia and LOHC [DNV GL, 2018].

Based on the results in Figure 6.4, it is evident that LH_2 is the most expensive value chain, with conversion responsible for most of the costs. According to DNV GL [2018], the cost is driven by the the energy losses from the liquefaction process and the high costs of transporting pure H_2 by ship.

On the other hand, while CGH_2 and ammonia have similar costs, it is important to recognise that the costs components between the two differ. In the case of ammonia, conversion is responsible for the bulk of the total costs. This makes ammonia a suitable option for instances where long distances and an increased need for storage are a factor [DNV GL, 2018]. On a similar note concerning ammonia, IEA [2019] states that transporting ammonia would be even more ideal if it used as it is by the end-consumer. This is because the costs of reconverting the ammonia to H_2 can be avoided. Conversely, storage and transport are the dominant cost components for CGH_2. In instances where geological formations are possible, DNV GL [2018] argues that this is a cheaper storage alternative for CGH_2 instead of storage in tanks.

Finally, with storage and transport being a minuscule component of the total costs, LOHC is the overall cheapest option.

6.2.3 Importing green hydrogen

According to FCH [2019], one of the key advantages of H_2 is that it provides a bridge between countries with cheap RE and those that are demand centers. It does this by enabling the transportation of hydrogen-based energy by pipelines or ships over long distances at a cost that is less than power transmission lines [FCH, 2019]. Research by Germany's Federal Government states that establishing a strong domestic market for H_2 production and use is the first step to accelerating the roll-out of H_2 technology [Federal Government, 2020]. Federal Government [2020] also notes that H_2 will have to be imported because domestic production of green H_2 will not satisfy all new demand.

The research by IEA [2019] suggests that there are certain trade routes where importing green H_2 could be more sensible than producing it domestically. Consider an example where ammonia is used without the need for re-conversion to H_2 by the end-user.

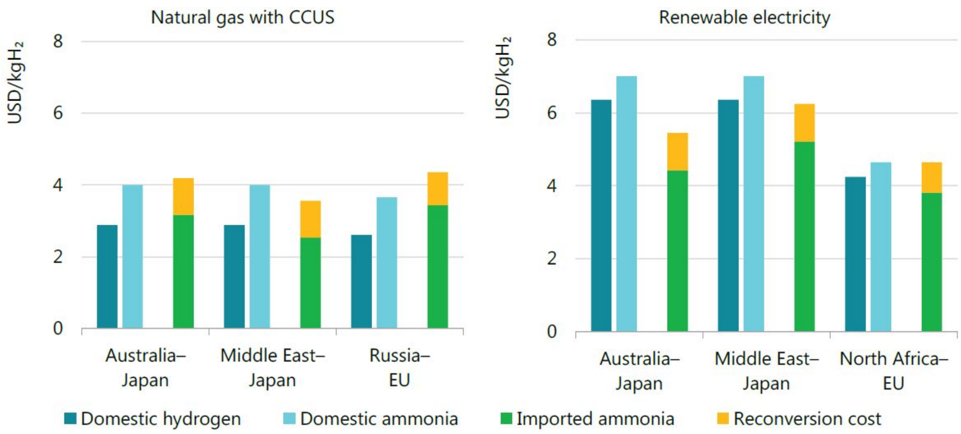

Figure 6.5. Image illustrating a number of trade routes where imported H_2 could be financially attractive than domestically produced H_2 in 2030 [IEA, 2019].

Against this backdrop, Figure 6.5 makes a comparison between green H_2 that is produced domestically and imported across specific trade routes in 2030. Paying close attention to the trade route between North Africa and the EU, it becomes apparent that ammonia imported from North Africa is cheaper than ammonia produced in the EU.

In the context of SA, Roos og Wright [2021] calculated the levelised cost of transport (LCOT) for shipping green H_2 from SA to Kobe in Japan. The distance from Coega in SA to Kobe is 14 300km. A distance that is notably longer than that from the Port of Saldanha to the Port of Rotterdam (i.e. 11 200km). The results of his calculation are shown in Figure 6.6. The assumptions and differences between the scenarios are the same as those described for Figure 6.1.

Carrier	Scenario		
	Optimistic (US$/kg)	Reference (US$/kg)	Pessimistic (US$/kg)
NH_3	0.13	0.14	0.16
MeOH	0.25	0.27	0.30
LOHC	0.59	0.63	0.69
CLH_2	2.30	2.64	3.15

Figure 6.6. Image showing three scenarios of the LCOT for shipping ammonia, methanol, LOHC and CLH_2 from Coega to Kobe [Roos og Wright, 2021].

From the results in Figure 6.6, it becomes evident that ammonia and methanol have the lowest LCOT for all three scenarios. While Kobe is much further than the Port of Rotterdam, the results from these scenarios provide a baseline that can be used as a reference point for evaluating and discussing suitable transport options for delivering H_2 to the EU in a cost-effective manner.

6.3 South Africa's energy trading relationship

SA has the strongest economy in Sub-Saharan Africa, making it the EU's biggest trading partner in Africa [European Commission, 2020e]. In Figure 6.7, it is evident that Africa is a prominent trade partner to the EU. To this point, European Commission [2018] states that globally, the EU remains the most open market to trade from Africa.

Figure 6.7. Image showing the trade relationship between Africa and the EU in relation to other trade partners in 2017 [European Commission, 2018].

Because SA will be competing with other countries for the export of H_2 to Europe, ACIL Allen [2018] states that having preexisting energy trading relations is advantageous for keeping export costs at a minimum. SA has a long-standing trade agreement in place with the EU which translates to SA paying little to no duties on exports to the EU [European Commission, 2018]. This relationship gives SA another competitive advantage over other potential H_2 suppliers that could be leveraged to export clean energy cost-effectively.

6.4 Sub-Conclusion

This chapter delved into the different storage and transport options that make it possible for H_2 to be stored and delivered cost-competitively. In closing, the following sub-conclusions were noted:

1. A low LCOS is achieved when methanol, CGH_2 and LOHC are used as storage mediums for H_2.

2. The distance between SA and Europe suggests that shipping will be the most suitable transportation option. Where the state of H_2 is concerned, transporting it as ammonia or LOHC is the cheapest option.
3. Analysis by IEA [2019] demonstrated that green ammonia imported from North Africa is cheaper than green H_2 produced domestically in Europe. This result implies that a compelling case can be made for SA to ship H_2 as green ammonia or LOHC as the need for reconversion to H_2 would be removed.

The following chapter will show the research problem from different perspectives by analysing expert opinions from the identified stakeholders.

Analysis and results 7

This chapter is informed by insights from the stakeholder interviews as well as expert opinions from the email correspondence. Utilising the methodological approach outline in Chapter 4, this chapter shows the research problem from different perspectives.

7.1 Email correspondence & interview insights

The knowledge and insight obtained via interviews and email correspondence will be analysed and discussed in this section. To the extent that is possible, and where applicable, parallels of how these insights relate to the reviewed literature and the theories applied in this report will be drawn. The interviews and email correspondence were carried out using the method described in section 4.4 and 4.5 respectively. Evidence of the correspondence can be seen in Appendix 2, and the details of who was interviewed are revealed in Appendix 1. Finally, it is important to reiterate that the views in the emails and interviews are personal opinions and do not reflect the views of the organisation the respondents represents.

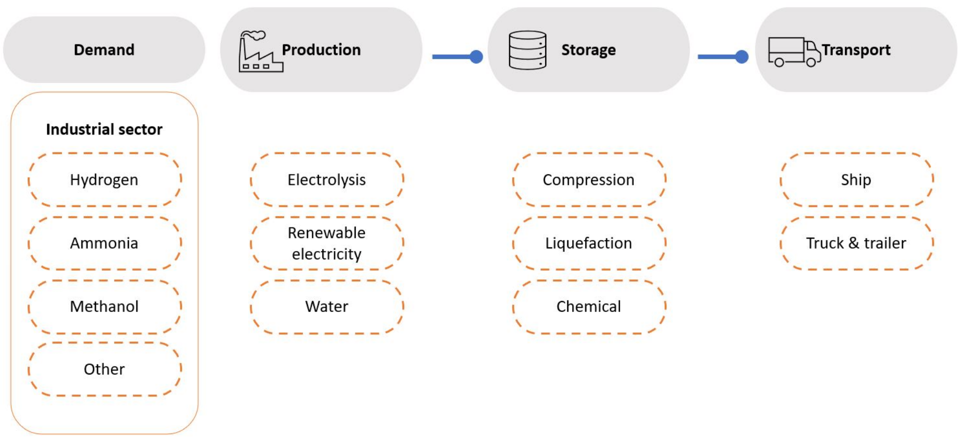

Figure 7.1. Image showing an oversimplified schematic of the H_2 supply chain. Own image. Adapted from [KPMG, 2019].

The information from the email and interviews will be broken down into constituent parts that address aspects of the green H_2 supply chain illustrated in Figure 7.1. The main elements of the supply chain are explained as follows:

- **Demand**: refers to the EU's industrial energy demand that must be met by H_2 and other hydrogen-based energy carriers. It is important to clarify that this part was not discussed with the respondents and is merely included for illustrative purposes.
- **Production**: refers to the renewable resource and technology that must be utilised to meet the required H_2 demand.
- **Storage**: this is the various states the H_2 can be stored in to meet demand.

- **Transport**: refers to the different modes of transporting and delivering the H_2 to the EU.

7.1.1 Production

Both the interviews and email correspondence will be analysed and discussed for knowledge and insight concerning the production component of the supply chain illustrated in Figure 7.1.

Major components/drivers for achieving low-cost hydrogen

Herib Blanco is a Senior Energy Consultant with a focus on H_2 policy at IRENA. With green H_2 largely considered a long-term opportunity, he was questioned, via email, for his thoughts on drivers required to produce green H_2 at a low cost. To this, Herib had the following to say:

1. **Low electricity price with high enough operating hours**. Herib argued that the record PV auction price is already in the range of approximately USD 10/MWh. However, the operating hours of the PV are still low, resulting in the electrolyser Capex not being reduced by much. By his account, batteries or coupling the PV with wind or concentrated solar power (CSP) would increase the operating hours, but it would also increase the electricity price.
2. **Low electrolyzer investment**. Herib writes that this can be achieved through the following means: (a) Economies of scale during manufacturing. (b) Economies of scale by having larger modules of at least 50MW, ideally 100 MW. This would reduce the balance of payment. (c) Innovation. (d) Optimizing the supply chain and achieving economies of scale for all the components.
3. **Familiarization from different stakeholders**. Herib wrote that this approach will reduce capital costs by lowering the perceived risk. In turn, this will translate into projects being executed, facilitated, evaluated, and approved more easily and at lower costs.
4. **Long-term commitments and market creation**. Herib suggests that the existence of a market with multiple suppliers would lead to innovation from the suppliers, competition, thereby driving costs down.

When one compares the views shared by Herib with the literature reviewed in this project, there are some noticeable parallels. Herib's views bear similarities with research done by IEA [2019], ACIL Allen [2018] and Roos og Wright [2021], to mention a few.

A similar question was posed to Erik Hektor who works at DNV's Corporate Research and Development unit in Oslo. His focus is on low carbon technologies, primarily towards the oil and gas industry, helping them with solutions to decarbonise the industry, where H_2 is an important component of that.

Erik gave a slightly different response to the question of drivers needed to achieve low-cost H_2. Unlike Herib who spoke to concrete and specified elements of the production process, Erik expressed that he thought it was important to look at the value chain/supply chain in its entirety. According to his understanding, the supply chain of producing H_2 consists of several factors. For instance, the H_2 has to be stored, transported, converted etc. That said, how one sets up his/her supply chain will determine what the total cost picture looks like. To clarify his point, Erik explained that one could either produce the H_2 right next to his/her wind or solar power, store and transport the H_2. Alternatively, one could first transport the power, then produce and convert the H_2 close to the end-user. From his nuanced perspective, Erik implied that there is no one-size-fits-all approach. Instead, a case by case approach may be more telling.

Cosmas Chiteme and Mbangiseni Mabudafhasi are both representatives from the Department of Science and Innovation (DSI) in SA. Under the DSI, they belong to a program called Technology Innovation which has H_2 and Energy as one of its chief directorates. Much like Herib and Erik, they too were asked a similar question on drivers for low-cost H_2 production.

Cosmas and Mbangiseni shared the following thoughts:

- **Skills development and creating the necessary knowledge**. According to Cosmos, "this would at least allow SA to turn its comparative advantages into competitive advantages."
- **Leveraging existing knowledge**. Mbangiseni commented that SA, unlike other countries, is not starting from a clean slate with H_2. This is because Sasol and others alike have been working with H_2 for decades in SA and "this will be valuable to the development of this market in SA", stated Mbangiseni.
- **A roadmap with very specific actions**. According to Cosmas, the process will encourage valuable stakeholder engagement and identify policy gaps that currently exist.

Herib's first point on low electricity prices with high enough hours echoes much of what is described in chapter 5 of the report. More specifically, the second line of section 5.1 states that the cost of electricity is responsible for about 50% - 70% of the LCOH. This excerpt is taken from research by PwC [2020]. This understanding coupled with Herib's view makes it apparent that the cost of electricity will be one of the key drivers.

The water-intensive nature of producing hydrogen

Herib and Erik were questioned on whether they thought the water-intensive nature of the H_2 production process is cause for concernment to SA as a water-stressed country.

According to Herib, desalination can be used for water-stressed regions. Herib added that desalination has limited energy consumption and cost when compared to the electricity input. In his view, the challenge is sustainability and dealing with the brine that is produced as a by-product. Similarly, Erik commented that "initially when you are scaling up this might not be a problem". However, Erik implied there may be cause for concern when the scales are bigger.

Reviewed literature by Verkehrswende og Energiewende [2018] and IEA [2019] are some of the publications that address the issue of water and H_2 production. In the context of the water-energy nexus, Herib's view of utilisation desalination to reduce the water footprint of H_2 production are echoed in these publications.

Summation

To bring the analysis of the production supply chain to a close, different view on what respondents considered as key drivers for achieving low-cost H_2 were also observed. Taking all the varying perspectives into account, it becomes apparent that a convergence of several elements and factors will drive H_2 production costs down. Cosmas, Mbangiseni and Herib made points about the value of skills, knowledge development, involvement of different stakeholders and long-term commitments. These viewpoints are in alignment with elements that the MLP theory considers being characteristic of system innovations. These characteristics are listed in section 3.2, paragraph 2 of the report.

Concerning water use, literature review and insights from Erik and Herib recognise the value of utilising desalination to minimise the water footprint of the energy production process. Finally, in the context of electricity, it is becoming evident that the use of renewable electricity will be one of the major drivers for keeping H_2 production costs low.

7.1.2 Storage & transport

This subsection analyses the email and interviews for knowledge and insight about the storage and transport part of the supply chain illustrated in Figure 7.1.

State of transport

In this instance, Herib and Erik were both probed on their expert opinions on the state of transporting H_2. The question was posed to determine whether they thought it was better to store and transport H_2 in its pure form or as an intermediate energy carrier like ammonia or LOHC.

According to Erik, you have energy losses in the conversion when you utilise a liquid platform or LOHC. Herib shared a similar view. He argued that LH_2 has disadvantages that include (i) large energy losses for liquefaction, (ii) high investment costs, and (iii) higher losses during transport. Herib went on to comment that LOHC also have drawbacks to it. These include (i) high reconversion losses at the import port where renewable electricity is more expensive, (ii) high cost for the carrier (increasing the initial investment and needed to compensate the losses), (iii) use of a carbon-containing carrier, and (iv) open question on the carrier to be used.

Despite this, Erik contended that there is a noticeable demand for other kinds of H_2 or hydrogen-based fuels like ammonia, methanol etc. In his view, these fuels are much easier to handle, store and transport, and perhaps, this is an easier way to supply demand. "The maritime sector is showing more and more interest in ammonia as a fuel. The sector can utilise ammonia directly, avoiding conversion and energy losses", concluded Erik. Similarly, Herib echoed much of what was stated by Erik regarding the use of ammonia. In his email, Herib implied that transporting H_2 as ammonia held more prospects. According to Herib, this is because 180 ports around the world use ammonia, there is existing global trade, large-scale synthesis is already being done, and there are low losses during transport.

Of the reviewed literature, the input shared by both respondents correlates with research in studies by Shell [2017], DNV GL [2018] and KPMG [2019]. Their views also agree with the contents of Chapter 6.

Summation

In summing up the storage and transport parts of the supply chain, it is evident that there is a notable sense of congruence between what was shared by the respondents and what is prescribed in the literature about the state of H_2 storage. In addition, both literature and views from the respondents made it evident that it was better to transport H_2 as a chemical in the form of ammonia.

7.2 Additional stakeholder opinions

Section 7.1 analysed and discussed insights from stakeholders that directly addressed aspects of the H_2 supply chain in Figure 7.1. This section goes a step further by analysing additional stakeholder opinions that do not necessarily address the supply chain but were still equally important to address the research problem.

SA's comparative advantage

Mbangiseni and Cosmas were asked for their thoughts on SA's comparative advantage with producing green H_2. They had the following to say:

- Beneficiation of PGMs. According to Cosmas, this is part of a transition to a knowledge-based economy that is in line with SA's National Development Plans (NDP).
- Optimal wind and solar resources.
- Contributing to issues of energy security and improved energy access.
- The need to decarbonise.
- The ability to tap into an existing skill and knowledge base through Sasol's experience.

"Having those resources is a comparative advantage and the goal is to shift this to a competitive advantage", concluded Cosmas. The views shared by Cosmas and Mbangiseni corroborate certain aspects of the information in section 1.2 of the report. Where a strong RE offering, the FT advantage and an unmatched platinum footprint are cited as comparative advantages that SA could leverage.

SA's predisposition to carbon lock-in

When questioned about the extent to which SA is predisposed to carbon lock-in, Herib seemed confident that SA's reliance on coal will undoubtedly lead to path dependency.

He anticipates that fossil fuel path dependency will be driven by the vested interest of private stakeholders who derive revenue and business from the continued use of fossil fuels. Moreover, jobs and skills that will be lost or need to be re-skilled in the wake of the energy transition could be a factor that fosters carbon lock-in, added Herib. Finally, changing from a domestic industry to perhaps import of technologies and the perception that coal can be used as firm capacity complementing wind/solar but leaving out other flexibility options such as storage, interconnection, etc are all factors that could contribute to path dependency.

The carbon lock-in theory described in section 3.3 speaks to exactly these tendencies. All the technological, institutional and social factors that Herib described confirm that SA's longstanding dependence on coal will make it difficult for the country to wean itself off fossil fuels despite the existence of low-carbon and cost-effective alternatives.

Challenges and concerns for SA

As a parting thought, Herib and Erik were questioned on challenges or concerns they foresee for countries like SA as players in the hydrogen landscape. Herib expressed the following thoughts:

1. SA would first need to decarbonise the electricity mix before considering renewable H_2 (i.e. make the best use of the limited renewable capacity deployed).
2. SA's current dependence on coal production might be a challenge to export to countries like Europe that are looking only to renewable H_2.
3. SA's distance to potential markets. To this point, Cosmas and Mbangiseni maintained that geological proximity to potential markets is not the only consideration potential importers will consider. Cosmas and Mbangiseni expressed that political stability and perceived risks will also be considered as these will affect the security of supply and possibly affect costs.
4. Perceived high risk which translates into a high cost of capital.
5. A certification scheme for H_2 production. Herib implied that SA may need to comply with standards from importers and demonstrate that H_2 meets the importers' sustainability requirements.

Erik commented that "Energy demand will not go down, it will soar." He went on to mention that this growth will see development in the rest of Africa as well, where SA is an industrial front-runner. Moreover, Erik commented on the likelihood of demand in neighbouring countries and so on. As a final thought, Erik brought up the role of policy. He echoed Herib's final point by emphasising the importance of policy. Erik implied that this will ensure that SA aligns with the H_2 classifications and standards of the EU.

The following chapter will propose policy recommendations that could help foster a scaled green H_2 market in SA.

Policy recommendations 8

There is growing consensus in research that market forces alone will not sufficiently drive decarbonisation. Therefore, this chapter speaks to suggestive policy priorities for the development of SA's nascent green H_2 market.

8.1 Policy priorities

According to Metcalfe et al. [2020], H_2 will undoubtedly play a crucial role in achieving the decarbonisation goal earmarked by the Paris Agreement. By the same token, IEA [2019] writes that it takes time for emerging energy technologies to infiltrate existing markets. This rationale implies that market forces alone will not be enough to drive the needed decarbonisation. With that understanding, this section shares policy recommendations needed to develop SA's green H_2 market at scale.

8.1.1 Prescribing hydrogen into the Integrated Resource Plan

SA's Integrated Resource Plan (IRP) is intended to be a living policy document that sets the tone for the country's energy future [Power Futures SA, 2019]. According to Dixit et al. [2014], "the purpose of an IRP is to minimize present and future costs of meeting energy requirements while considering impacts on utilities, government, and society." In SA's context, the IRP functions as a blueprint that details how much energy the country will need in the future, this includes the technical aspect of determining the generational capacity mix. It outlines how the demand will be supplied and financial investments that will be necessary to meet its objectives, while simultaneously aligning that with the country's economic, social, political and environmental interests [Power Futures SA, 2019].

Figure 8.1 shows a snapshot of SA's updated energy mix from 2019 to the year 2030. Looking into this image, it is clear that H_2 is not prescribed in the energy mix of the future. Power Futures SA [2019] writes that for the IRP to maintain its relevance, it needs to consider fluctuating technology costs and changes in the economy. With this understanding, if SA intends on becoming a prominent exporter of green H_2, this project recommends that H_2 should be prescribed in the country's IRP. This will create policy certainty, encourage investor confidence and most importantly, it will position the country's electricity future towards a low-carbon generation pathway.

Mapula Tshangela who is the Director of Climate Change Mitigation at the Department of Environmental Affairs (DEA) in SA shared a similar view during her interview. She stated that "in the energy space, the IRP dictates the country's generation mix. And once the mix is defined in the IRP's policy plan, it drives demand, certainty, investment, research, training etc." With this comment, Mapula implied H_2 not being defined in the IRP will affect the speed and investment H_2 needs to become mainstream.

	Coal	Coal (Decommis-sioning)	Nuclear	Hydro	Storage	PV	Wind	CSP	Gas & Diesel	Other (Distributed Generation, CoGen, Biomass, Landfill)
Current Base	37,149		1 860	2,100	2 912	1 474	1 980	300	3 830	499
2019	2,155	-2,373					244	300		Allocation to the extent of the short term capacity and energy gap.
2020	1,433	-557				114	300			
2021	1,433	-1403				300	818			
2022	711	-844			513	400 1,000	1,600			
2023	750	-555				1000	1,600			500
2024			1,860				1,600		1000	500
2025						1000	1,600			500
2026		-1,219					1,600			500
2027	750	-847					1,600		2000	500
2028		-475				1000	1,600			500
2029		-1,694			1575	1000	1,600			500
2030		-1,050		2,500		1000	1,600			500
TOTAL INSTALLED CAPACITY by 2030 (MW)	33,364		1,860	4,600	5,000	8,288	17,742	600	6,380	
% Total Installed Capacity (% of MW)	43		2.36	5.84	6.35	10.52	22.53	0.76	8.1	
% Annual Energy Contribution (% of MWh)	58.8		4.5	8.4	1.2*	6.3	17.8	0.6	1.3	

Installed Capacity
Committed/Already Contracted Capacity
Capacity Decommissioned
New Additional Capacity
Extension of Koeberg Plant Design Life
Includes Distributed Generation Capacity for own use

- 2030 Coal Installed Capacity is less capacity decommissioned between years 2020 and 2030.
- Koeberg power station rated/installed capacity will revert to 1,926MW (original design capacity) following design life extension work.
- Other/ Distributed generation includes all generation facilities in circumstances in which the facility is operated solely to supply electricity to an end-use customer within the same property with the facility.

Figure 8.1. Image showing SA's updated energy mix as prescribed in the latest IRP document [Govender, 2019].

8.1.2 Technology and innovation clusters in hydrogen technology

Technology clusters are a catalyst for the diffusion of ideas and knowledge development in an industry [OECD, n.d.]. OECD [n.d.] further states that the strategic distribution of academic institutions, supporting organisations, suppliers, core firms, and customers within proximity of the clusters creates fertile grounds for knowledge sharing and resource development [OECD, n.d.].

In SA, this could translate to economic development agencies, academic institutions, RE development associations, public and private agencies coordinating efforts to stimulate cluster development and local networking. This would be particularly beneficial for novel technologies with low technology-readiness levels such as the SOEC electrolyser. Moreover, adopting this approach would ensure that:

1. Leading universities and training institutions in SA offer courses and other learning programs that are tailored to meet the needs of a H_2 future. In turn, this will not only create a new skilled workforce for the country but will also contribute towards upskilling workers in the coal sector.
2. It will accelerate the transition towards green H_2 through collaboration, R&D and cross-sectoral interventions. This approach will also enable valuable partnerships between the public and private sector.

8.1.3 Internationally recognised framework to enable energy trading

European Commission [2020c] defines green H_2 in the following manner: "*hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources. The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero. Renewable hydrogen* *may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.*".

For hydrogen-based synthetic fuels such as ammonia and methanol, European Commission [2020c] gives the following definition: "*refer to a variety of gaseous and liquid fuels on the basis of hydrogen and carbon. For synthetic fuels to be considered renewable, the hydrogen part of the syngas should be renewable. Synthetic fuels include for instance synthetic kerosene in aviation, synthetic diesel for cars, and various molecules used in the production of chemicals and fertilisers.*"

In contrast, SA's H_2 strategy is still in its infancy, with no official definitions for green H_2 and other hydrogen-based energy carriers. To that effect, and to facilitate energy trading between SA and the EU, the project recommends the development of an internationally recognised framework between the two regions. This framework will ensure there is congruence on cross-cutting issues such as the definition of green H_2, water sustainability requirements, transport standards and other elements of the value chain.

As a final point, this project openly acknowledges that anytime there is a new approach to doing things, there are also new, and sometimes, unintended consequences to be deciphered and understood. As such, the recommendations shared in this chapter are not meant to be the final word. Instead, they ought to be seen as merely educated guesses to addressing an age-old problem of coal dependency in SA.

Conclusion 9

Drawing from the knowledge acquired through the literature review and insights gained from the stakeholder engagements, this chapter will conclude on the research questions presented in section 1.9.

"Using green H_2 as an enabler for decarbonisation between 2030 and 2050 in the industrial sector, how will the projected increase in the EU's H_2 demand influence SA's ability to export carbon-free energy?"

Using the EU as a trade partner, this project has attempted to evaluate whether H_2 and other hydrogen-based energy carriers could be an alternative route for SA to maintain its role as a prominent energy exporter. To carry out the evaluation, the project investigated and highlighted technical and economical elements that have an impact on producing green H_2 cost-effectively. It has been argued that there is a relationship between electricity prices and the LCOH. Where it has been shown that the higher the price of electricity, the higher the LCOH. While other economical and technical factors influence H_2 production cost, it is asserted that the cost of electricity will be one of the key drivers.

Recognising that energy trading will be challenging without efficient storage and transport, the economics of storing and transporting H_2 were evaluated. The project asserted that storing H_2 as a chemical was more cost-effective than storing H_2 in its pure form. Moreover, the project found shipping was the more financially viable mode for carrying H_2 over long distances.

Drawing from the stakeholder engagements, it was suggested that a convergence of several elements and factors will drive H_2 production costs down, making SA's transition to a H_2 export market characteristic of system innovations identified in the MLP theory. Moreover, stakeholders argued that SA's dependence on coal will lead to technical, social and institutional tendencies that foster carbon lock-in.

Because emerging energy technologies take time to infiltrate existing markets, the project suggested policy priorities to enable the growth of SA's nascent green H_2 market:

1. **Prescribing hydrogen into the IRP**. This will create policy certainty, encourage investor confidence and most importantly, it will position the country's electricity future towards a low-carbon generation pathway.
2. **Technology and innovation clusters in hydrogen technology**. This approach will accelerate the transition towards green H2through collaboration.
3. **Internationally recognised framework to enable energy trading**. This framework will ensure there is congruence on cross-cutting issues such as the definition of green H2, water sustainability requirements, transport standards and other elements of the value chain.

As a parting thought, readers are encouraged to view these recommendations, not as a final word, but as educated guesses to help the nation transition from an age-old problem of coal dependency.

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