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GREEN HYDROGEN: A POTENTIAL EXPORT COMMODITY IN A NEW GLOBAL MARKETPLACE

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CONTENTS

ABBREVIATIONS

BF-BOF	Blast Furnace-Basic Oxygen Furnace
CCUS	Carbon capture, utilisation and storage
CLT	Coal-to-liquid
CSIR	Council for Scientific and Industrial Research
DRI-EAF	Direct Reduction of Iron-Electric Arc Furnace
DRI	Direct Reduced Iron
DSI	Department of Science and Innovation
dtic (the)	Department of Trade, Industry and Competition
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch (process)
GHG	Greenhouse gas
HFC	Hydrogen Fuel Cell
HySA	Hydrogen South Africa
IDZ	Industrial Development Zone
IEA	International Energy Agency
IPHE	International Partnerships for Hydrogen and Fuel Cells in the Economy
MEA	Membrane electrode assembly
MoU	Memorandum of Understanding
R&D	Research and Development
SAASTA	South African Agency for Science and Technology Advancement
SAREM	South African Renewable Energy Masterplan
SOEC	Solid Oxide Electrolysis Cell
PEM	Proton Exchange Membrane
PGMs	Platinum group metals
PV	Photovoltaic
WACC	Weighted Average Cost of Capital

1. INTRODUCTION

Globally, countries are mobilising resources to deal with the climate crisis. Climate change stands to impact countries collectively, with the impacts most severely felt by the vulnerable in society. Countries, including South Africa, have to think carefully about improving their resilience to the direct physical impacts of climate change and the effects of the transition. Part of the response involves transforming notorious, high-emitting industries, such as energy and petrochemicals, towards cleaner production. Responses by countries differ; however, what is certain is that the nature of trade, production and investment will change in this transformation. Countries that contribute heavily to emissions and make no substantial mitigation and adaptation efforts stand to be isolated internationally through punitive measures such as trade barriers and reduced foreign investment, thus incurring severe costs on growth and development.

Given South Africa's high dependency on coal, and the combustion of coal being associated with high CO_2 emissions, South Africa will have to transform key value chains towards more sustainable production. This transformation not only protects the country's resources from future climate events but also secures South Africa's future in the global marketplace.

The hydrogen economy offers one potential and complementary pathway to a sustainable future. South Africa's rich endowment of ideal weather conditions for solar and wind power generation, technological capabilities around the Fischer-Tropsch (FT) process, and access to platinum resources, place the country at an advantage for developing the hydrogen value chain and being a key supplier into the global hydrogen market.

There is increasing international interest and investment directed towards hydrogen as an energy carrier and its application in the production of energy and a variety of important chemical products. This provides South Africa with a window of opportunity to investigate and develop a domestic hydrogen economy, attract investment into developing a new capability, and benefit from this heightened interest in the creation of a new export product.

Developing this sector has many potential benefits for the country. Hydrogen assists with the storage of renewable energy. While storage and battery technologies are still in development, the use of renewable energy to produce hydrogen allows the energy generated to be stored as hydrogen. Energy can then be used to produce electricity as a possible substitute for coal-based electricity as well as supplement supply when energy demand is high. Another benefit of hydrogen is the decarbonisation of traditionally carbon-intensive sectors of the economy, which is assisting South Africa to mitigate carbon emissions and align to a greater extent with the 2015 Paris Agreement. South Africa's petrochemical complex is an example of how hydrogen can reduce emissions. The production of vital chemicals such as fuels and other petrochemicals constitute important feedstocks in downstream markets for which alternate low-carbon options are limited.

The development of the hydrogen economy also provides South Africa with a new sustainable technological capability that it can leverage in the global marketplace. With Japan, South Korea and the European Union (EU) indicating significant demand for hydrogen in the near future, other countries and regions are beginning to follow. An early entry into the market can secure South Africa as a competitive player on the global stage, providing it with scale and cost advantages. Finally, the development of the hydrogen economy can assist in alleviating South Africa's challenges around poverty, inequality and unemployment by drawing in vulnerable groups into the hydrogen economy and increasing overall economic growth. The hydrogen economy has a role to play in South Africa's just energy transition, providing employment and support to vulnerable workers, communities and small businesses in a post-coal economy.

This case study focuses specifically on the emerging export opportunities for South Africa in the development of green hydrogen. This refers to hydrogen that is produced through the process of electrolysis that is combined with a renewable energy source of power. While green hydrogen development has gone through a number of historical waves of interest, the current momentum is being driven globally, with a number of countries developing hydrogen roadmaps and strategies to capitalise domestically and in the global marketplace.

Section 1 reviews the exiting hydrogen production methods available and the current products which use hydrogen to produce.

Section 2 focuses on green hydrogen and explores the production technologies, cost dynamics and the sustainable products that can be produced with the technology.

Section 3 tracks the support and developments in South Africa around green hydrogen from both the public and private sectors.

Section 4 examines South Africa's competitive advantages in green hydrogen production and possible avenues for deployment of green hydrogen production.

Section 5 concludes.

2. CURRENT PRODUCTION AND USES

Current production methods

Hydrogen production currently takes place via a number of feedstock inputs. These feedstocks include fossil fuels, biomass, and electrolysis (water and electricity). Fossil fuels dominate as the chief source of hydrogen production today, with natural gas alone accounting for 75% of hydrogen produced currently. Following this, coal accounts for a further 23% of hydrogen production. The remaining production is accounted for by oil and electrolysis, with electrolysis currently accounting for less than 2% of global hydrogen production (IEA, 2019).

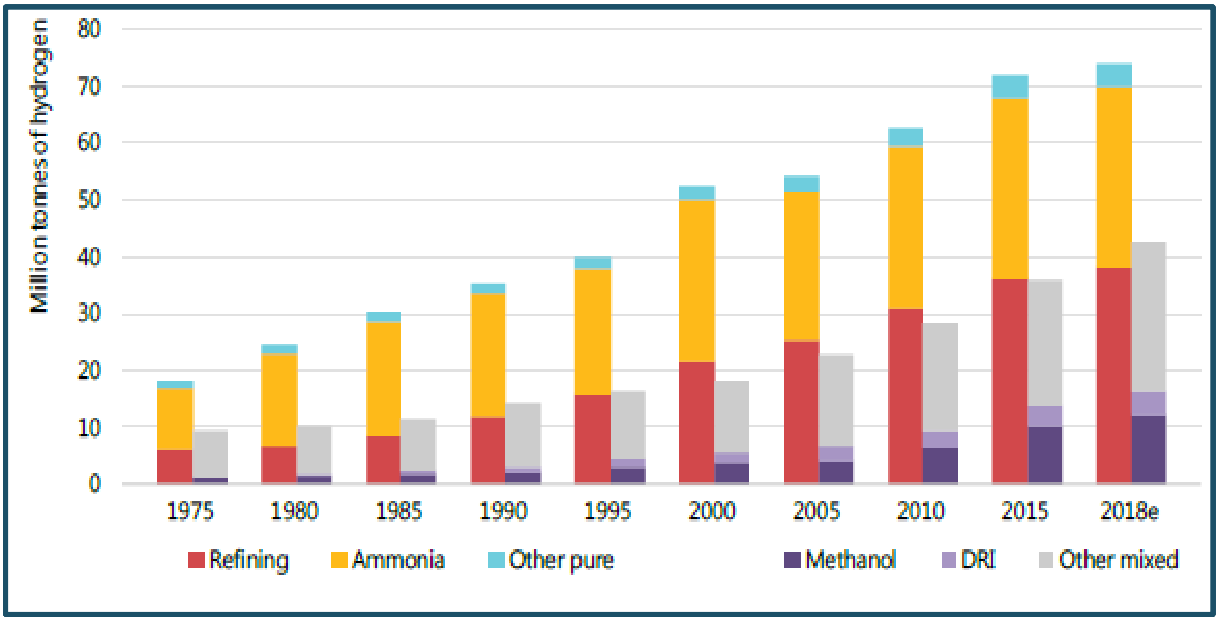
Hydrogen is produced via three main technologies – reformation, gasification and electrolysis. Reformation consists of different sub-technologies which utilise different sources of oxygen; however steam reformation is the most predominant technology and uses water (in the form of steam) and is typically applied to natural gas (IEA, 2019). Partial reformation uses air as a source of oxygen and is usually used with oil and biomass feedstocks. Then, the autothermal technology combines air and water to produce hydrogen. Gasification is a technology that is typically employed with coal or biomass feedstocks. In both reformation and gasification processes, carbon monoxide and hydrogen are created as part of a synthesis gas, and subsequently converted into hydrogen and CO_2. The production of CO_2 renders these processes as carbon intensive. Finally, electrolysis uses water and electricity to generate hydrogen by passing an electrical current through water and splitting the water into hydrogen and oxygen. Electricity inputs can be supplied via fossil fuel or renewable energy sources, and this technology is a low-carbon route when renewable energy inputs are used.

Due to the high reliance of current hydrogen production on fossil fuel inputs, hydrogen production is currently carbon intensive. The carbon intensity of hydrogen production depends on the feedstock employed: natural gas (10 tCO_2/tH_2), oil (12 tCO_2/tH_2), and coal (19 tCO_2/tH_2) (IEA, 2019). As a result of this carbon intensity, total emissions from hydrogen production equates to 830 $MtCO_2$/year associated with 70Mt of dedicated hydrogen production annually. Put in perspective, this emission intensity roughly equates to the average annual CO_2 emissions of Indonesia and the United Kingdom combined.

Current uses of hydrogen

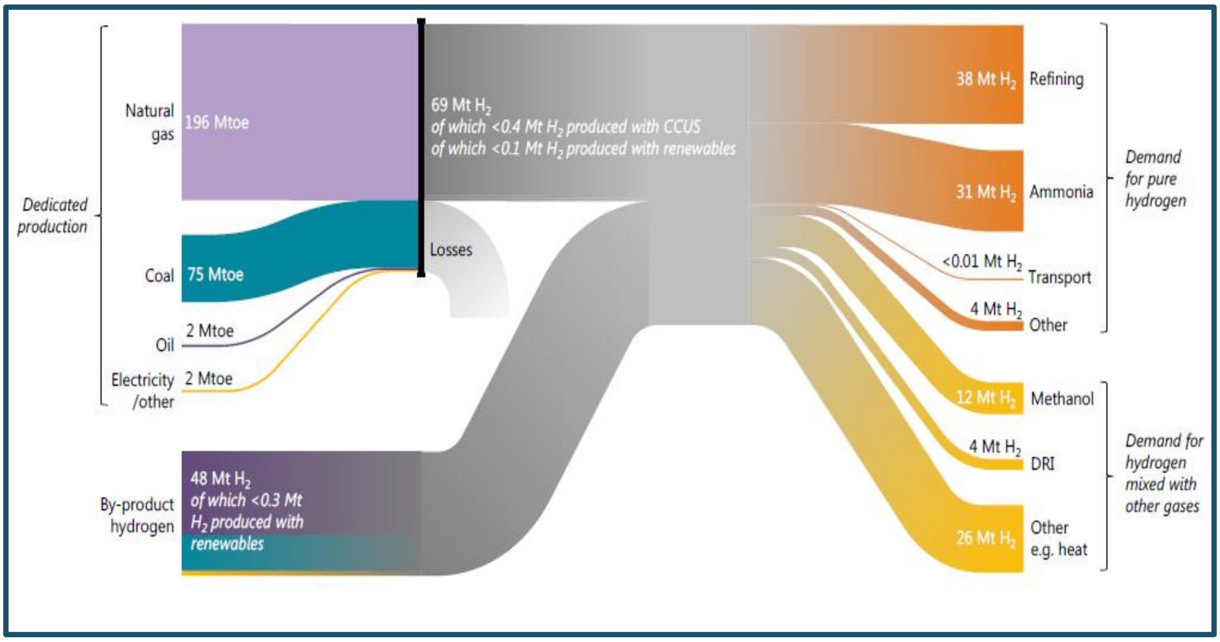
Globally, hydrogen production is currently geared towards industrial consumption. Demand for hydrogen has been growing over time with total demand in 2018 at levels three times the total demand in 1975 (see Figure 1). Major consumers include oil refining, chemical production (principally methanol and ammonia), and iron and steel production. Together, these routes of production account for about 74% of hydrogen use. In 2018, demand for hydrogen in its pure form was around 70 million tonnes a year (MtH_2/yr) (See Figure 2). This hydrogen is almost entirely supplied from fossil fuels, with 6% of global natural gas and 2% of global coal going to hydrogen production. Additionally, 45 MtH_2/yr are consumed by industries such as steel and methanol production, where separation of hydrogen from other gases is not a requisite. To put hydrogen demand into perspective, the total global hydrogen demand is about 330 million tonnes of oil equivalent a year, which exceeds the total primary energy supply of Germany (IEA, 2019).

Figure 1. Global annual demand for hydrogen, 1975-2018



Source: (IEA, 2019). *Notes:* 1. DRI = direct reduced iron for steel production. 2. Refining, ammonia and the "other pure" category represent demand for specific applications that require hydrogen with minimal additives/contaminants. 3. Methanol, DRI and "other mixed" represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock.

Figure 2. Link between global hydrogen feedstock and product value chains, 2018



Source: (IEA, 2019). *Notes:* 1. Line thicknesses are proportional to the energy contents of the flows. 2. Other forms of pure hydrogen demand include the chemicals, metals, electronics and glass-making industries. 3. Other forms of demand for hydrogen mixed with other gases include the generation of heat from steel works arising gases and by-product gases from steam crackers.

A substantial proportion of hydrogen (38%) is currently used to produce ammonia and methanol (see Table 1). Ammonia is used to produce fertilisers and explosives and represents a key input into those downstream industries. Methanol is also an important input chemical that is used in the production of polymers. Hydrogen also has applications in the refining of oil where it is used to obtain high-grade petrol and in the removal of sulphur compounds that are harmful to motor vehicles (Zohuri, 2019).

Table 1. Current major uses of hydrogen

INDUSTRIAL APPLICATION	PROPORTION OF CURRENT GLOBAL HYDROGEN USE	DESCRIPTION OF USE
Oil refining	33%	Hydrogen is used to remove impurities from crude oil and upgrade heavier crude. Hydrogen is also used for oil sands and biofuels in smaller volumes.
Chemical production	38%	Hydrogen is a key input in ammonia and methanol production. Hydrogen is also used in other smaller scale chemical processes.
Iron and steel production	3%	Hydrogen is used in the DRI route for steel production.

Source: Author based on (IEA, 2019).

In South Africa, the market for hydrogen supply is concentrated, with a limited number of hydrogen producers. Currently, hydrogen production is based on fossil fuel inputs. Sasol produces hydrogen for internal use and for sale to other firms in high and low purity forms at its Secunda facilities. Afrox also produces hydrogen for sale in the domestic market at its manufacturing plant in Pelindaba (Engineering News, 2014). The Pelindaba plant was upgraded in 2014 (at a cost of R14 million) modernising the technology. Air Liquide has a national presence, being involved in South Africa since the 1960s. Being involved in the hydrogen space, Air Liquide has set goals for reducing its carbon footprint associated with hydrogen production with the aim of producing 50% of hydrogen by carbon-free processes by 2020 (Air Liquide, 2016).

3. THE ROLE OF GREEN HYDROGEN

Green hydrogen technology routes

Over time, different terms have evolved as a means of describing the production routes for hydrogen. Future low-carbon routes consist of "green" and "blue" hydrogen. Green hydrogen refers to hydrogen produced via renewable energy-based electricity and electrolysis. Blue hydrogen generally refers to the production of hydrogen from fossil fuels (mainly natural gas) combined with carbon capture technologies. While blue hydrogen does refer to a potentially low-carbon production route, its development is contingent on the technological maturity of carbon capture solutions which are still highly capital intensive and have yet to reach wide scale commercial deployment. Despite this, many countries view the carbon capture method as a potential transitional form towards an ultimately carbon-free production through green hydrogen electrolysis.

Box 1. Sustainable properties of hydrogen

Hydrogen has two chemical properties which make it attractive from a sustainable development point of view – it has a high energy density and it is a source of clean combustion. Energy density refers to the amount of energy contained in a given volume or mass. Hydrogen contains a greater concentration of energy per unit mass when compared to fossil fuels and other sources of energy.[1] When hydrogen is combusted, it is also associated with lower air pollution when compared to conventional gasoline (Dou et al., 2017). The only waste produced from pure hydrogen is water, which results from the bonding of hydrogen and oxygen atoms (NPEP, 2017). This is attractive from an emissions point of view compared to fossil fuel sources of energy such as coal, oil and natural gas that emit higher amounts of CO_2.

[1] For example, the energy contained in a kilogram of hydrogen gas is roughly equal to the energy in 2.8 kg of gasoline (United States DOE, n.d.))

Electrolysis refers broadly to a process that utilises electrical energy to drive a chemical reaction that does not happen naturally (Chang and Goldsby, 2016). When applied to hydrogen production, electrolysis is the process of using electricity to break up water into hydrogen and oxygen (United States DOE, n.d.). The principle inputs into green hydrogen production via electrolysis are electricity and water. There are three major electrolysis technologies in use today and these differ in costs, scale and lifetime. The principal properties of each technology are indicated in Table 2.

Table 2. Electrolysis technology properties

ELECTROLYSIS TECHNOLOGY	ALKALINE ELECTROLYSIS		PROTON EXCHANGE MEMBRANE (PEM)		SOLID OXIDE ELECTROLYSIS CELL (SOEC)	
Timeframe	2019	>2030	2019	>2030	2019	>2030
Lifetime (operating hours)	60 000 – 90 000	100 000 – 150 000	30 000 – 90 000	100 000 – 150 000	10 000 – 30 000	75 000 – 100 000
Operating temperature (^0C)	60 - 80	Not available	50 – 80	Not available	650 - 1000	Not available
Electrical efficiency (%, LHV)	63 – 70	70 - 80	56 – 60	67 - 74	74 – 81	77 - 90
Plant footprint (m^2/kWe)	0.095	Not available	0.048	Not available	Not available	
Capital expenditure (US$/kWe)	500 – 1400	200 – 700	1 100 – 1 800	200 – 900	2 800 – 5 600	500 – 1 000

Source: TIPS based on (EC, 2018; IEA, 2019). *Notes:* LHV = lower heating value; m^2/kWe = square metre per kilowatt electrical. Capital costs refer to system costs and include power electronics, gas conditioning and balance of plant, where ranges reflect different system sizes and uncertainties in future estimates. *Balance of plant* refers to supporting components and auxiliary systems beyond the generating unit and includes equipment such as transformers, inverters, and supporting structures.

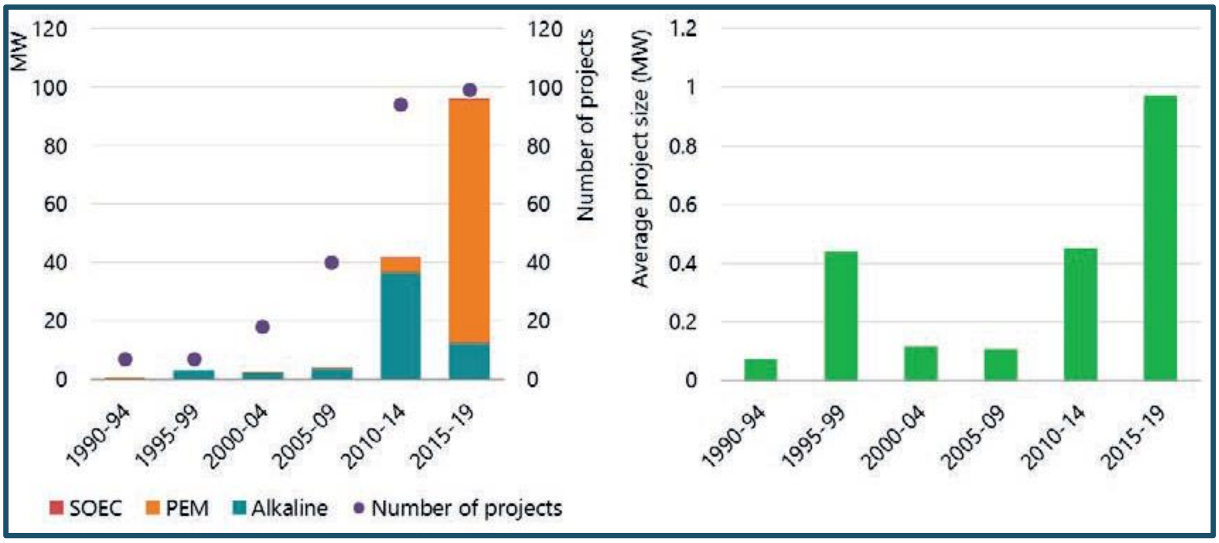
Alkaline electrolysis is the oldest electrolysis technology with the longest standing commercial viability. This technology contains two electrodes immersed in a liquid alkaline electrolyte consisting of a caustic potash solution, and has a diaphragm, which separates the product gases (Carmo et al., 2013). The technology is a typical feature in the fertiliser and chlorine industries, and generally attracts the lowest capital costs among electrolysis technologies, as it does not require precious materials as an input (IEA, 2019; Schmidt et al., 2017). Compared to other electrolysis technologies, it has the lowest capital expenditure and the longest lifetime.

Proton Exchange Membrane (PEM) electrolyser systems use a proton exchange membrane to produce hydrogen (EC, 2018). PEM electrolyser systems are a newer technology that have superior properties than older alkaline electrolysis systems in certain applications. Alkaline systems have higher costs associated with the recovery and recycling of electrolyte solutions, whereas in PEM systems pure water is used and is associated with lower costs in use (IEA, 2019). PEM systems, compared to alkaline systems, also occupy less space, are capable of compressing hydrogen to a greater degree, and offer flexible operation. This flexibility allows the system to operate with variable electricity supply, and there is evidence of PEM systems currently being the most flexible to variations in electricity supply when compared to alkaline and SOEC systems (EC, 2018). Despite these advantages, PEM systems are costlier than alkaline systems due to expensive electrode catalysts (like platinum and iridium), and the need for membrane materials. Furthermore, their lifetimes are shorter when compared to alkaline systems. The main cost drivers for PEM systems are the cost of catalysts and membranes.

Finally, Solid Oxide Electrolysis Cell (SOEC) technology is the newest electrolysis technology and is not yet in commercial operation. SOECs are electrically efficient, and typically attract low material costs, however, they are highly expensive in capital expenditure terms with shorter lifetimes compared to other electrolysis technologies. Further, these systems require heat as they operate at high temperatures and are most cost-effective when waste heat is available. This shorter lifetime is due to the use of high temperatures resulting in the materials degrading. They operate at a high temperature and use ceramic electrolytes. A unique feature of the SOEC technology that distinguishes it from other technologies is the ability of the system to work in reverse mode, allowing for hydrogen to produce electricity (EC, 2018; IEA, 2019). This feature allows for electricity generation in times when grid-based electricity is constrained. Current research and development focuses on finding new materials that can: (i) withstand the high temperatures that SOEC systems operate at, or (ii) to maintain production at lower temperatures (EC, 2018).

SOEC systems remain a very new and costly technology and most new installations favour the PEM technology.

Figure 3. Electrolyser installation by technology and electrolyser size



Source: (IEA, 2019). *Notes:* Capacity additions refer to already-installed capacity additions and are cumulated over the specified five-year periods

In terms of individual project scale, the average unit electrolyser size has increased roughly 10-fold from 0.1 MW_e in the 2000-09 period to 1.0 MW_e in the 2015-19 period, with a shift from pilot projects to commercial projects (see Figure 3). The increase in scale has motivated future project plans to consider electrolyser sizes in excess of 100 MW_e.

Cost dynamics

The unit production costs of hydrogen from water electrolysis are largely determined by capital costs, electricity costs and annual system operating hours.

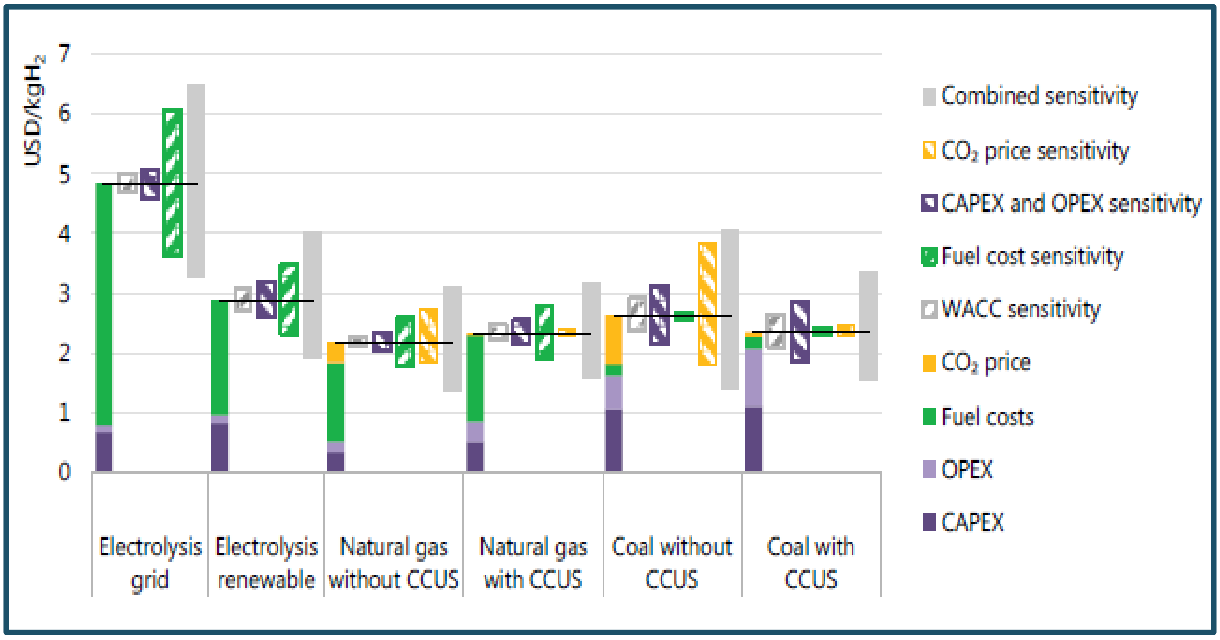
As indicated in Table 2, capital costs for alkaline, PEM and SOEC electrolysers are in the ranges of US$500-US$1 400/kWe, US$1 100-US$1 800/kWe and US$2 800-US$5 600/kWe, respectively. Based on available data, the electrolyser stack[1] is responsible for 50% and 60% of the capital costs of alkaline and PEM electrolysers, respectively. Further cost reductions are possible through the addition of more

[1] In a similar manner to fuel cells, electrolyser single cells are connected to make a cell stack. Many stacks are combined to create the entire system. See (EC, 2018; Hydrogenics, n.d.).

electrolyser stacks to increase system capacity. The ratio between costs varies depending on the number of hours that the system is operated. As electrolyser operating hours increase, the impact of capital costs declines and the impact of electricity costs increases (IEA, 2019). Accordingly, for systems that are operated for a high number of hours, low-cost electricity supply is paramount. Low-cost electricity is therefore essential for the production of low-cost hydrogen to be produced in significant volumes. With declining costs for solar photovoltaic (PV) and wind generation, the construction of electrolysers with dedicated renewable energy-based generation in regions with good renewable resource conditions, are seen as optimal for achieving a low hydrogen cost of production.

Comparing the green hydrogen route to hydrogen produced by other routes provides insight into the main cost drivers behind the technology. Figure 4 below indicates the variation in product costs based on a combination of different cost driver sensitivities. The combined sensitivity indicates the total production cost variation for the given technology route.

Figure 4. Production costs of different hydrogen production routes



Source: (IEA, 2019, p. 52, Figure 16), *Notes*: 1. WACC = weighted average cost of capital 2. Assumptions refer to Europe in 2030. 3. Renewable electricity price = US$40/MWh at 4 000 full load hours at best locations 4. Sensitivity analysis based on +/-30% variation in CAPEX, OPEX and fuel costs 5. +/-3% change in default WACC of 8% and a variation in default CO_2 price of US$40/t$CO_2$ to US$0/t$CO_2$ and US$100/t$CO_2$

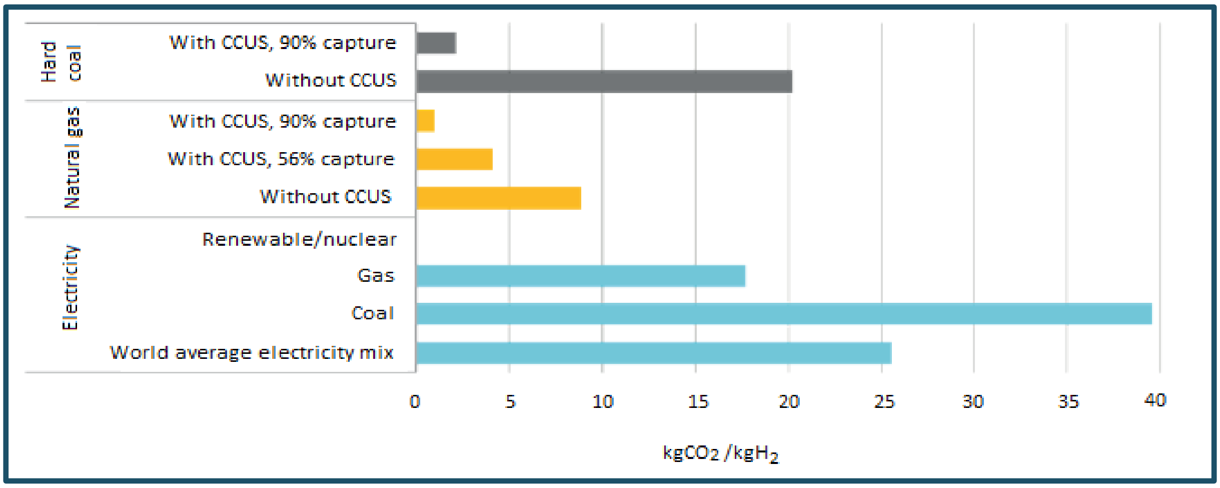
It is estimated that over the next decade (up until 2030), hydrogen production from natural gas (without carbon capture, utilisation and storage – CCUS), which is the current predominant method of global hydrogen production, will persist as the cheapest production option, ranging between US$1/kg$H_2$ and US$3/kg$H_2$ based on the combined sensitivity, and primarily depending on the local gas price. This technological route is also sensitive to carbon emissions and the associated carbon emissions price.

The production cost evolution of electrolytic hydrogen will primarily depend on fuel costs, which relate to the cost of electricity. Renewable energy-based electrolysis attracts cheaper production costs due to the lower cost of electricity. In addition, the number of full load hours with electrolysis impacts on capital expenditure costs which in turn impact on production costs.

Carbon intensity of production routes

There is a wide variation in greenhouse gas (GHG) emissions when comparing the different hydrogen production routes (Figure 5). The CO_2 intensity of electrolysis varies based on the source of electricity. Electrolysis based on renewable energy does not generate carbon emissions. Due to conversion losses, electricity-based hydrogen production from fossil-fuel sources produces higher CO_2 emissions when compared to the direct use of fossil fuels to produce hydrogen. Given this technical feature, the CO_2 intensity of electrolysis needs to be limited to below 185 gCO_2/kWh generated for the CO_2 emissions of electrolysis to be comparable to hydrogen production based on natural gas without CCUS. This level of CO_2 intensity equates to approximately half the emissions of a modern combined-cycle gas power plant. In other words, a low carbon source of electricity is necessary for electrolysis to produce lower amounts of CO_2 compared to the existing natural gas route without CCS.

Figure 5. Carbon emissions by hydrogen production route



Source: (IEA, 2019, p. 53, Figure 17) *Notes:* 1. Capture rate of 56% for natural gas with CCUS refers to capturing only the feedstock-related CO_2, whereas for 90% capture rate CCUS is also applied to the fuel-related CO_2 emissions 2. CO_2 intensities of electricity take into account only direct CO_2 emissions at the electricity generation plant: world average 2017 = 491 gCO_2/kWh, gas-fired power generation = 336 gCO_2/kWh, coal-fired power generation = 760 gCO_2/kWh. 3. The CO_2 intensities for hydrogen do not include CO_2 emissions linked to the transmission and distribution of hydrogen to end users.

From a sustainability perspective, another factor to take into account is the water intensity of hydrogen productions routes. Green hydrogen is associated with a higher water intensity when compared to steam reformation using natural gas, equating to approximately 1.3 times the water intensity of the traditional steam methane reforming route of hydrogen production (IEA, 2019).

Green hydrogen products

Hydrogen can be used as an input for a number of potential low-carbon products. Product opportunities can be segmented in low-carbon industrial uses, where it dominates today, and future uses in transport, buildings and power generation, where not much hydrogen is used currently.

Decarbonising current industrial use

Industrial use of hydrogen is currently predominantly devoted to oil refining, chemical production, and iron and steel production. Within each of these uses, low-carbon pathways are possible using low-carbon green hydrogen routes.

Demand for hydrogen in oil refining depends on a number of complex factors. These include the overall demand for oil and its outlook, the extent to which environmental regulations increase the quantity of hydrogen in fuels for lower sulphur content, and the quality of crude oil in the market. The

International Energy Agency (IEA) predicts that overall demand for oil can be mostly[2] met with existing refinery capacity up until 2030, indicating that low-carbon modifications to existing refineries appear to be the least-cost hydrogen production route. This would necessitate the retrofitting of existing refineries with carbon capture technologies, which is viewed as a transition route to full green hydrogen production. The lack of a sufficient carbon price to warrant investment in carbon capture technologies combined with complexities around the commercial viability and offtake consumers for CO_2 complicate this low-carbon route. Despite these complications, the retrofitting of existing refineries is still regarded as a low-cost route compared to setting up new and dedicated green hydrogen production for oil refining. This option is the route to green hydrogen development in the EU until 2030, for example, as indicated in the EU Hydrogen Roadmap (2020).[3]

Despite this view, some refineries are already planning to invest in dedicated electrolytic capacity. For now, these investments are planned in Europe. Shell, in partnership with ITM Power, has announced a 10 MW PEM electrolyser project for 2020 at its Rheinland Refinery in Germany, which intends to replace gas-based supply (1 ktH_2/year) to meet approximately around 1% of the refinery's hydrogen needs. This project is intended to test the technology and be scaled up if successful (Shell, 2019). Heide, a small refinery in Germany, has also announced a large 30 MW electrolyser combined with offshore wind power to substitute purchases of up to 3 ktH_2/year. It has developed the project in conjunction with ThyssenKrupp Industrial Solutions, and plan to scale the project to a 700 MW plant after a period of five years of successful operation (Raffinerie Heide, 2019). BP, Nouryon and the Port of Rotterdam Authority are conducting a feasibility analysis for a 250 MW electrolysis plant that can produce 45 ktH_2/year for the BP refinery in Rotterdam (Nouryon, 2019).

Within chemicals production, hydrogen is the essential input into ammonia and methanol production and is used in several other smaller-scale chemical processes. Based on IEA estimates, the demand for hydrogen for chemicals is expected to rise from 44 Mt/yr in 2019 to 57 Mt/yr by 2030. This is attributed to an increased demand for ammonia (mainly used in fertilisers) and methanol. An important determinant of the future demand for ammonia is based on the extent to which hydrogen-based products such as ammonia and methanol become energy carriers for hydrogen. When hydrogen is transported via ship for example, it has to be compressed or changed in form to ease transport. Increased trade in hydrogen and the adoption of ammonia-based transport could increase growth in hydrogen production further than estimated.

A number of initiatives are currently in development to integrate green hydrogen production in chemicals. Yara, the world's largest ammonia producer, announced in early 2019 a collaboration with energy company ENGIE to conduct a feasibility study of integrating electrolysis-based hydrogen into its existing operations in Australia (Yara, 2019). More recently, in October 2020, the two firms announced a green ammonia project in the Netherlands (Yara, 2020). Feasibility studies that have a strong chemicals focus also include projects in the Chilean regions of Antofagasta and Atacama (IKI, 2018) to develop the hydrogen value chain, and in Morocco, where the Moroccan fertiliser producer OCP Group has signed a Memorandum of Understanding (MoU) with German research organisation, Fraunhofer, to increase renewables-based hydrogen and ammonia production (World Fertiliser Magazine, 2018). Work is also being undertaken in Iowa in the United States in farming applications to produce ammonia using hydrogen from solar-powered electrolysis for use as a fertiliser and a tractor fuel (Schmuecker Pinehurst Farm LLC, 2018).

[2] The IEA estimates that 80%-90% of supply can be met with dedicated on-site production and merchant procurement.

[3] See (FCH, 2019)

Hydrogen is used in iron and steel production and the source of hydrogen differs by the production route. There are two primary production methods for steel at present: the blast furnace-basic oxygen furnace (BF-BOF) route, and the direct reduction of iron-electric arc furnace (DRI-EAF) route. BF-BOF accounts for approximately 90% of global steel production, while DRI-EAF accounts for approximately 7% of global steel production (IEA, 2019). BF-BOF typically relies on coal as an input and hydrogen is produced within the process as a by-product, which is then used within the industry or sold to other industries. Decarbonisation of this route focuses on the application carbon capture technologies to the production process. This contrasts with the DRI-EAF route which requires hydrogen produced externally and fed into the process. Here, green hydrogen production can substitute for dedicated hydrogen production that occurs and is fed into the process. In the DRI-EAF route, approximately 75% of the hydrogen is generated from natural gas while the remaining 25% uses coal. Given that externally generated hydrogen is required for the DRI-EAF route, the demand for green hydrogen in the future of steelmaking will arise from demand for steel from the DRI-EAF route, since green hydrogen production can easily substitute for current production that relies on dedicated hydrogen production from natural gas and coal. Given the projected increased demand for steel for construction and development, the demand for steel from the DRI-EAF route is expected to double from the current 7% in 2019 to 14% in 2030, increasing the demand for dedicated hydrogen (IEA, 2019).

Integrating green hydrogen into iron and steel production is being spearheaded by a number of initiatives globally. The HYBRIT joint venture in Sweden is exploring the feasibility of hydrogen-based steelmaking, using a modified DRI-EAF process design that relies green hydrogen (HYBRIT, n.d.). The project is in the pilot phase, with commercial production expected to begin in 2036. The SALCOS venture is another project in Germany which combines natural gas with hydrogen generated from wind power also using a modified DRI-EAF route for production of iron and steel (SALCOS, n.d.). Unlike the HYBRIT project, the SALCOS project begins with natural gas supplementation with the eventual view of transitioning to complete green hydrogen use in the future. Another notable development in the integration of green hydrogen with steelmaking includes using ammonia to produce steel in Japan. The technology currently functions at laboratory scale, however, it is deemed to be revolutionary should commercial viability be proven (IEA, 2019).

New opportunities – transport, buildings and power generation

A number of new applications for green hydrogen have emerged in sectors beyond the traditional industrial markets in which hydrogen supply is typically required. New applications appear in the transport, buildings and power generation industries.

Transport applications involve the use of hydrogen-based Fuel Cell Electric Vehicles (FCEVs) that use hydrogen as an input to drive electric motors. FCEVs offer attractive options for long-distance driving as other types of EVs, such as electric battery-based cars, become less competitive beyond 400 -500 km of travel (IEA, 2019). FCEVs are closer to internal combustion vehicles in driving range and refueling patterns. While much attention has been placed on FCEVs for cars, hydrogen can be applied to heavy-duty vehicles such as trucks, buses and forklifts. In other modes of transport such as maritime and aviation, which have thus far been difficult to decarbonise, hydrogen offers a route to further carbon mitigation. In shipping, hydrogen, ammonia (from green hydrogen) or hydrogen-based synthetic fuels can substitute for heavy fuel oil that is currently associated with high-carbon emissions and poor air quality.

Hydrogen offers solutions in building heating with blending and pure hydrogen-based heat generation (IEA, 2019). Short- to medium-term options involve the blending of hydrogen with existing natural gas pipelines. This reduces the carbon emissions associated with the combustion of natural gas, provided that the hydrogen is produced through a low-carbon route, such as electrolysis with renewable energy. Longer-term solutions involve using pure hydrogen in boilers or fuel cells and would require investment into infrastructure upgrades.

In the domain of power generation, hydrogen and hydrogen-based products (e.g. ammonia) cannot be produced only from renewable resources but can also act as an energy source to produce electricity. The ability to store hydrogen and generate power when required assists with the energy storage problem currently associated with variable renewable energy technologies that depend on climate conditions, such as solar PV and wind generation. During periods when electricity supply exceeds demand, excess electricity can be used to drive hydrogen production or hydrogen products such as ammonia, which store energy. While pure hydrogen or hydrogen-product-based large-scale electricity production is being developed, in the short term, the co-firing of ammonia based on hydrogen in coal-fired power plants reduces the CO_2 emissions from coal-based electricity. Hydrogen and ammonia can also be used in gas turbines or fuel cells in peaking/flexible generation options. In the longer term, power generation based exclusively on hydrogen or hydrogen-based products can provide energy security, when combined with hydrogen storage.

4. HYDROGEN ACTIVITY IN SOUTH AFRICA

Public sector

In 2008, the Department of Science and Technology launched a 15-year Hydrogen and Fuel Cell Technologies Research, Development, and Innovation strategy to guide the development of the hydrogen economy. Hydrogen South Africa (HySA) was born out of this initiative and consists of three competence centres. HySA's overall aim is to develop the hydrogen economy with a distinct focus on drawing in platinum group metals (PGMs) into the technology, given South Africa's resource endowment of PGMs.

The three competence centres each have a differing focus: HySA Infrastructure, HySA Systems and HySA Catalysis (SAASTA, n.d.):

- HySA Infrastructure is a collection of resources from North West University and the Council for Scientific and Industrial Research (CSIR), and focuses on developing hydrogen production technologies, distribution, and storage. HySA Infrastructure has also been successfully operating a solar-to-hydrogen system since 2013 (Engineering News, 2019a).
- HySA Systems is based at the University of the Western Cape and focuses on the development of high-temperature membrane electrode assemblies (MEAs), hydrogen purifiers, solid state hydrogen storage and compressors (metal hydrides), batteries, and other electrical devices. HySA Systems is also responsible for technology validation and system integration involving end-users.
- HySA Catalysis is a collaboration between the University of Cape Town and Mintek and focuses on the development of fuel cell catalysts, low-temperature MEAs and fuel processors.

In 2018, HySA indicated its intention to begin looking into manufacturing capability around hydrogen technologies to grow the domestic hydrogen fuel cell market (SAASTA, n.d.). HySA is currently conducting a study to determine the costs to transport hydrogen by land and sea, including shipping to Japan (Polity, 2019). Furthermore, it is investigating the time within which it is feasible for South Africa to competitively export hydrogen to Japan, a potential high-demand hydrogen export partner. An offtake agreement with Japan would be required to make the necessary investments into infrastructure. The ultimate goal of the HySA strategy is to enable South Africa to supply 25% of global PGM-based catalyst demand for the hydrogen and fuel cell industry by 2020 (NPEP, 2017). More recently, since July 2020, the Department of Science and Innovation (DSI) in co-ordination with HySA is developing a hydrogen roadmap for South Africa with other government and industry stakeholders (Mining Weekly, 2020).

Another policy process that involves the development of the hydrogen economy is the South African Renewable Energy Masterplan (SAREM) process for industrialisation of the renewable energy sector, currently being spearheaded by the Department of Trade, Industry and Competition (the dtic). The process is based on extensive stakeholder consultation in developing an industrialisation plan for renewable energy. Given the complexities of the energy sector, which is facing adjustments and transitions in various forms, the SAREM employs a scenario planning approach for development. The development of green hydrogen features one of the possible industrialisation scenarios[4] likely to play out. Importantly, it is acknowledged in the SAREM that a combination of scenarios is likely.

DSI also networks with international experts on the hydrogen economy to understand the potential role that South Africa can play in the global hydrogen economy and develop the domestic industrial capabilities to feed into these markets. DSI and the South African Agency for Science and Technology Advancement (SAASTA) hosted the 30th International Partnerships for Hydrogen and Fuel Cells in the Economy (IPHE) Steering Committee Meetings in Pretoria from 4 to 7 December 2018. IPHE encourages global collaborations to accelerate progress and widespread penetration of Hydrogen Fuel Cell (HFC) technologies across sectors. The partnership has a clear focus on energy security, improved resilience, emissions reduction, and economic prosperity. Members of the partnership collectively invest about US$1 billion a year in HFCs. The event also included site visits by global experts to Mintek, the Mineral Council of South Africa, Impala Platinum Refineries, Poelano High School, HySA Infrastructure Centre of Competence, North West University and Mponeng Mine (SAASTA, n.d.).

There has also been high-level national government interest in the hydrogen economy. President Cyril Ramaphosa and then Minister of Science and Technology Naledi Pandor attended the Japan South Africa hydrogen and fuel cell symposium, where the president operated a HFC vehicle (Engineering News, 2019a). At an Impala Platinum launch of a fuel cell forklift and hydrogen refilling station in Springs, Minister Pandor expressed support for South Africa to investigate hydrogen distribution. The President's economic adviser, Trudy Makhaya, has expressed support for the hydrogen economy development, indicating that the hydrogen economy had many positives in its favour (Engineering News, 2019b).

Beyond the exclusive consideration of the hydrogen value chain, the just transition framework[5] and narrative has surfaced as arguably South Africa's most major developmental challenge in the medium to long term. Pressure is growing on the country to depart from coal-based electricity and petrochemical production, and the just transition framework intends to support the most vulnerable in society, particularly the vulnerable local municipalities in Mpumalanga. Eskom and Sasol, as the two major upstream providers of electricity and petrochemicals respectively, are considering future opportunities for displaced workers, communities and small businesses, and both are considering the potential for green hydrogen as part of a just transition policy.

[4] The scenario is termed the "High road" and involves a major economic restructuring and leveraging demand growth through catalytic opportunities, based off the September 2020 SAREM inception report. This was referred to as the "Full policy flexibility" scenario in previous versions. See (dtic et al., 2020)

[5] The just transition refers the developmental imperative of shielding the most vulnerable in society during structural economic transitions and providing opportunities for these groups in the transition.

Private sector

South Africa also has technological capabilities related to the hydrogen economy through private firms.

Through Sasol, South Africa has the skills and expertise in the FT process, which is required for the conversion of hydrogen into liquid fuels. Access to this expertise places South Africa at a unique advantage for producing liquid fuels from hydrogen.

Private mining firms have also supported initiatives to develop the hydrogen economy. This is presumably due to their future demand for PGMs being highly vulnerable to demand-side impacts. These impacts include the transition away from internal combustion engines vehicles, which use PGMs, and the increased incidence of platinum recycling cannibalising demand for virgin platinum. Impala Platinum Holdings (Implats) has injected R6 million into HySA Systems for fuel cell prototype development in mining applications. These applications concern material handling and underground mining equipment (NPEP, 2017). Implats have also supports HySA Catalysis through supplying platinum for South African-developed fuel cell catalysts that are to be scaled up. Anglo American Platinum installed standby power based on fuel cells in selected schools in the Eastern Cape (NPEP, 2017). In 2015, Anglo American Platinum in partnership with the Young Engineers and Scientists of Africa (YESA) group and SAASTA through HySA developed an education programme about the science of fuel cells that was rolled out to schools in Cofimvaba (NPEP, 2017). About 3 500 learners across all levels of schooling in the Eastern Cape had contact with the programme.

Isondo Precious Metals is investigating the manufacture of MEA at the proposed OR Tambo International Special Economic Zone at Johannesburg International Airport (Polity, 2019). MEAs are the core components of electrolysers and fuel cells. Isondo is currently seeking capital to fund its local manufacturing plans and believes that South Africa's endowment of sunlight, wind, platinum and base metals can be combined within a value chain to offer a pathway to future sustainable growth.

CHEM Corporation, a Taiwanese manufacturer and distributor of electric solutions, is expected to build a fuel cell manufacturing plant in in KwaZulu-Natal through its subsidiary, CHEM Energy South Africa. Telecommunications network provider Vodacom has used CHEM's fuel cell solutions for its South African network since 2011. CHEM's latest fuel cell product provides greater reliability than batteries or diesel generators at a lower cost and with lower emissions.

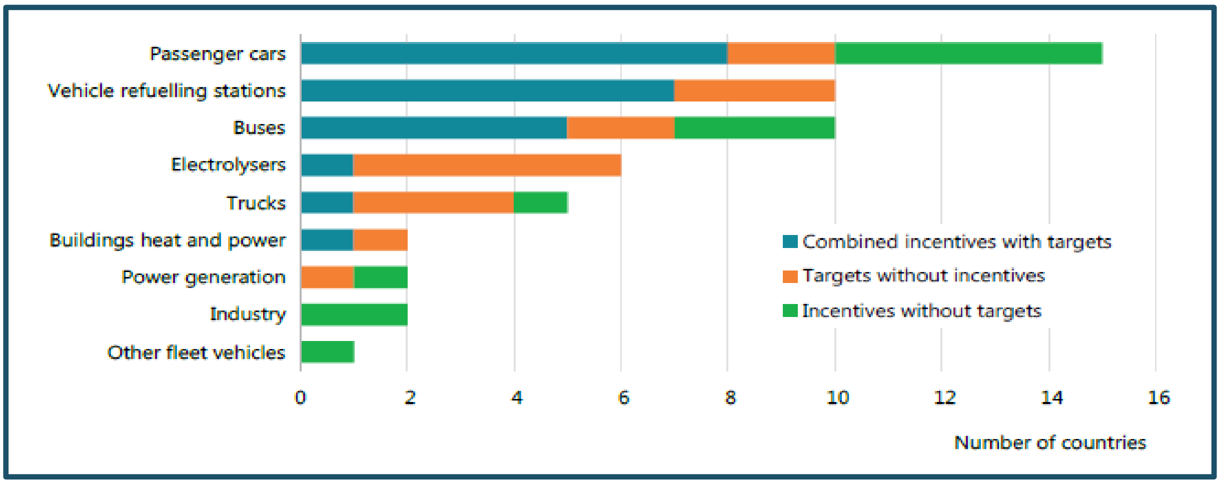
The Minerals Council of South Africa has also included the hydrogen economy and fuel cell industrial development in South Africa in its National Platinum Strategy as a potential source of demand for platinum, given the current but shrinking glut of platinum in global markets, and the pressure on platinum miners as a result (Engineering News, 2019c).

Hydrox Holdings in a South African company that is investigating using acid mine drainage water to produce hydrogen at a price competitive with the petrol price (Polity, 2019). As part of its strategy, Hydrox Holdings wants to increase the penetration of hydrogen as a fuel source. Hydrox has also developed a divergent electrode flow-through electrolyser technology that can operate at higher temperatures than conventional systems, owing to the absence of membranes. This membrane-free system targets hydrogen production at a cost of below US$7.5/kg.

5. DEMAND FOR GREEN HYDROGEN

A number of countries have been developing and enacting policy to support the hydrogen economy through the formulation of strategies, setting targets and incentivising hydrogen research and development, pilot projects and infrastructure. By mid-2019, a combined total of 50 targets, mandates and policy incentives were in place globally in support of the hydrogen economy (IEA, 2019). Countries are beginning to place themselves in global hydrogen value chains and signal to the market their intentions related to the import, production, or export of hydrogen. Countries have been driven by the increased cost-competitiveness of hydrogen, the search for further decarbonisation options and energy security concerns. Among the Group of Twenty (G20) and the European Union, 11 have such policies in place and nine have national roadmaps for hydrogen energy.

Figure 6. Hydrogen policies and sectoral decomposition

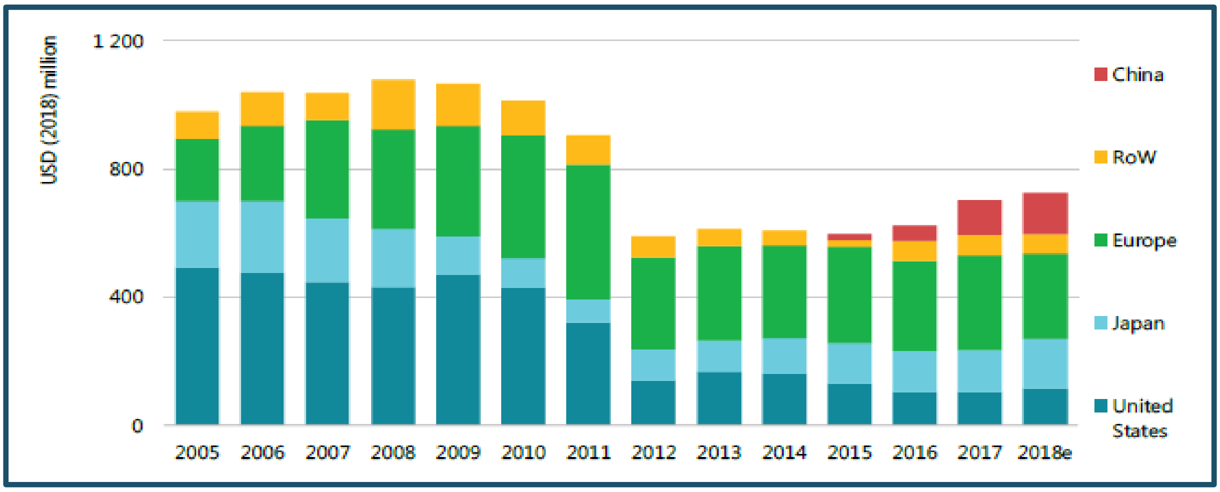


Source: (IEA, 2019, p. 20, Figure 2).

In addition, countries have incorporated a range of policy tools to drive the hydrogen economy. They include funding mechanisms, targets for hydrogen applications, subsidy mechanisms, investment funds, and tax credit schemes (see Appendix for a list of country developments, development focus and policy tools to date).

The interest in the hydrogen economy is further emphasised by examining the research and development (R&D) spend by countries on hydrogen and fuel cells.

Figure 7. R&D budgets for hydrogen and fuel cells by country/region



Source: (IEA, 2019, p. 20, Figure 3) *Notes:* 1. Government spending includes European Commission funding, but does not include sub-national funding. 2. 2018e = estimated; RoW = rest of world

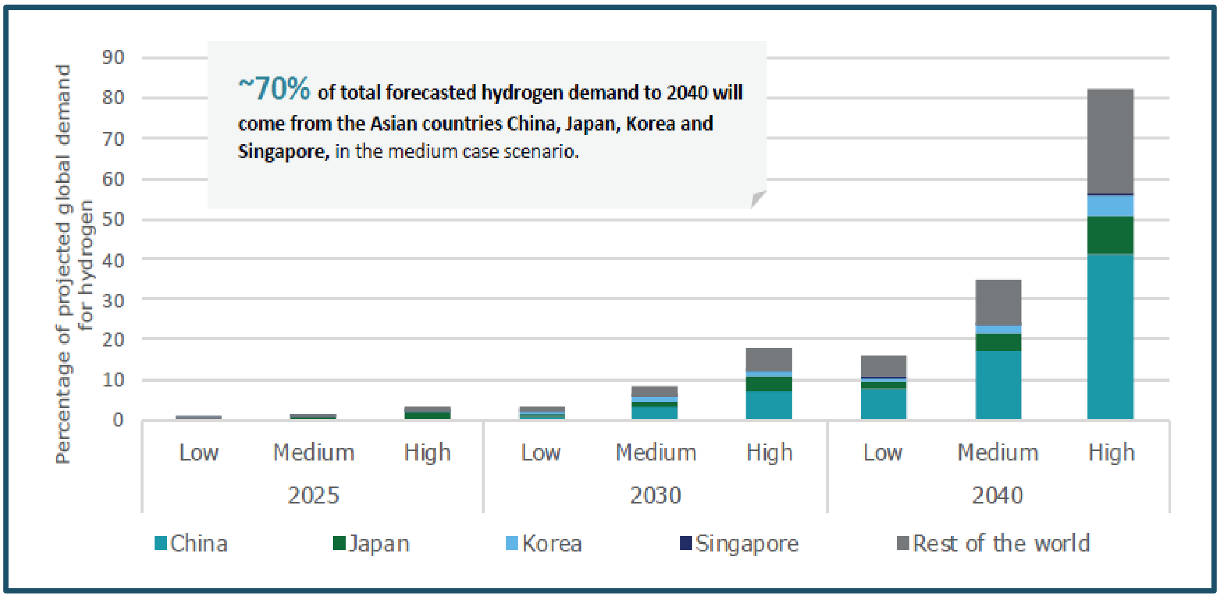
As indicated in figure 7, hydrogen interest and investments have fluctuated over time.

In the early 2000s hydrogen investments were driven by concern over climate change through investments mainly in the transport sector over debates about peak oil approaching. After these early investments, lack of momentum due to the need for the co-development of infrastructure and vehicles prevented the substantial uptake of technologies. From 2010 three principal factors drove the decline in interest in hydrogen development, mainly from the United States. The peak oil narrative began to fall out of favour, battery electric vehicles saw greater development due to their lower infrastructure needs in comparison to hydrogen vehicles, and uncertainty began to surface around climate policy developments.

More recently, since 2012, a renewed interest in hydrogen has manifested. Countries have begun devoting greater resources to hydrogen development. Much of this funding has been driven by the EU, Japan and the United States historically, with China increasing funding from 2015 onwards. The latest interest in hydrogen is more strongly motivated, compared to previous waves of interest, on the basis of four significant factors. First, there is a strong global focus on the deep emissions reductions that hydrogen can help deliver, particularly in sectors that are difficult to decarbonise, such as petrochemicals. Second, hydrogen is regarded as able to fulfil a wide range of policy objectives that include energy security, local air pollution, economic development, and energy access. Third, hydrogen has synergies with renewable electricity generation, in that hydrogen can act as an energy storage vector for electricity produced from renewables. Finally, the successful investment momentum generated from other sustainable technologies such as solar PV and wind generation, and electric vehicles, places hydrogen in good stead as a future industry benefitting from private capital. In these industries, initial support was provided by the state but as they grew and were profitable, they attracted private capital and became self-sustaining industries.

While countries are developing policies and channeling funding towards the development of the hydrogen economy, three large potential demand sources emerge for the medium term (next 10 years), namely Japan, South Korea and the EU.

Figure 8. Hydrogen demand



Source: (Deloitte, 2019).

Japan

Japan represents a key potential demand destination for green hydrogen and has made substantial developments around increasing the use of hydrogen in its economy and scaling the hydrogen economy globally. In 2014, the Strategic Roadmap for Hydrogen and Fuel Cells was developed and, in 2017, Japan developed its Basic Hydrogen Strategy which aimed to identify actions for implementation by 2030 to develop the hydrogen economy in Japan until a 2050 time horizon (METI, 2017a). The Strategic Roadmap for Hydrogen and Fuel Cells was later updated to include new targets on basic technology specification and costs; interventions for achieving these targets; and the country's intention to convene an expert working group to review the implementation status of the Roadmap (METI, 2019). Japan also hosted the first Hydrogen Energy Ministerial Meeting in October 2018, a global ministerial-level meeting that drew together 21 countries along with private sector players. The meeting culminated in the release of the joint Tokyo Statement which represented a shared view by countries that hydrogen contained the potential to be a key energy carrier that would support a transition to a clean energy future, and be a vital component of countries' energy portfolios (METI, 2018).

Table 3. Japan's Basic Hydrogen Strategy elements related to imported hydrogen demand

STRATEGIC ELEMENT	DESCRIPTION
Utilising overseas unused energy and renewable energy	Substantial quantities of hydrogen can be imported to develop hydrogen value chains. Japan will develop commercial-scale supply chains by 2030 to procure 300 000 tons of hydrogen annually. Demand for hydrogen will then be ramped up through the development of FCEVs and hydrogen power generation.
Developing international hydrogen supply chains	Japan will develop supply chains for hydrogen and hydrogen-based energy carriers such as liquid hydrogen, methylcyclohexane, ammonia and methane.
Renewable energy expansion in Japan and regional revitalisation	From 2020, Japan will promote the commercialisation and installation of power-to-gas systems to store surplus electricity from renewable energy, with the aim of commercialising power-to-gas systems by 2032.
Hydrogen use for power generation	The commercialisation of new combustion technologies to simultaneously achieve NOx reduction, higher generation efficiency, and high-density combustion of hydrogen and natural gas will be pursued. Power generation is seen as a key to achieve scale with demand for hydrogen at 300 000 tons by 2030 (1GW capacity) and ramped up to five to 10 million tons per annum beyond 2030 (15-30GW).
Hydrogen use in mobility	Japan aims to increase the number of FCEVs in the country to 40 000 units by 2020, to 200 000 units by 2025, and to 800 000 units by 2030. Japan also aims to expand the number of domestic hydrogen stations to 160 by FY2020 and to 320 by FY2025 and make hydrogen stations independent by the second half of the 2020s. Mobility development also includes renewable energy-based hydrogen stations, fuel cell buses, fuel cell forklifts, fuel cell trucks, and fuel cell ships.

STRATEGIC ELEMENT	DESCRIPTION
Potential hydrogen use in industrial processes and heat utilisation	The substitution of industrial processes (steelmaking and oil refining) produced from fossil fuels with CO_2-free hydrogen to reduce CO_2 emissions.
Fuel cell technologies	Japan will attempt to lower the prices of standard polymer electrolyte fuel cell and standard solid-oxide fuel cell (to shorten the investment recovery period to seven to eight years) by around 2020. Japan will also aim to shorten the investment recovery period to five years by around 2030.

Source: TIPS, based on (METI, 2017b).

Provision is made in the Basic Hydrogen Strategy for the importation of green hydrogen based on renewable energy generation, from countries which have good renewable energy resources and are able to produce hydrogen competitively (METI, 2017b). Hydrogen is seen as a decarbonisation option in the Japanese economy with applications as a storage medium for power generation; with fuel cells for mobility solutions; a feedstock for industrial processes and heat; and for use in fuel cells for power generation.

The Development Bank of Japan is part of a consortium of companies which launched Japan H2 Mobility, a company that targets the building of 80 hydrogen refuelling stations by 2021 and aims to act as a catalyst for hydrogen demand in Japan. Further, the Green Ammonia Consortium was launched in 2019 to establish a value chain involving hydrogen-based ammonia. The consortium conducts studies on technological and economic assessments, and develops policy proposals for hydrogen development. In March 2019, the first import of green hydrogen into Japan was sourced from Australia in a proof of concept test arranged between the Queensland University of Technology and the then large Japanese petroleum conglomerate, JXTG (QUT, 2019). This arrangement further solidified Japan's commitment to green hydrogen as a key decarbonisation option. More recently, Japan announced a strong focus on the development of green hydrogen and carbon capture technologies through stimulus recovery packages in response to the COVID-19 crisis (Farand, 2020).

South Korea

South Korea's National Basic Plan for New and Renewable Energies was formulated in 2014. It aimed for the country to invest in excess of US$2 billion on hydrogen infrastructure, manufacturing and technology. In October 2019, the National Roadmap of Hydrogen Technology Development was published. It plans for the development of fuel cell technologies and hydrogen in South Korea (IPHE, 2020). The Roadmap focuses on hydrogen development in power, transport, industry, buildings, and industrial feedstock applications. The Roadmap channeled investments into long-term preliminary feasibility studies in technology development for hydrogen and fuel cells; the deployment of FCEVs (cars and buses) and hydrogen refuelling stations, development of the Hydrogen Model City[6] infrastructure and technology, and the promotion of innovative hydrogen energy technologies.

[6] The hydrogen city model refers to pilot smart cities that are entirely powered by hydrogen. See (WEF, 2019).

Table 4. Demand for hydrogen based on the National Roadmap of Hydrogen Technology Development

	2018	2022	2030	2040
Total hydrogen demand (Mt/annum)	0.13	0.47	1.94	5.26
Source of supply	By-product hydrogen (1%) Hydrogen extraction from LNG (99%)	By-product hydrogen Hydrogen extraction Water electrolysis	By-product hydrogen Water electrolysis (50%) Imported Hydrogen Extraction from LNG (50%)	By-product hydrogen Water electrolysis (70%) Imported Hydrogen Extraction from LNG (30%)
Imputed import demand (Mt/annum)	–	–	0.32	1.23

Source: TIPS, based on (Government of Korea, 2019) *Notes:* Imputed import demand is calculated based on total demand from all sources and estimated proportion of import demand. Import demand percentages are estimated assuming an equal distribution for by-product hydrogen, domestic water electrolysis and imported hydrogen from 2030 onwards, in the absence of available data.

Demand for hydrogen in South Korea is expected to rise to 5.26 Mt in 2040, from a current base of 0.13 Mt. Demand is anticipated to slowly rise until 2030, followed by a sharp rise after 2030, driven by investments, technological advancement, customer adoption and cumulative end-user equipment purchases. High demand is expected from transport and buildings, with South Korea leveraging its existing capabilities in stationary and mobile fuel cell applications. The Roadmap allows for the import of green hydrogen from countries with good renewable energy resources, such as Australia and Canada. The import of hydrogen is seen as an opportunity beyond 2030 to stabilise the domestic hydrogen prices and saving resources related domestic investment in hydrogen production infrastructure. From 2022, the Roadmap plans for the development of infrastructure and technology related to the import of hydrogen, such as liquefaction technology, transportation vessels, and liquefaction plants, as well as the construction of hydrogen production bases out of the country (Government of Korea, 2019).

More recently, the country saw further development in the hydrogen economy. In January 2020, the Hydrogen Economy Promotion and Hydrogen Safety Management Law was passed which formed the Hydrogen Economy Committee and provided a legal basis for state support to hydrogen-specialised companies and education programmes (IPHE, 2020).

European Union

Developments in the EU point towards the region being a potential offtaker of green hydrogen. The recently released Hydrogen Roadmap Europe (2020) sets the scene for the development of the hydrogen economy in Europe. The Roadmap adopts an ambitious view of hydrogen development, with plans to install 6 GW of renewable energy-based hydrogen electrolysers by 2024 and 40 GW by

2030. While the Roadmap does not specify specific import volumes, integral to the EU's approach is the engagement with regional and international partners to diversify supply and to ensure stable and secure supply chains (European Commission, 2020).

The EU intends to actively promote new opportunities for co-operation on clean hydrogen and contribute to sustainable energy transitions, and identifies Africa as a region with high renewable energy potential and a potential supplier to the region. Through the Africa-Europe Green Energy Initiative, the European Commission plans to support awareness raising of clean hydrogen opportunities among public and private African partners, including joint research and innovation projects. The Roadmap also acknowledges the potential for decarbonisation requirements and hydrogen development being tied to state recovery packages within the EU.

In sectors with limited options for decarbonisation, such as aviation, EU Member States have attached strict mitigation regulations to COVID-19 rescue packages and state recovery support.

In France and the Netherlands, support packages for COVID-19 were provided on the basis that Air France and KLM airlines halve their CO_2 emissions by 2030 (Fortune, 2020). Hydrogen offers the only technically possible route to that degree of carbon mitigation if these airlines are to stay running and grow, which point to further national-level demand for hydrogen. Further, recent French funding to the aerospace sector saw an obligation on the sector to ringfence 10% of a US$16.8 billion package towards developing a hydrogen-powered plane by 2035.

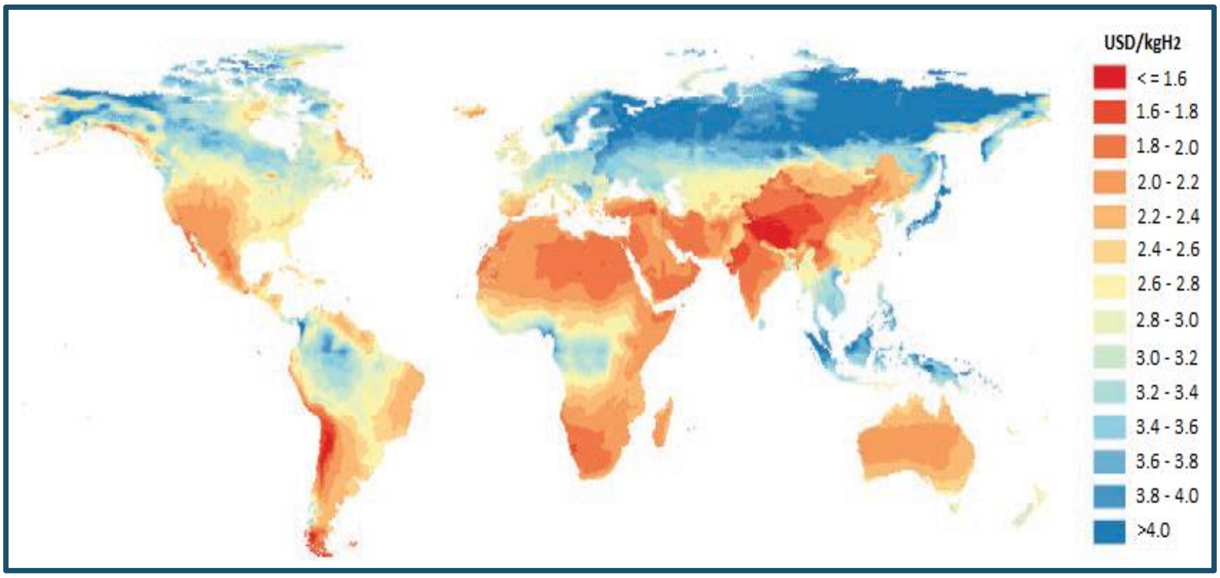
6. SOUTH AFRICA'S COMPETITIVE ADVANTAGES AND DEVELOPMENT

Competitive advantages

South Africa possesses a unique combination of advantages which place it in a good position to enter the future global hydrogen market. Specifically, South Africa has three chief advantages – ideal renewable energy conditions, Fischer-Tropsch skills and capabilities, and access to local platinum resources.

South Africa has ideal weather conditions for solar and wind generation, which are the renewable energy options typically deployed in green hydrogen production. High solar and wind availability factors increase the utilisation factors of the hydrogen electrolysers, ultimately lowering the cost of clean hydrogen production and make investments attractive to investors (Polity, 2019).

Figure 9. Hydrogen production costs by geography (with wind and solar generation)



Source: (IEA, 2019).

According to the CSIR, South Africa has excellent conditions for wind and solar energy, which can be generated and then stored using hydrogen as a medium (see Figure 9). South Africa's combined solar and wind power could provide a hydrogen production capacity factor of almost 100% during daylight hours (Engineering News, 2019a). In the evening, wind generation could be harnessed to produce hydrogen at a capacity factor of about 30%, which exceeds the international norm of approximately 22% (Engineering News, 2019a).

Hydrogen can be combined with CO_2 to produce synthetic hydrocarbons, such as methane, diesel, or jet fuel. South has a unique capability in this regard with the patented FT process owned by Sasol (IEA, 2019). The process is proven commercially, notably through Sasol's largest coal-to-liquid (CTL) plant in the world, based in Secunda. In the production of synthetic diesel or kerosene, the FT process is used to convert carbon monoxide (derived from CO_2) into raw liquid fuels and synthetic diesel or kerosene. The technical expertise and skills which have developed around the Sasol processes provide South Africa with an edge in the production of liquid fuels based on the hydrogen route. South Africa's competitiveness in this regard is time-sensitive, however. As other countries with good renewable energy conditions invest in green hydrogen production, they will likely develop expertise and capabilities, thus South Africa will have to develop the hydrogen value chain fairly rapidly if it is to capitalise on a first-mover advantage.

Finally, South Africa is the largest producer of PGMs in the world, and accounts for approximately 71% of global supply (Engineering News, 2019c). PGMs serve as a key component of electrolysers in hydrogen production and as catalysts in fuel cells. South Africa has close proximity to platinum supplies, which can reduce the costs of transport and the other costs associated with importation of key materials. The proximity to platinum, which is an essential component of the PEM system, allows costs advantages to filter to the final hydrogen production price, increasing the competitiveness of South African green hydrogen.

Possible developments

South Africa has an opportunity to create new value chains by penetrating the fuel cell market. The Integrated Resource Plan (2019) provides for greater renewable energy intensity and the hydrogen economy can support this. While the potential avenues for hydrogen production continue to be investigated in South Africa, the following areas offer potential opportunities to catalyse the domestic hydrogen economy.

To leverage South Africa's cost advantages in hydrogen production and to ensure a competitive export price, hydrogen export costs can be mitigated by situating hydrogen production facilities close to major ports, reducing the transmission/transport costs. Road transport costs increase substantially with distance and can render the export cost uncompetitive. The Port of Ncqura in the Coega Industrial Development Zone (IDZ) has been identified as a potential port for exported hydrogen, due to its proximity to renewable energy-based production. To this effect, the CSIR, among other stakeholders, is engaging with the Coega IDZ to investigate the development of hydrogen production in that location and the possible leverage of the existing gas and port infrastructure there.

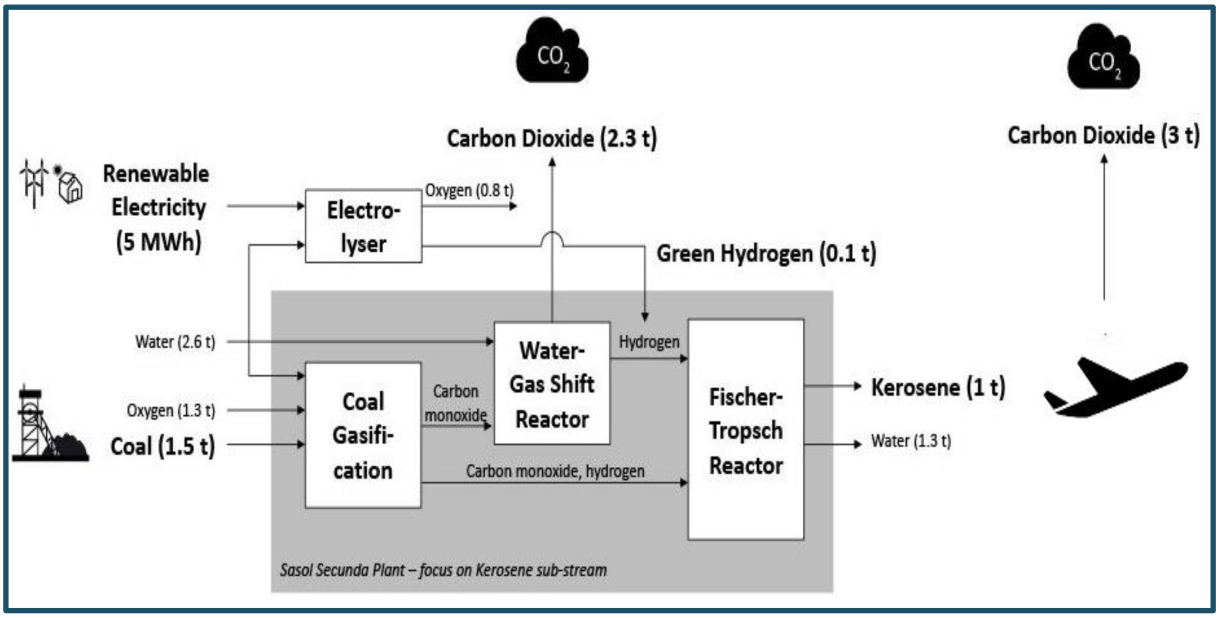
Further cost and access advantages can be developed through the use of sea water as a substitute for potable water input. Given the water intensity of green hydrogen production and South Africa's water security issues, one possible avenue to secure access to input water is to use desalination to convert brackish water into desalinated water and then to use the desalinated water in a hydrogen electrolysis process to produce hydrogen (Engineering News, 2019a). It is estimated that 50kWh of energy is required to produce 1kg of hydrogen. While desalination is a highly energy intensive process, the potential coupling with renewable energy sources and the high costs of hydrogen production imply that energy costs in desalination account for a small proportion of total costs. The CSIR has advocated for the coupling of renewable energy with desalination and the use of the desalinated water to feed into the electrolyser, which then produces hydrogen from water as an energy storage medium (Polity, 2019). Combined with the fact that the Eastern Cape province, where Coega is located, is susceptible to water shortages, this allows the potential facility to divert from hydrogen production to potable water production should water supply from conventional sources be limited. To meet demand for hydrogen exports, it may be required for some electrolysis infrastructure to be exclusively devoted to hydrogen production. In cases of excess supply, renewable energy-based electricity could be fed back into the grid based on the appropriate regulatory framework being in place.

In inland areas, brackish water from mining activities (acid-mine drainage) can be desalinated and used to produce hydrogen. This system also has the advantage of supplying water to municipalities during water-stressed times. A dual-supply model uses water to run the electrolyser and to produce potable water, and the capital costs of desalination can be built into hydrogen production of a project. Thus municipalities face a reduced cost of potable water, having only to pay the energy costs for desalinated water which may make water supply costs cheaper for potable uses from desalination.

The development of green hydrogen can also be linked to the retrofitting of existing production facilities. This allows for the recovery of production assets that face future declines due to climate change policy and investor pressures against fossil fuels.

Currently, the Sasol Secunda petrochemical complex is under threat due to its high reliance on coal feedstocks. These production processes should be investigated for the ability to decarbonise existing production routes through the incorporation of sustainable production technologies. One avenue for decarbonisation that meets high market demand is for the decarbonisation of aviation fuel for the production of carbon-neutral aviation fuel.

Figure 10. Stylised decarbonisation of Sasol's aviation fuel line



Source: Author's adaptation of (Bischof-Niemz, 2019).

The chief sources of GHG emissions in aviation occur in the production process and during flight when kerosene is combusted. Based on Sasol's current production, for every ton of kerosene produced, four tons of CO_2 are generated in production and three tons of CO_2 are generated in transport. Therefore, approximately 57% of GHG emissions are generated in production, while the remaining 43% are generated in flight. To produce kerosene, coal initially goes through a gasification step in which hydrogen and carbon monoxide is produced. To increase the yields of hydrogen, the carbon monoxide is fed into a water-gas shift reactor which converts carbon monoxide into additional hydrogen. An option for green hydrogen integration is to progressively substitute the additional hydrogen produced from the water-shift gas reactor with hydrogen produced directly from a green hydrogen system based on renewable energy-based generation. For a system that produces one ton of kerosene, supplementation with green hydrogen, based on a renewable energy-based generation capacity of 5MWh, production-related GHG emissions can be reduced by 43% (from four tons to 2.3 tons). Over time, these process emissions can be reduced completely by increasing green hydrogen production through additional renewable energy-based capacity and from directly capturing air from the environment. In this configuration, CO_2 and hydrogen are absorbed into the process from the environment. This capture absorbs CO_2, which in theory can transform the carbon lifecycle of aviation into a carbon neutral one, as the Sasol process would act as a carbon sink.

PetroSA's production process offers an alternative retrofitting potential. PetroSA's access to gas resources are nearly depleted with uncertainty around future gas sources. PetroSA's facilities in Mossel Bay could be retrofitted to produce hydrogen. This site is ideal for hydrogen as the facility is close to a harbor, reducing the costs of export through a reduced road transport element.

7. CONCLUSION

With an increased focus on climate change mitigation, green hydrogen offers a complementary pathway to decarbonisation with applications across a number of sectors. For some sectors, such as aviation and shipping, green hydrogen is the only feasible decarbonisation option. Many countries and regions have sent signals to the international market indicating their intent to develop hydrogen value chains and engage in the international hydrogen market.

It is an important time for South Africa to position itself as a key supplier of green hydrogen into the international hydrogen market. South Africa has key resources to leverage, which can place it as a competitive supplier of green hydrogen. These include good renewable energy resources from solar and wind, embedded expertise and capabilities in the FT process, and access to platinum resources which are a key input into electrolysers. In the medium to long term (10 years and beyond), Japan, South Korea and the EU emerge as the main export destinations for (South African) green hydrogen. While these partners appear most proximal as consumers of South Africa's green hydrogen, demand for hydrogen from other countries is anticipated to rise significantly as more and more formulate their policies around hydrogen.

Developing the green hydrogen value chain in South Africa will not be easy and will require co-ordination between the most important stakeholders from state departments, industry, labour unions and civil society. Opportunities for development will have to be identified, taking into account the impact of investments on the final price of hydrogen and competitiveness, lock-in and pathway dependence on a specific technology, demand markets and transport costs, and the overall impact on South Africa's development trajectory. Options for deployment include greenfield investments into new production as well as the retrofitting of existing carbon-intensive production.

From a policy perspective, the right mix of incentives and penalties is required to generate a hydrogen market. Resources and incentives on the supply side can assist in the formulation of pilot projects that feed into existing processes and set up independent production which can be scaled as commercial viability is proven. The existing strengths and progress developed through initiatives by DSI and HySA, for example, can be driven further through such policy support. Engagements with key carbon-intensive production by Sasol and PetroSA are also vital to decarbonise existing process and leverage existing assets.

South Africa has the right mix of endowments to create a new and sustainable export commodity in the form of green hydrogen. This comes at a crucial time in South Africa's development trajectory in that the country is facing growing pressure to transition away from coal as an energy source for power generation, petrochemicals production and iron and steel production. A just transition has surfaced as a key imperative for the country and the hydrogen economy has a role to play in providing opportunities for displaced workers, communities and small businesses. A number of key decisions still have to be made in this regard. A policy roadmap outlining the development of the value chain is underway and this is vital to provide certainty to investors as well as the regulatory direction for development and should be fast-tracked.

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APPENDIX

Table 5. Recent hydrogen policy developments by country

COUNTRY	DEVELOPMENTS	AREA(S) OF DEVELOPMENT	POLICY TOOL(S)
Austria	Announced that a hydrogen strategy based on renewable electricity would be developed in 2019 as part of the Austrian Climate and Energy Strategy for 2030.	Hydrogen strategy development	
Belgium	Published a government-approved hydrogen roadmap in 2018, with specific targets set for 2030 and 2050 and an associated €50 million regional investment plan for power-to-gas.	Hydrogen strategy development	Targets
Brazil	Included hydrogen in the Science, Technology and Innovation Plan for Renewables and Biofuels. Hosted and supported the 22nd World Hydrogen Energy Conference in 2018.	Hydrogen strategy development	
China	Announced that the Ten Cities programme that launched battery electric vehicles in the People's Republic of China ("China") would be replicated for hydrogen transport in Beijing, Shanghai and Chengdu, among others. Announced that Wuhan will become the first Chinese Hydrogen City, with up to 100 fuel cell automakers and related enterprises and up to 300 filling stations by 2025. Announced targets of 5 000 FCEVs by 2020 and recommitted to a 2015 target of one million FCEVs by 2030, plus 1 000 refuelling stations. Exempted FCEVs (and battery electric vehicles) from vehicle and vessel tax.	Transport	
The Netherlands	Published a hydrogen roadmap, including a chapter on hydrogen in the Dutch Climate Agreement and spearheaded the first meeting of the Pentalateral Energy Forum of Belgium, the Netherlands, Luxembourg, France, Germany and Austria in support of co-operation on hydrogen in northwest Europe. The Dutch provinces of Groningen and Drenthe have drawn up a €2.8 billion plan that is supported by over 50 partners around the world to be a springboard for hydrogen industry. The project is to bring hydrogen production to scale and includes projects related to production, pipelines, storage sites, hydrogen refuelling stations and residential heating. Further, Amsterdam has banned gasoline and diesel fuelled cars and motorcycles from 2030.	Transport Power systems (electricity and gas) Hydrogen strategy development	Direct initiative through ban
New Zealand	Signed a memorandum of co-operation with Japan to work on joint hydrogen projects. Further, began preparing a New Zealand Green Hydrogen Paper and Hydrogen Strategy. As part of these developments has set up a Green Investment Fund to invest in business, including those commercialising hydrogen.	Hydrogen strategy development	Investment fund

COUNTRY	DEVELOPMENTS	AREA(S) OF DEVELOPMENT	POLICY TOOL(S)
Norway	Awarded funding for development of a hydrogenpowered ferry and a coastal route vessel. Norway has made commitments to decarbonise fossil fuel cars and light vans by 2025 and has sales targets for zero-emission vehicles of 100 percent heavy duty vehicles, 75 per cent long distance coaches, 50 per cent new trucks by 2030 – however, it should be noted that these vehicles could be either electric or hydrogen. There is also progress being made on a National Hydrogen Strategy.	Transport Hydrogen strategy development	Funding mechanism and tax mechanism
France	Unveiled a Hydrogen Deployment Plan, EUR 100 million funding and 2023 and 2028 targets for low-carbon hydrogen in industry, transport and in relation to the power system through renewable energy storage, including for islands.	Transport Power systems (electricity and gas) Hydrogen strategy development	Target focused, funding mechanism
Germany	Approved the National Innovation Programme for Hydrogen and Fuel Cell Technologies for another 10 years with €1.4 billion of funding, including subsidies for publicly accessible hydrogen refuelling stations, fuel cell vehicles and micro co-generation purchases, to be complemented by €2 billion of private investment. Supported the first commercial operation of a hydrogen-powered train, and the largest annual increase in refuelling stations in the country, though the H2 Mobility programme. Additional work is being assessed, such as power-to-gas and gas blending projects. Germany released a Hydrogen Strategy in June 2020	Transport Power systems (electricity and gas)	Subsidy mechanism, funding mechanism
Japan	Hosted the first Hydrogen Energy Ministerial Meeting of representatives from 21 countries, plus companies, resulting in a joint Tokyo Statement on international co-ordination. Updated its Strategic Roadmap to implement the Basic Hydrogen Strategy, including new targets for hydrogen and fuel cell costs and deployment, and firing hydrogen carriers in power plants. The Development Bank of Japan joined a consortium of companies to launch Japan H2 Mobility with a target to build 80 hydrogen refuelling stations by 2021 under the guidance of the Japanese central government's Ministerial Council on Renewable Energy, Hydrogen and Related Issues. The Cross-Ministerial Strategic Innovation Promotion Program	Transport Power systems (electricity and gas) Hydrogen strategy development	Target focused

COUNTRY	DEVELOPMENTS	AREA(S) OF DEVELOPMENT	POLICY TOOL(S)
	Energy Carriers initiative concluded its 2014-2018 work programme and a Green Ammonia Consortium was launched to help support the next phase.		
Korea	Published a hydrogen economy roadmap with 2022 and 2040 targets for buses, FCEVs and refuelling stations, and expressed a vision to shift all commercial vehicles to hydrogen by 2025. Provided financial support for refuelling stations and eased permitting. Announced that it would work on a technological roadmap for the hydrogen economy. Work is also being undertaken in relation to hydrogen gas pipeline development to 2030 and beyond.	Transport Hydrogen strategy development	Funding mechanism
Saudi Arabia	Saudi Aramco and Air Products announced they are to build Saudi Arabia's first hydrogen refuelling station.	Transport	
South Africa	Included fuel cell vehicles as part of Green Transport Strategy to promote the use of fuel cell public buses in metropolitan and peri-urban areas of the country, as well as deployment of hydrogen fuelled vehicles on mine sites.	Transport	
United Kingdom	Set up two £20 million funds for innovation in low-carbon hydrogen supply and innovation in storage at scale including Power-to-X. Published a review of evidence on options for achieving long-term heat decarbonisation, including hydrogen for buildings. The UK are testing blending up to 20% hydrogen in part of the United Kingdom's natural gas network. Further, announced decarbonising Industrial Clusters Mission supported by £170 million of public investment from the Industrial Strategy Challenge Fund.	Power systems (electricity and gas) Hydrogen strategy development	Investment fund
United States	Extended and enhanced the 45Q tax credit that rewards the storage of carbon emissions in geological storage sites, and added provisions to reward the conversion of carbon emissions to other products, including through combination with hydrogen. California amended the Low Carbon Fuel Standard to require a more stringent reduction in carbon intensity by 2030, incentivise development of refuelling stations, and enable CCUS operators to participate in generating credits from low-carbon hydrogen. California Fuel Cell Partnership outlined targets for 1 000 hydrogen refuelling stations and one million FCEVs by 2030, matching China's targets.	Transport	Tax credit, target focused

Source: TIPS, based on (Deloitte, 2019; IEA, 2019).