EU-South Africa (EU-SA)

Partners for Growth

EuropeAid/139363/DH/SER/MULTI

This project is funded by the European Union

EU-South Africa (EU-SA)

Partners for Growth

EuropeAid/139363/DH/SER/MULTI

Service Contract No: PI/2018/399500

Powerfuels and Green Hydrogen (public version)

Thomas Roos and Jarrad Wright

Submitted to:

European Commission

Service for Foreign Policy Instruments

EEAS Loi 02/306

B-1049 Brussels

Belgium

December 2020

Table of Contents

List of Figures

List of Tables

Abbreviations

AEC	alkali electrolyser cell
CAPEX	Capital Expenditure
CCU	Carbon Capture and Utilisation
DENA	German Energy Agency (Deutsche Energie-Agentur)
EC	European Commission
EE	Energy efficiency
EPA	Economic Partnership Agreement
EU	European Union
EUD	EU Delegation
FCEV	Fuel Cell Electric Vehicle
FLH	Full Load Hours (of annual operation)
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IRENA	International Renewable Energy Agency
KOH	Potassium Hydroxide
LOHC	Liquid Organic Hydrogen Carrier
METI	Ministry of Economy, Trade and Industry (Japan)
NHS	National Hydrogen Strategy (Germany)
PEM	Proton Exchange Membrane
PtG	Power-to-Gas
PtL	Power-to-Liquids
PtX	Power-to-X
PV	Photovoltaic
RE	Renewable energy, Renewable electricity
RED	Renewable Energy Directive
RSA	Republic of South Africa
REIPPP	Renewable Energy Independent Power Producer Procurement
SA	South Africa
SADC	Southern African Development Community
SAT PV	Single Axis Tracking PV
SOEC	Solid Oxide Electrolyser Cell
TFA PV	Tilted Fixed-Axis PV
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar

WACC	Weighted Average Cost of Capital
WITS	University of Witwatersrand

Executive Summary

Powerfuels are synthetic gaseous or liquid fuels based on renewable hydrogen, which is hydrogen obtained by the electrolysis of water using renewable electricity. Powerfuels are therefore a renewable alternative to fossil fuels (as their use avoids net emissions of CO_2), to be used in sectors which may be difficult to decarbonise and may not be easily driven directly by renewables-based electricity.

The EU-SA Partners for Growth Programme, which supports the EU Delegation in South Africa, hosted a technical workshop on Powerfuels together with WITS Business School in December 2019 in South Africa. Following on from the successful workshop, the EU-SA Partnership plan to host a study tour to Europe for South African policymakers and companies to demonstrate Powerfuels expertise and know-how. This Research Paper has been commissioned by the EU-SA Partnership to prepare for this Powerfuels study tour.

At least three countries, Japan, Germany and the Netherlands, plan to import Powerfuels products in bulk. The strength of the South African solar and wind resource means that Powerfuels may be produced competitively in South Africa, leading to new export markets. By way of illustration, Japan plans to import hydrogen in bulk from 2030, at a target cost delivered to Japan of $3/kg, but only requires the imported hydrogen to be carbon-free from 2040 onwards. However, hydrogen may be generated from renewable electricity in South Africa, stored and transported to Japan at or below this target price before 2040.

To produce hydrogen by electrolysis, water is required, but South Africa is a water-stressed country. Fortunately, the cost component of seawater desalination for the feedwater per kilogram of hydrogen produced is less than $0.02/kg (less than 1% of the Japanese target cost of $3/kg). A Powerfuels industry would therefore be better placed to afford the financing of desalination infrastructure than agriculture or other water-consuming businesses, leading to increased water resilience for water-stressed regions in South Africa.

An overview is given of the South African legislative and policy environment with respect to renewable electricity and Powerfuels. This includes focussed discussions on South African industrial policy, climate change policy, energy policy and innovation policy. The requisite policy environment across these areas is shown to be supportive of Powerfuels. However, there is a definitive need to shift from an already existing supportive policy environment in most of these areas to one that is enabling and ambitious. This would empower South Africa to realise the Powerfuels opportunity via initial pilot implementation and roll-out at scale thereafter.

The submissions provided at the Powerfuels Workshop from DENA, IEA, ENERTRAG and Sasol are reviewed and analysed. The industries in South Africa most likely to benefit from Powerfuels are discussed and include petrochemicals and refineries, underground mining, the banking sector, renewable power developers, hydrogen and fuel cell companies, gas handling companies, Transnet Port Terminals (TPT), the Coega and Saldanha Bay industrial development zones (IDZs), urban bus transport entities, long-distance trucking businesses, steelmaking and cement plants.

Barriers to Powerfuels are also briefly discussed and include legal and regulatory, market conditions, human and technical capacity and infrastructure. Finally, suggestions are made for an itinerary and South African delegate list for a prospective study tour to Europe (excluded for this public version of the Research Paper).

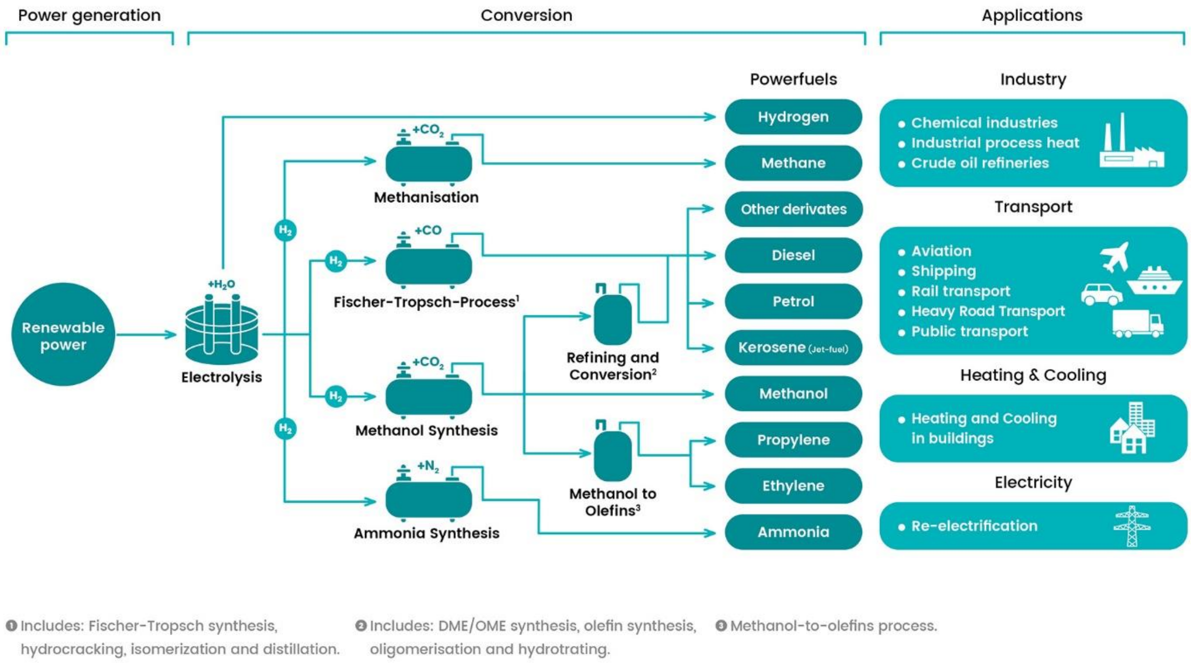
1 Background and context

1.1 Introduction

The EU-SA Partners for Growth Programme supports the EU Delegation (EUD) in South Africa (SA) in its efforts to maximise bilateral trade and investment flows between the EU and SA.

The EU-SA Partnership has initiated a programme for Powerfuels. Powerfuels[1] are synthetic gaseous or liquid fuels based on renewable hydrogen, which is hydrogen (H_2) obtained by the electrolysis of water using renewable electricity[2]. Powerfuels comprise pure hydrogen, hydrocarbons and ammonia (Figure 1).

Figure 1: Different Powerfuels products based on renewable power [1]



Source: [1]

Some Powerfuels are hydrocarbons, in which case the carbon required for their production must be obtained from captured CO_2. While the EU Hydrogen Strategy does not currently place conditions on the CO_2 used, in future the feedstock and process will be relevant when greenhouse gas emissions thresholds will be set[3].

---

[1] Also referred to as electrofuels, e-fuels, Power-to-Gas (PtG) for gaseous fuels, Power-to-Liquids (PtL) for liquid fuels, or Power-to-X (PtX) as an all-encompassing term.

[2] Renewable hydrogen (also commonly referred to as green hydrogen) may also be produced from biogas or by biochemical conversion of biomass, if in compliance with sustainability requirements [15]. This is however not the focus of this Research Paper.

[3] The Energy System Integration (ESI) strategy of the EU states **Invalid source specified.**: An alternative to the permanent storage of CO_2 is to combine it with renewable hydrogen to produce synthetic gases, fuels and feedstock (Carbon Capture and Use, or CCU). Synthetic fuels can be associated with very different levels of greenhouse gas emissions depending on

Powerfuels are therefore a renewable alternative to fossil fuels, as their use avoids net emissions of CO_2. In many applications they are regarded as a necessary requirement to meet climate goals, alongside renewable energy and energy efficiency.

A technical workshop on Powerfuels was held in December 2019 in South Africa, hosted by the EU-SA Partnership together with WITS Business School. The aims of the workshop were to explore the potential of a Powerfuels economy in South Africa, and to identify hurdles that could hinder the establishment of South Africa as a major supplier to Europe and other bulk markets. The agenda for the workshop is given in 0.

Following on from the successful workshop, the EU-SA Partnership plan to host a study tour to Europe to demonstrate Powerfuels expertise and know-how. Selected South African companies and relevant government policy makers will be invited to visit industrial plants, market leaders and EU officials in order to strengthen their understanding of the potential and benefits of Powerfuels. This Research Paper has been commissioned by the EU-SA Partnership to prepare for this Powerfuels study tour, and has the following structure:

- Chapter 1 (this chapter) introduces Powerfuels and the context giving rise to their prominence;
- Chapter 2 describes the economics and components of Powerfuels production, and explores their applicability to South Africa;
- Chapter 3 presents a review of existing government policy and regulations which would support or frustrate Powerfuels, with suggested interventions;
- Chapter 4 discusses and summarises the presentations made at the Powerfuels workshop;
- Chapter 5 comprises suggestions for industries in South Africa most likely to benefit from Powerfuels, both South African and EU businesses;
- Chapter 6 explores potential barriers to Powerfuels: Regulatory, Capacity, Political, Financial and Technical;
- Chapter 7 (excluded in this public version of the report) explores potential measures to address technical barriers (real or perceived) which a study tour may start to remedy.

1.2 Climate policy context

One area of common interest between South Africa and the EU is support for the Paris Agreement, whose central aim is to keep the rise in global temperature this century well below 2°C above pre-industrial levels, and further to attempt to limit this temperature increase to 1.5°C. The Agreement was ratified by the EU as a bloc on 5 October 2016 and by South Africa on 1 November 2016, and the Agreement itself came into force shortly afterwards on 4 November

the origin of CO_2 (fossil, biogenic, or captured from the air), and the process used. Fully carbon-neutral synthetic fuels require sourcing the CO_2 from biomass or the atmosphere. Synthetic fuels are currently inefficient in terms of energy required for production and are confronted with high production costs. Support to progress the development of this conversion technology, including demonstration and upscaling of the full production process, is relevant with a view to having substitutes for fossil fuels in particular in the most difficult to decarbonise sectors, which may continue to rely on high energy density liquid fuels, such as aviation. As their production requires large amounts of renewable energy, their uptake would have to be matched by a corresponding increase in renewable energy supply.

2016[4]. The Agreement requires all signatories to report regularly on their greenhouse gas (GHG) emissions and on their GHG mitigation implementation efforts [2].

Further, in December 2019, the EU heads of state endorsed the objective of achieving a climate neutral EU by 2050 (with one Member State indicating at the time that it cannot commit to implement this objective as far as it is concerned[5]). On 15 January 2020, the European Parliament adopted a resolution supportive of the European Green Deal and the climate neutrality deadline of 2050, adding targets of increased ambition for 2030 [3]. The EU and its Member States submitted this objective and the related European Council conclusions to the United Nations Framework Convention on Climate Change (UNFCCC) in March 2020 [4].

As part of the European Green Deal priority of the EU to achieve this long-term climate neutrality objective, in July 2020 the European Commission presented the Hydrogen Strategy for a climate neutral Europe, in 3 phases [5]:

- 2020-2024: Install at least 6 GW of renewable hydrogen electrolyser capacity in Europe, with an annual production of one million tonnes of hydrogen per year[6]. Aim to decarbonise existing hydrogen production (like in the chemicals sector), and promote it for new applications (such as industrial processes and heavy-duty transport);
- 2024-2030: Install at least 40 GW of renewable hydrogen electrolyser capacity in Europe, with an annual production of up to 10 million tonnes of renewable hydrogen. Make hydrogen an intrinsic part of an integrated energy system and use it in steel-making, trucks, rail and some maritime transport applications;
- 2030-2050: Deploy renewable hydrogen technologies at large scale to reach all hard-to-decarbonise sectors.

The Hydrogen Strategy mentions an EU industry plan to reach a cumulative total of electrolyser installed capacity by 2030 of 40 GW in Europe, and a further 40 GW "in Europe's neighbourhood" with export to the EU.

The majority (65%) of anthropogenic GHG emitted globally comprises CO_2 released by the combustion of fossil fuels and industrial processes [6].

Under the Stated Policies Scenario of the International Energy Agency World Energy Outlook (reflecting the impact of existing policy frameworks and current announced policy intentions), energy demand between 2018 and 2040 is expected to increase by 33% globally [7], and by 60% in Africa [8]. The higher growth expected in Africa reflects:

- Anticipated population growth: While Africa's population (1.29 billion in 2018) is currently less that of India (1.35 billion in 2018) and China (1.40 billion in 2018), it is among the fastest growing and youngest in the world. It is expected to grow to 2.1 billion by 2040, overtaking India (1.59 billion by 2040) and China (1.42 billion by 2040) by 2023 [8];
- Increased urbanisation: Currently about 600 million people do not have access to electricity [8]. These are more likely to be rural than urban [9]:
  - Electricity access in sub-Saharan Africa is 43% overall, but for rural areas the figure drops to 25%

[4] Thirty days after the date on which at least 55 Parties to the Convention (together accounting for at least an estimated 55% of the total global GHG) had deposited their instruments of ratification, acceptance, approval or accession with the Depositary

[5] There are signs that Poland may soon formally endorse this objective as well [15]

[6] This implies an electrolyser capacity factor of 95%

- The share of Africans living in urban areas is projected to grow from 38% in 2015 to 50% by 2040. Increased population density reduces the per capita cost of electrification, increasing its financial viability.

The future increase in energy demand, combined with a simultaneous ambition to decrease GHG emissions, requires a decoupling of energy supply from GHG emissions worldwide, but also in developing countries. This is only possible if the energy system is transformed according to two principles:

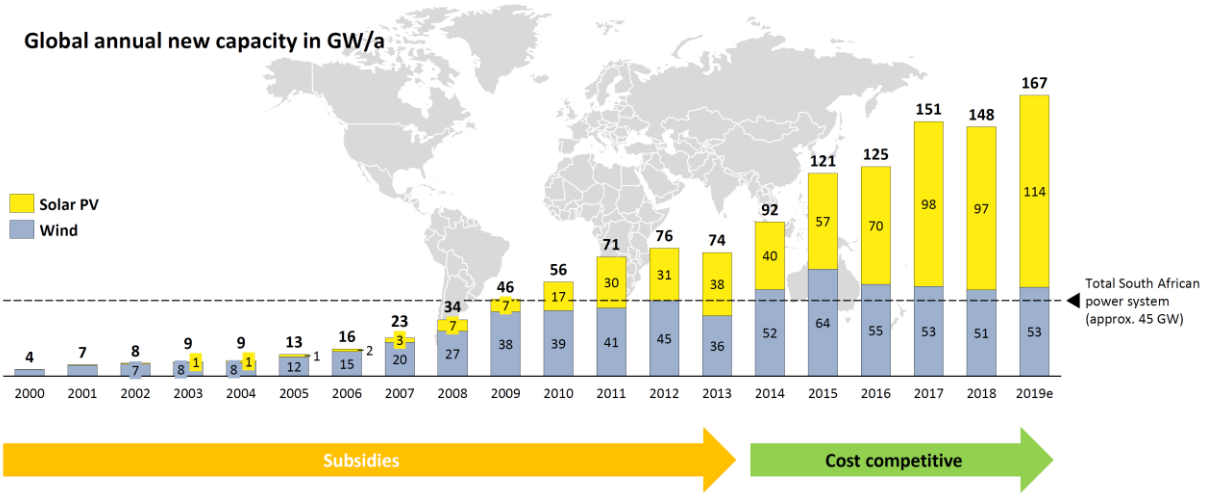
- Responsible, economical use of valuable resources (energy efficiency or EE),

Sustainable, climate-friendly energy sources (renewable energies or RE)

1.3 Renewable power economics

A combination of national policies and subsidies has led to progressive expansion of renewable power capacity being built worldwide between 2000 and 2013. This has driven down costs to the point that from about 2014, new-build renewable power plants have become competitive with new-build fossil power plants in many areas of the world that have good renewable resources (Figure 2).

Figure 2: New capacity of solar PV and wind added annually since 2000



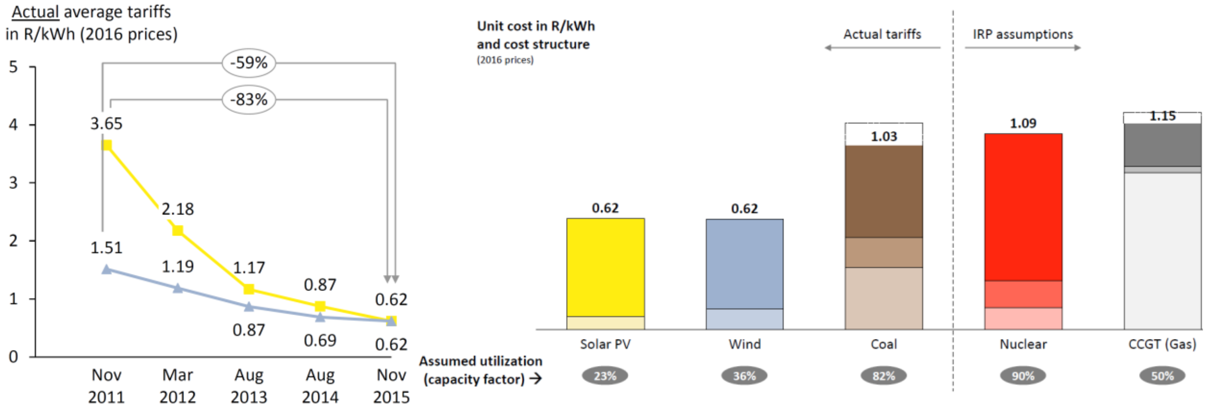
Source: [10]

This has resulted in a more rapid rollout: between 2014 and 2019, an average of 55 GW of wind and 79 GW of solar PV has been installed worldwide annually, compared with an annual average of 22 GW of wind and 10 GW of solar PV between 2000 and 2013. This trajectory of decreasing cost is also true for South Africa, where in the last bidding round of the REIPPP[7] in November 2015, bid prices of R0.62/kWh were obtained for both solar PV and wind (Figure 3), having reduced about 80% and 60% respectively from prices in the 1st bidding round four years earlier. This is 40% lower than bid prices of R1.03/kWh for new-build coal, and for the IRP cost assumptions of R1.09/kWh for new-build nuclear and R1.15/kWh from new-build

[7] Renewable Energy Independent Power Producer Procurement Programme

combined cycle power stations powered by natural gas (all prices adjusted to 2016) [10]. This trend is positive for achieving decarbonisation goals in the electricity supply sector.

Figure 3: Bid tariffs of solar PV and wind in the different REIPPP bidding rounds



Source: [10]

1.4 Hard-to-abate sectors

Powerfuels are required in sectors where the direct use of renewable electricity is not feasible or difficult. These sectors (Heavy, long-distance transport and Industry) have been termed the hard-to-abate sectors [11, 12], as they are particularly difficult to decarbonise.

1.4.1 Heavy-duty, long-distance transport [11, 13]

Buses and long-haul trucks

While battery-electric trucks [14] and buses[8] exist, battery range (160 – 560 km claimed) and charging times remain an issue for long-distance travel. Battery density improvement of 2 to 3 times would make battery electric vehicles dominant for long-distance surface transport, but would require more fundamental changes in battery chemistry [11]. It is understood that the EU consensus in this regard is that hydrogen fuel cells should power heavy-duty long-distance road transport, rather than synthetic e-fuels [15].

Commercial aviation [11]

Battery-electric aircraft are emerging, but only in light aircraft for short-range transportation. Heavier, longer range aircraft, particularly for international flights, will for the foreseeable future require the volumetric and gravimetric energy density of liquid hydrocarbon fuels[9].

---

[8] Shenzhen (China) is the first city in the world to electrify 100% of its public buses, a total of 16 359 buses. In 2016, the average distance travelled was 174.4 km per day [11]

[9] The Horizon Europe project CleanSky resulted in several findings: for ranges up to 2000 km, an Airbus A320 propelled by H_2 is feasible. France will start commercial H_2 flights from 2035. For ranges up to 5000 km, a hybrid aircraft powered by liquid H_2 is proposed. The fuselage is lengthened to accommodate the liquid H_2 tank. For ranges up to 10000 km, a liquid H_2 approach is not possible with the current aircraft configuration. Instead, a blended wing design powered by liquid H_2 is envisioned after 2050 [16].

Along with biofuels, synthetic (Powerfuels) kerosene allows decarbonisation via zero-carbon fuels in existing engines, avoiding major capital investment [11]. Methanol is also being considered for aviation, as it has higher volumetric energy density than ammonia and does not require pressurisation to maintain as a liquid [16].

Maritime shipping

Battery electric drivetrains are efficient for short-haul, but battery density improvement of 5 to 10 times would be required to make electrification feasible for long-distance shipping, also requiring more fundamental changes in battery chemistry. Ammonia in existing engines is considered a promising carbon-free alternative [11]. In this context, ammonia provides the best total cost of ownership and makes most sense for large ocean-going shipping, but for the internal waterways of Europe, H_2 with fuel cells is preferred due to NOx emissions from ammonia combustion [16].

Rail transport [17]

Decarbonising non-electrified train lines is not a trivial task, as overhead power lines are difficult and expensive to retrofit. Fuel cells provide non-electrified train lines a decarbonisation pathway away from diesel, making use of existing infrastructure [18]. It is understood that 42% of European railways are not electrified. Fuel cell H_2 trains have been found to make economic sense for non-electrified routes longer than 100 km, and for main routes with very low utilisation (<10 trains per day) [19].

1.4.2 Industry

Almost 45% of global CO_2 emissions from industry in 2015 resulted from the manufacturing and production of cement (3 Gt CO_2), steel (2.9 Gt CO_2), ammonia (0.5 Gt CO_2), and ethylene (0.2 Gt CO_2). In these four production processes, 48% of CO_2 emissions came from burning fossil fuels to generate heat (35% for high temperature, and 13% for medium- or low-temperature heat) [13]:

Iron production for steelmaking [11, 13]

Coke is first produced by baking metallurgical coal in the absence of air, to drive off volatiles and moisture. Coke is then loaded together with iron ore and small amounts of flux into a blast furnace. Carbon monoxide (CO) is produced by the incomplete combustion of the coke in preheated oxygen blown into the furnace [20]. The iron oxide is reduced to iron, as CO has a stronger affinity for the oxygen in iron ore than the iron does [21]. The coke is therefore both a fuel and a reducing agent. However, the coke may be replaced with hydrogen, allowing direct reduction of iron (DRI) and directly avoiding CO_2 emissions in steelmaking [11, 15].

Cement manufacture [11, 13]

In the process of making cement, the input materials - mainly limestone (calcium carbonate or $CaCO_3$), with smaller amounts of iron oxide (Fe_2O_3), alumina (Al_2O_3) and silica (SiO_2) - are milled to powder and then progressively heated to 1450°C. Only 30-40% of direct CO_2 emissions from cement manufacture are due to fuel combustion to supply the heat required: the majority is due to the decomposition of $CaCO_3$ [22]:

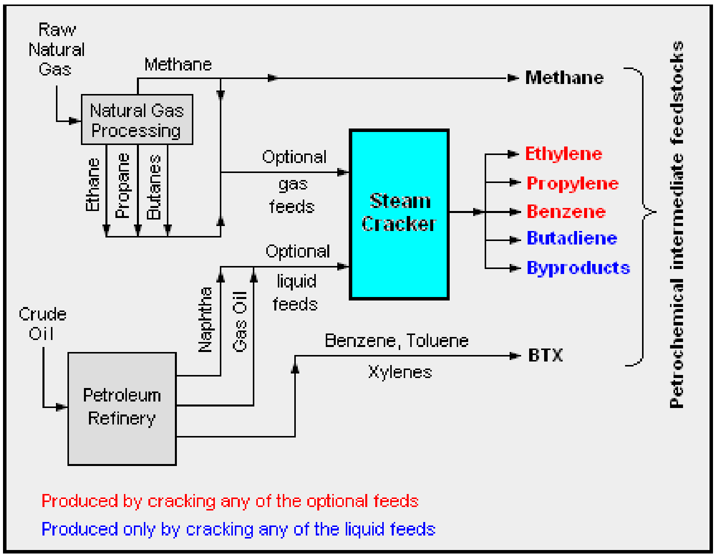
$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Plastics [11, 13]

The two most common petrochemical classes are olefins (including ethylene and propylene) and aromatics (including benzene, toluene and xylene isomers). Olefins are used to create plastics, resins, fibres, elastomers, lubricants, and gels. Olefins and aromatics form the building blocks of solvents, detergents, and adhesives. Global annual production levels are 115 Mt for ethylene, and 70 Mt each for propylene and aromatics. Olefins are produced by steam cracking of natural gas liquids or catalytic cracking of petroleum fractions (Figure 4) [23].

Cracking is an endothermic process [24, 25]. Ethylene production has CO_2 emissions from fuel for high-temperature heat required in the steam cracking process. These fuels are partly or completely sourced from gases produced in the same cracking process [13]. Plastics also give rise to CO_2 emissions at end-of-life, from incineration or decomposition [11].

Figure 4: Petrochemical feedstock sources

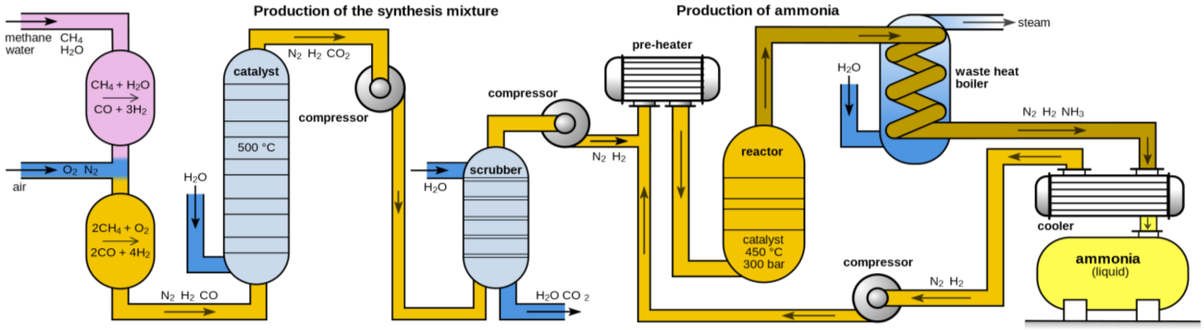


Source: [23]

Ammonia [13]

Synthesis gas (syngas: mixture of H_2 and CO) is generally obtained from natural gas by steam methane reforming (SMR), but ammonia producers in China obtain syngas via coal gasification. Next, in the water-gas shift step, CO in the syngas is reacted with steam to produce CO_2 and more H_2. Nitrogen from an air separation plant is then added, and the mixture is synthesised into ammonia at high pressure in the Haber-Bosch process (Figure 5). The CO_2 is removed and emitted in a nearly pure stream. The water-gas shift reactor is the primary source of CO_2 emissions in ammonia production.

Figure 5: Haber-Bosch process



Source: [26]

1.5 Emerging Powerfuels markets

Several large global future markets have emerged for low-carbon Powerfuels specifically. These markets provide opportunities for businesses located in South Africa, both EU businesses and South African businesses.

1.5.1 Japan

Japan was the first jurisdiction to pursue the explicit importation of Powerfuels as a national policy. Japan is a major net energy importing country, ranked in the top four global importers of the three main fossil fuels: No. 2 in coal [27], No. 1 in natural gas [28] and No. 4 in crude oil [29]. Having signed the Kyoto Protocol on 28 April 1998 (and ratified it on 4 June 2002), Japan has climate obligations. The Fukushima nuclear disaster in 2011, however, significantly reduced public acceptance of nuclear power, constraining the decarbonisation options available.

In 2014, the Ministry of Economy, Trade and Industry (METI) of Japan released the Strategic Road Map for Hydrogen and Fuel Cells [30]. The strategy seeks to move at least 3 sectors of the Japanese economy from fossil fuels to hydrogen:

- Mobility: fuel cell electric vehicles (FCEVs) using H_2
- Residences: Stationary fuel cells using H_2, providing both electricity and hot water
- Power generation: Combined cycle power plants using PtX ammonia as fuel.

The strategy gives three H_2 import-related targets:

- By 2025: Reduce the cost of H_2 delivered to Japan to ¥30/Nm^3 (about USD3/kg).
- 2030: Begin bulk import of H_2 from overseas to Japan
- 2040: All imported H_2 is to be CO_2-free.

The motivations for Japan behind the Strategic Road Map for Hydrogen and Fuel Cells and the Basic Hydrogen Strategy are not driven exclusively by climate considerations but also by industrial policy. Japan regards fuel cell technology as a key Japanese competence and sees the move towards H_2 as a way to re-industrialise Japan and position Japanese companies for international success. From the beginning, an important component of the strategy has been to demonstrate H_2 and fuel cell technologies at the 2020 Tokyo Olympics (currently postponed to July 2021).

The three H_2 import-related targets were subsequently confirmed in the Basic Hydrogen Strategy of 2017 [31]. The volumes of H_2 to be imported from 2030 begin at about 300 000 tonnes annually, growing to between 5 and 10 million tonnes by about 2050 [31, 32]. The target hydrogen price by 2050 is USD 2/kg [32].

Hydrogen played a significant role at Japanese-hosted 2019 G20 Summit in Tokyo. Reports were requested from, and supplied by, IEA [12] and IRENA [33], exploring the applications, pathways, technologies, options, and economics of hydrogen production and use.

1.5.2 The European Union

In addition to Japan, Europe is emerging as an additional Powerfuels market. The European Commission (EC) sought to begin decarbonising transport with the 2009 version of the Renewable Energy Directive (RED) [34]; requiring EU member states to ensure that a minimum of 10% of the energy consumed within that state in transport was of renewable origin[10]. Unfortunately, this had the unintended consequence of a significant increase in the cultivation of 1st generation biofuels, distorting food prices and changing land use [35].

A 2015 amendment to the RED [36] limited the contribution of 1st generation biofuels towards the 10% target to a maximum of 7 percentage points. The remaining 3 percentage points (as a minimum) should be made up of "Annex IX" fuels: cultivated algae, various types of bio-wastes, used cooking oil, and "carbon capture and utilisation for transport purposes, if the energy source is renewable" (essentially PtX fuels). These "Annex IX" fuels will count twice their calorific value towards the national renewable transport targets, to make up for the fact that the "Annex IX" fuels are currently more expensive than 1st generation biofuels.

The RED does not require that:

- The CO_2 used to make the carbon capture and utilisation (CCU) fuels be of renewable origin (e.g. biomass), only that the energy itself used to convert the CO_2 into fuel must be renewable.
- The CCU fuel be manufactured in Europe, only that it be consumed in EU Member States

The 2018 version of the RED (RED II) currently has a 14% minimum renewable energy target for transport to be achieved by 2030 [37], and many EU member states have adopted much higher targets than this in their National Energy and Climate Plans (NECPs) [15]. The RED II includes 'recycled carbon fuels'[11] that may be counted towards these targets [37].

The relevant act is to be adopted by January 2021, and is to come into force in June 2021[12].

More recently, the European Green Deal [38] is the most ambitious EC climate policy to date. In addition to the goal of Europe being climate neutral by 2050, the ambition for 2030 is a cut of 50-55% in GHG emissions compared with 1990 levels, in contrast with the previously-planned 40% cut. Every EU law and regulation, including the Renewable Energy Directive, will be reviewed in order to be aligned to the new climate goals. A circular economy action

---

[10] In this version, aviation was considered difficult to decarbonise, so partial exemptions were written in for island regions such as Malta and Cyprus

[11] The RED II provides this definition: 'recycled carbon fuels' means liquid and gaseous fuels that are produced from liquid or solid waste streams of non- renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations;

[12] The RED II States: "By 1 January 2021, the Commission shall adopt a delegated act in accordance with Article 35 to supplement this Directive by establishing appropriate minimum thresholds for greenhouse gas emissions savings of recycled carbon fuels through a life-cycle assessment that takes into account the specificities of each fuel."

plan will, among other things, examine carbon-intensive industries like steel, cement and textiles, with an objective being to prepare for "clean steelmaking" using hydrogen by 2030. Biofuels and hydrogen will be promoted in aviation, shipping and heavy duty road transport where electrification is currently not possible [39].

1.5.3 Germany

In November 2019, the German Federal Government released a draft National Hydrogen Strategy (NHS) for comment. On 10 June 2020, the final version of the NHS was passed by the German Federal Cabinet [40].

The NHS states that Germany is expected to need an annual volume of hydrogen of between 90-110 TWh (2.7-3.3 Mt) by 2030[13]. Of this total, it plans to generate 14 TWh (420 kt) annually in Germany, from 5 GW of new renewable electricity generation capacity[14]. A further 5 GW of RE capacity are to be added between 2035 and 2040. The NHS concedes that domestic generation will be insufficient to cover all the expected new green hydrogen demand, so most of the hydrogen needed will have to be imported. Some will be sourced from elsewhere in the EU: from countries bordering the North Sea and Baltic Sea (making use primarily of offshore wind), and the countries of southern Europe (making use of their solar resource and presumably wind as well).

Of particular importance to South Africa is the stated fact that the Federal Government aims to systematically develop production sites in partner countries within German development cooperation that offer great renewable energy potential for PtX production. South Africa meets both of these requirements.

1.5.4 The Netherlands

On 6 April 2020, the Government of the Netherlands published a letter titled "Government Strategy on Hydrogen" [41], setting out the government's strategy on hydrogen as well as the corresponding policy agenda.

The strategy acknowledges that to become a 100% climate-neutral economy by 2050, zero-carbon hydrogen is crucial to integrate and apply sustainable solar and wind energy. Further, there are limits to what can be achieved in the Netherlands using renewable electricity and heat in terms of technology, systemic costs and space. In regions where cheap renewable electricity can be generated on a large scale, such as in the Middle East, North Africa, Spain and Portugal, opportunities have been identified for the development of an export sector for hydrogen [41].

The strategy states that it is crucial from a strategic perspective to retain the current hub function played by ports, and the Port of Rotterdam in particular, within international energy flows. Given:

- The potential for sustainable hydrogen to become a globally traded commodity, and
- the significant expected demand for sustainable hydrogen in industry in Northwest Europe,

---

[13] About 55 TWh (1.65 Mt) of hydrogen is used annually for industrial applications in Germany, mostly produced from fossil sources.

[14] The assumption made in here is that the electrolyser capacity will operate at 4 000 hours full-load hours annually, at an efficiency of 70%.

it would therefore be highly advantageous for the Netherlands to become the linchpin in that supply chain and to use existing infrastructure for that purpose. Countries with cheap solar energy will focus on the export of hydrogen and the Netherlands will be able to continue to act as an energy hub in the future due to its favourable location, its ports and its extensive gas grid and storage capacity [41].

To make aviation more sustainable, the production and consumption of sustainable fuels, including synthetic kerosene, is regarded as essential. The Netherlands is firmly committed to a blending obligation, preferably at European level; but if necessary at a national level as of 2023. The negotiated (draft) Sustainable Aviation Agreement with the sector included the commitment to reach 14% blending of sustainable fuels by 2030 and 100% by 2050. Given the limited availability of biomass, this is expected to consist largely of synthetic fuels. Sufficient availability of hydrogen for the aviation sector is a prerequisite in this regard [41].

Apart from the Government of the Netherlands, the Port of Rotterdam in its own right is pursuing a hydrogen economy. It is Europe's largest deep-sea port, with 30 000 ocean-going vessels and 120 000 barges operating in it on a yearly basis. Truck, train and barge linkages make the port a gateway port for large parts of Europe, especially Germany, Austria and Switzerland. One of the many industrial clusters within the 45km long port is petrochemicals - refining, handling and shipping. This provides a significant fraction of the Port's revenue [42]. Since Northwest Europe consumes far more power than can be generated locally from renewable sources, the region is required to import hydrogen (or hydrogen-based compounds like ammonia) on a large scale. The national government asked the Port Authority to map out the various options to import hydrogen from abroad, so the port of Rotterdam can retain its pivotal role in international transport fuels. Similar to how the port presently imports large volumes of oil and coal for the Netherlands, Germany and Belgium, in the near future, Rotterdam will serve as a major hub for renewable energy flows [43].

The domestic demand for hydrogen is expected to increase to approximately 14 Mt per year by 2050. If half of this volume is sourced via Rotterdam, the port will be handling some 7 Mt in throughput. According to prognoses, there will also be a sizeable demand from neighbouring countries (and specifically Germany) for hydrogen via Rotterdam: approximately 13 Mt by 2050. This puts the required volume of hydrogen produced or imported in Rotterdam at 20 Mt. This volume would require 200 GW in operational wind farm capacity. The Dutch section of the North Sea currently accommodates 1 GW in wind farm capacity. This can be increased to 60-70 GW by 2050. The lion’s share of the required hydrogen will therefore need to be imported [43].

While the focus has been on hydrogen being supplied from nearby sources (Morocco, Portugal), based on perceived high transport costs would make import from further sources (South America, South Africa, Australia) uneconomic, the port is continually monitoring and revising this view in the light of decreasing production costs, and keeps all options open [42].

1.5.5 Port of Antwerp, Belgium

In a similar manner to the Port of Rotterdam, the Port of Antwerp (PoA) in Belgium has high green hydrogen ambitions. Currently, 10-15% of EU hydrogen production takes place in the Port of Antwerp, ~200 kt/y from merchant steam methane reforming (SMR), ~50 kt/y from captive SMR and ~120 kt/y as by-product [44]. Belgium has 613 km of hydrogen pipeline networks, at 100 bar, operated by Air Liquide [45]. For comparison, the lengths of hydrogen pipeline networks is 2608 km in USA, 376 km in Germany, 303 km in France, 237 km in the Netherlands and 147 km in Canada [44]. The PoA has an action plan for the production, transport and distribution of hydrogen, including hydrogen consumers. It wants to be a backbone of H_2 and CO_2 transport [44]:

- Importing wind-generated H_2 from Norway and solar-generated H_2 from the sunbelt, and conveying it to the industrial regions of Germany.
- Receiving industrial CCU CO_2 from German industry, exporting it to Norway
- Mutual exchange of CO_2 with Port of Rotterdam

PoA wants to demonstrate the circular economy, and establish a multifuel bunkering hub in Antwerp, targeting LNG, methanol and H_2. It has a project investigating methanol for tugboats [44]. PoA uses ~300 kt of methanol annually for chemical processes and fuel production, currently derived from fossil sources. PoA is developing a pilot project to produce 4-8 kt of methanol per year from CCU CO_2 and green hydrogen [46].

1.5.6 France

France produces more than 900 kt of industrial hydrogen per year, mostly from fossil fuels. In 2018, a national Plan on green hydrogen was adopted in order to support the transition to green hydrogen, based on the development of its use in three main areas: industry, mobility and energy. France intends to decarbonize industrial hydrogen production by about 10% by 2023, and by between 20% and 40% by 2028. At the national level, State financial support is up to 100 M €/year to support research and innovative industries, particularly transport. France has now set a target of 6.5GW of electrolysers for renewable and low-carbon hydrogen production.

The Les Hauts de France power-to-gas project aims to build five hydrogen electrolyser production units of 100 MW each over a five-year period, with the first unit operational by the end of 2021. The Port-Jérôme plant, to be built next to the Exxon refinery, aims to supply hydrogen to the petrochemical industry (Exxon, Total, Yara, etc.) to desulphurise fuels or to manufacture fertilisers. In Dunkirk, the project consists of introducing hydrogen into the natural gas distribution network, in order to decarbonise the natural gas used for heating and cooking as well as for mobility [33].

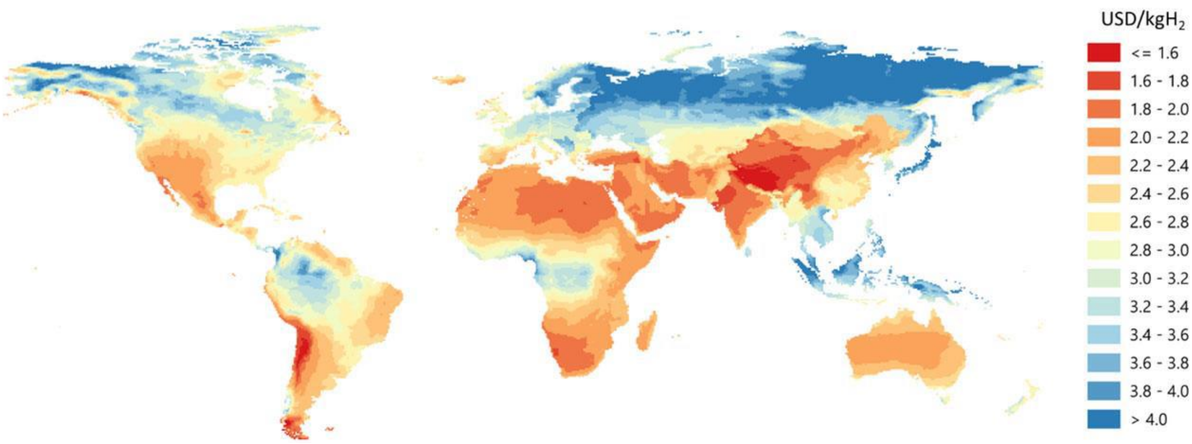
The French government announced plans on 8 September 2020 to use French nuclear power to generate hydrogen [47]. If the European Union decides that nuclear power will count as “sustainable” for green investments and recovery funding, it would be unlikely that France will import green hydrogen in bulk from overseas.

1.6 South African export opportunity

As highlighted, two large economies, the European Union and Japan, have each committed to the bulk import of hydrogen derived from renewable resources. This provides a market for green hydrogen and other green Powerfuels to be generated in South Africa and exported, which is an opportunity for South Africa and for businesses in South Africa (both European and South African).

Figure 6 illustrates future costs of hydrogen production using renewable electricity around the world, using future cost assumptions[15]. Here it may be seen that in the long term, renewable hydrogen may be produced in bulk in South Africa in a cost range of 1.8 - 2.0 USD/kgH_2, which meets the Japanese cost target for 2050. In addition, this range is competitive with most other coastal countries, and beaten only by the Patagonian region and Chile. This shows that South Africa can give rise to a new industry, supplying new export and domestic markets.

Figure 6: Hydrogen costs from hybrid solar PV and onshore wind systems in the long term



Source: [12, 48]

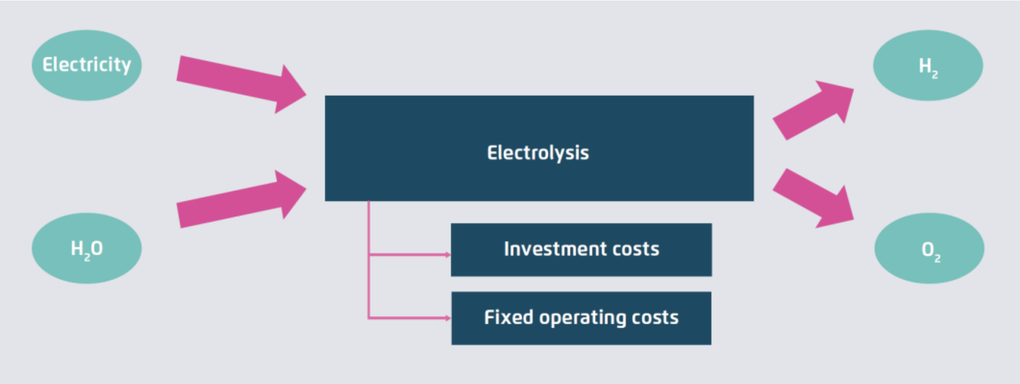
15 Electrolyser CAPEX = USD 450/kWe, efficiency (LHV) = 74%; solar PV CAPEX and onshore wind CAPEX = between USD 400–1 000/kW and USD 900–2 500/kW depending on the region; discount rate = 8% [12]

2 Overview of Powerfuels and their applicability to South Africa

2.1 Components of the economics of Powerfuels production

As introduced in Section 1.1, Powerfuels are based on hydrogen, with green Powerfuels based on green hydrogen production. Green hydrogen is obtained by the electrolysis of water (Figure 7), where the electricity used for the electrolysis is obtained from renewable sources.

Figure 7: Process of hydrogen production via electrolysis



Source: [49]

As may be deduced from Figure 7, the primary production costs of green hydrogen are made up of three components:

1) The cost of renewable electricity supply;
2) The cost of electrolysis; and
3) The cost of the water supply.

Two additional cost components are relevant:

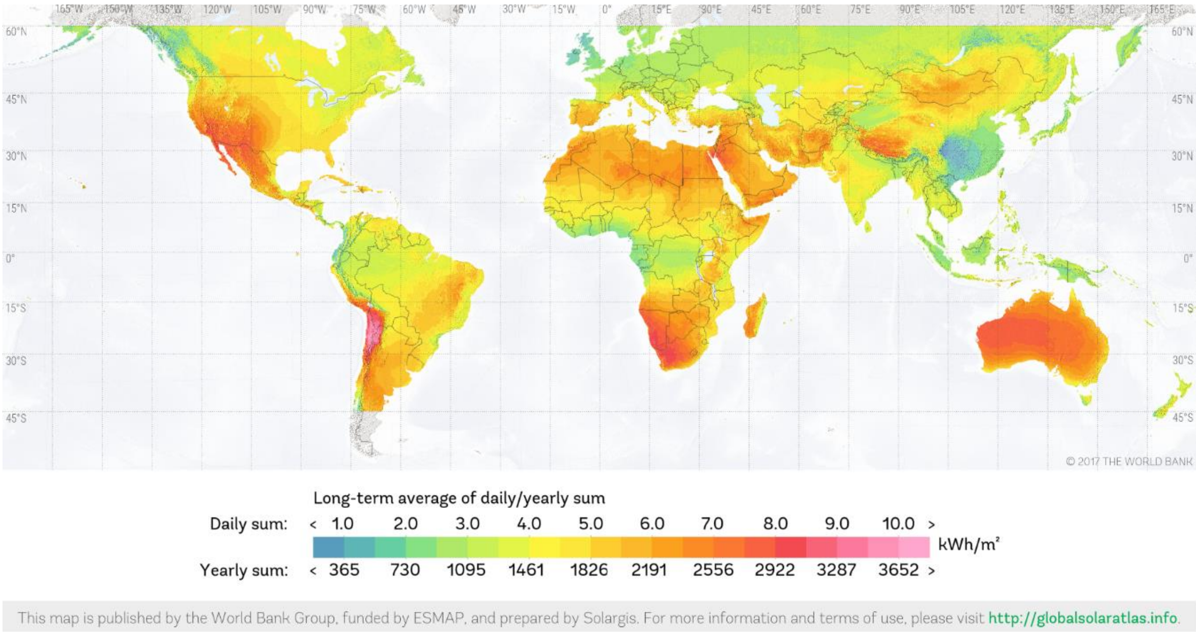
4) The cost of storing hydrogen, either as pure hydrogen (either as pressurised gas or as cryogenic liquid) or in chemical carriers, such as liquid organic hydrogen carrier (LOHC), ammonia or methanol);
5) The cost of transportation to markets

2.2 Renewable electricity costs

The decreasing costs of renewable electricity worldwide and in South Africa has been discussed in Section 0. The solar resource of Southern Africa is among the best in the world, significantly exceeded only by the Atacama Desert of Northern Chile (Figure 8). The South African wind resource is competitive with onshore European wind (Figure 9).

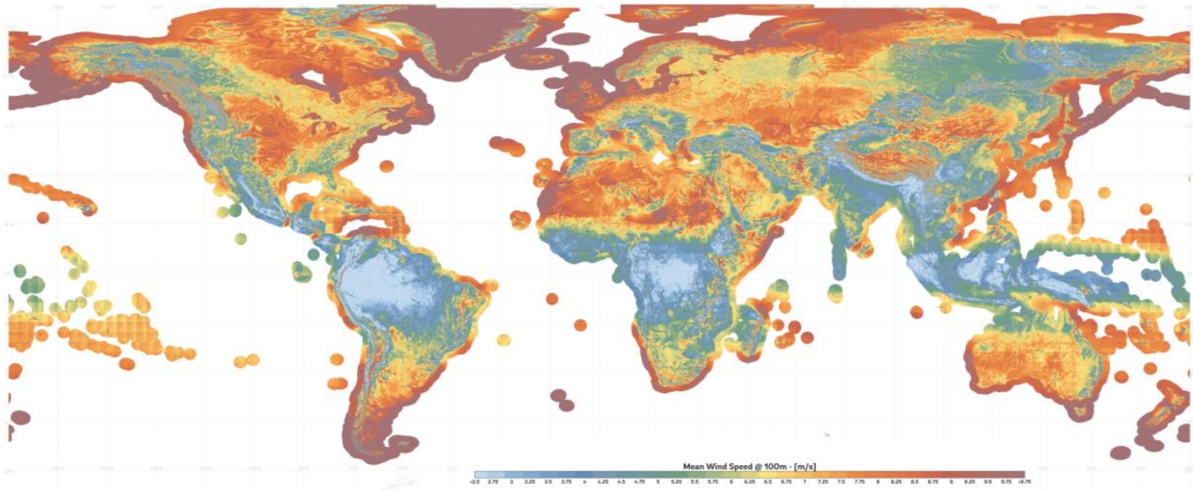
The combined wind and solar resource endowment is a permanent competitive advantage [10] and is the reason South Africa is calculated to be able to provide low-cost hydrogen shown in Figure 6.

Figure 8: **Global solar resource map of direct normal irradiation**



Source: [50]

Figure 9: **Global wind speed map at 100 m above ground level**



Source: [51]

2.3 Electrolysis costs

Three types of electrolyser technology exist: alkali electrolyser cells, proton-exchange membranes and solid oxide electrolyser cells:

- Alkali electrolyser cell (AEC): AEC is a mature and commercial technology using liquid water at temperatures of 80°C or below and has been used since the 1920s. Large electrolysers of electrical capacities of up to 165 MWe have been built, particularly for fertiliser and chlorine production. AEC electrolysis typically has relatively low capital costs due to the avoidance of precious materials, but the potassium hydroxide (KOH) electrolyte solution used must be recovered and recycled [12].

- Proton-exchange membrane (PEM): PEM systems use pure liquid water at temperatures of 80°C or below as an electrolyte solution, removing the requirement for recovery and recycling of KOH. PEM electrolysers are typically smaller than alkali electrolyser cell (AEC) electrolysers. They deliver hydrogen at higher pressure than AEC systems, so are more useful for supplying pressurised hydrogen storage tanks, such as at refuelling stations, as less booster compression is required. Their costs are higher than those of AEC, since they need expensive membrane materials and electrode catalysts such as platinum and iridium, and their lifetime at present is shorter than that of AEC [12].
- Solid oxide electrolyser cell (SOEC): SOECs are not yet at commercial maturity, but are at demonstration level. They operate at high temperatures and high electrical efficiency electrolysing steam (not liquid water) and use ceramics as the electrolyte. Since they electrolyse steam, they require a heat source to raise steam from the feedwater. Unlike AEC and PEM, SOEC's can be operated in reverse mode as a fuel cell, allowing hydrogen in inventory to be converted back into electricity. This would allow SOEC units to provide both hydrogen and grid balancing services. SOEC's can also co-electrolyse steam and carbon dioxide together to produce synthesis gas (carbon monoxide and hydrogen) for fuel synthesis, without requiring a water-gas shift step using valuable hydrogen to convert carbon dioxide to carbon monoxide [12].

The cost of electrolysis is dependent upon several parameters:

- Weighted average cost of capital (WACC)
- CAPEX
- Efficiency
- Annual full load hours (FLH)

These will now be discussed in turn.

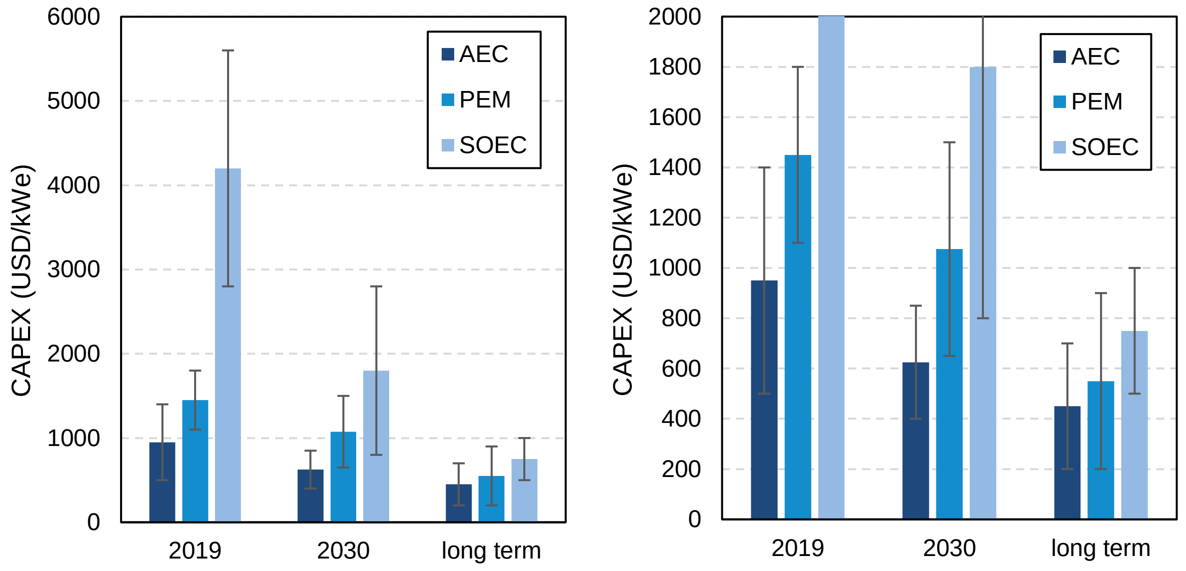
2.3.1 Weighted average cost of capital (WACC)

WACC is a measure of the interest rate at which finance may be raised to purchase the RE and electrolysis infrastructure. Higher WACC means higher annual finance charges, leading to more expensive hydrogen. WACC depends upon perceived project risk: risk will be regarded as low if the annual hydrogen volume to be purchased is underwritten by an advance off-take agreement with a sovereign entity, such as a purchasing government or state-owned entity. Also, lower finance rates are available from development financing institutions than commercial banks.

2.3.2 CAPEX

The high capital costs of new electrolysis infrastructure will decrease over time (Figure 10). As with RE infrastructure, this will occur as a function of the rate at which installed capacity is doubled, both globally (as a result of manufacturing scale effects, technology innovation and competition) and in-country (as a result of in-country experience and the development of supply chains).

Figure 10: Current and future electrolyser cost ranges – (a): full data range, (b): Close-up



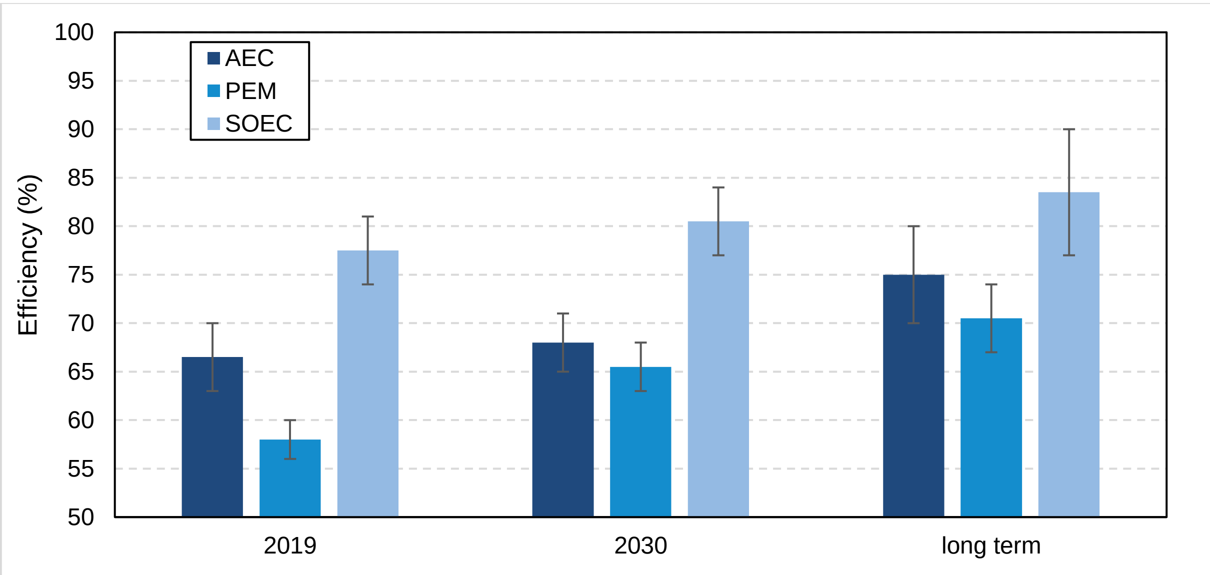
(a) **(b)**

Note: Data from [12]: Bar values indicate midpoint of ranges

2.3.3 Efficiency

Electrolysis incurs losses, so efficiency impacts green H2 production costs. Over time, the efficiency of new electrolyser plant will increase (Figure 11), for the same reasons that their costs will decrease.

Figure 11: Current and projected future electrolyser efficiencies



Note: Data from [12]: Bar values indicate midpoint of ranges

The notably higher efficiency of SOEC is due to the fact that part of the energy required can be supplied by the heat to convert the feedwater to steam. If, immediately after electrolysis, the H_2 is to undergo an exothermic chemical reaction either for storage or to produce a downstream compound, then the heat released by the exothermic reaction may be used to raise the steam. Examples of such exothermic reactions are:

- Being stored in liquid organic hydrogen carrier (LOHC)
- The manufacture of ammonia (NH_3) in the Haber-Bosch process
- The production of synthetic hydrocarbons such as methane (CH_4), methanol (CH_3OH) or Fischer-Tropsch synthesis products (petrol, kerosene and diesel)

This allows for the use of SOEC for these applications at a higher efficiency than the other electrolyser technologies. It is this inherent advantage that drives efforts to commercialise SOEC electrolysis technology.

2.3.4 Annual full load hours (FLH)

FLH are a measure of the utilisation factor of the infrastructure[16]. Since electrolysers have high capital costs, high utilisation factors (and therefore high FLH) are required for the production of low-cost green hydrogen. FLH values of at least 3000 to 4000 have been recently recommended [49]. High FLH may be promoted by meeting several requirements:

1) *Resource-optimally placed RE infrastructure:* The solar PV and wind infrastructure should be placed in areas of good solar and wind resource respectively. The RE infrastructure need not be co-located with the electrolysis plant and its water supply. It may be located further away in a region with good renewable resources and the electricity wheeled through the grid, provided sufficiently reasonable wheeling charges can be negotiated.
2) *Dedicated RE infrastructure:* It is not feasible to drive the electrolyser only with "excess" renewable power from the grid (even if the electricity tariff is low or even zero), because this will result in low electrolyser FLH values, and high hydrogen costs as a result [49]. Instead, dedicated RE infrastructure is required, where all of the electricity produced supplies the electrolyser plant exclusively, boosting the FLH of the electrolyser plant.
3) *Best in class RE technology:*
    a) Use tracking solar PV rather than stationary solar PV installations: PV installations that track the sun in one axis (single axis tracking PV or SAT PV) deliver higher annual FLH values than stationary PV installations (tilted fixed-axis PV or TFA PV), by about 30% for Morocco[17] and about 25% for South Africa[18]. By comparison, the CAPEX of SAT PV is only about 10-15% higher than TFA PV. The only reason for not installing SAT PV rather than TFA PV should be if wind-blown sand excessively increases OPEX by clogging the drive actuators [49].
    b) Maximum possible capacity factor wind turbines: Wind turbines should be designs allowing for the highest capacity factor possible, using the largest rotor diameter that road access, terrain installation, and local site specific wind resource will allow. The reason for this is that capacity factor (and therefore FLH) increase as hub height is increased[19]

[16] There are 8760 hours in a year. An annual utilization of 30% is equivalent to $\frac{30}{100} \times 8760 = 2628$ FLH

[17] 2344 for SAT PV versus 1790 for TFA PV [49]

[18] 2554 for SAT PV versus 2034 for TFA PV [59]

[19] Median capacity factor was found to increase by approximately 2 to 4 percentage points when going from 80m to 110m hub height, and by an additional 2 to 4 percentage points when going from 110m to 140m. Rising from 140m and 160 m increases median capacity values by approximately 1 percentage point

[52]. The resultant higher FLH of the electrolyser compensates for any increase in the wind electricity cost.

4) *Hybrid RE infrastructure:* Higher values of electrolyser FLH are possible if a hybrid fleet (both PV and wind) is used, where wind-generated electricity drives the electrolyser by night, and the combined hourly supply of wind and PV drive the electrolyser by day[20]. In this case, there will be some days in the year when the combined hourly wind and PV power during daylight hours will be greater than the capacity of the electrolyser. In the absence of additional flexible load or the ability to sell this electricity to other users, this excess will be curtailed. While this curtailment makes the electricity proportionally more expensive, the increased FLH of the electrolyser compensates for this[21].

Dedicated RE infrastructure is required not only to obtain high FLH values for the electrolysers (as mentioned above), but for other reasons as well. At least for the foreseeable future, even if the RE infrastructure is not co-located with the electrolyser plant so power must be wheeled over the grid, it will still be required that:

- Power to each electrolysis plant is *exclusively* supplied by dedicated, specifically contracted RE infrastructure (no nett power is sourced <u>from</u> the grid), and
- Each RE infrastructure plant built for electrolysis *exclusively* supplies specific electrolysis plant and its associated desalination plant (no nett power is supplied <u>to</u> the grid).

The reasons for this dedicated RE infrastructure are as follows:

1) *Compliance:* The SA grid is not 100% renewables based (it is predominantly coal-based). In order to qualify for European (non-transport) and Japanese (post-2040) renewable hydrogen markets, the hydrogen must be certified as being renewable in origin, and not supported by non-renewable grid power. If a given electrolyser plant is contractually linked to a given set of RE infrastructure, then compliance is easier to track. For renewable fuels of non-biological origin (RFNBO) for the European transport market, their GHG emissions must be 70% lower than those of fossil fuels, requiring the renewable content to be known and certifiable.
2) *Economic – learning rates:* the capital costs of RE infrastructure and electrolysers will decrease with cumulative installed capacity. It is envisaged that electrolyser capacity (with its supporting RE capacity) will be built in a sequence of bidding rounds, where each bidding round is backed by a separate offtake agreement with European or Japanese buyers, for a given annual production capacity of hydrogen at a given price trajectory. The earlier bids will therefore necessarily be more expensive than later bids. More expensive earlier capacity must operate for its full contractual term, with the hydrogen bought at the price trajectory agreed to at the time of awarding of the bid.

[20] It is this combination of wind and PV power that makes South Africa, Morocco, Egypt, Libya and Somalia more feasible for low cost hydrogen production than other African nations in Figure 6

[21] In the analysis of [49], the reference FLH values for SAT PV and wind were 2344 and 2700 respectively for North Africa and 2440 and 2450 respectively for the Middle East. Despite the fact that a relatively high curtailment fraction of 15% was assumed (leading to hybrid FLH values of 4287 and 4157 for North Africa and Middle East respectively), the costs of the resultant methane Powerfuel using hybrid power was comparable with (although slightly higher than) methane produced using PV alone. In a similar analysis for South Africa, the curtailment fraction was not assumed but calculated on an hour by hour basis. While electrolyser FLH values of 2554 and 3345 were obtained for SAT PV and wind respectively, for a hybrid SAT PV and wind fleet an electrolyser FLH of 5090 was obtained, implying an electrolyser capacity factor of 63.5% and a curtailment fraction of only 5.7%. The costs of the resultant hydrogen and downstream Powerfuels were lower than would have been the case from PV or wind alone [59].

3) *Political and public acceptance:* The presence of IPPs supplying electricity into the grid is a contested matter in South Africa. Despite the benefits to the climate of moving away from coal-based power, the livelihoods of individuals and companies linked to coal are affected, generating political pushback and causing significant delays in further IPP expansion [53]. For the Powerfuels initiative to succeed, delicate positioning is required. It must be made clear that no South African constituencies will be adversely affected by Powerfuels whilst demonstrating the opportunities presented by Powerfuels, since:
   a) The SA coal export market will shrink significantly in the medium term[22] [23] [24], affecting the same livelihoods. Powerfuels offers a way to replace foreign exchange lost by this export coal market decline, and possibly even jobs.
   b) Powerfuels will require RE power to be wheeled, providing income for transmission and distribution network owners.
   c) By definition, only renewable-based hydrogen qualifies for European (non-transport) and Japanese (post-2040) renewable hydrogen markets. For renewable fuels for the European transport market, the requirement that GHG emissions from the fuels must be must be at least 70% lower than those of fossil fuels requires the renewable electricity fraction for electrolysis must be even higher[25].
   d) RE capacity procured for Powerfuels will only be used by Powerfuels. It will not be consumed by the grid, will not directly displace coal-fired electricity and will not lead to coal-fired power stations being decommissioned earlier than already expected [54]. Additional capacity for the national grid is only acquired as part of the IRP: it meets additional future demand and replaces the remaining fleet of existing generators as they are decommissioned. Some of this expected new capacity is based on renewables (predominantly solar PV and wind) and would be procured via a newly released REIPPPP as a separate process. The Just Transition discussion is gaining traction in SA and would have notable implications for the deployment of new RE infrastructure.

While dedicated RE *generation infrastructure* is required, the same is not true for *transmission infrastructure*. By contrast, the aim should be to wheel the electricity through transmission and distribution networks wherever possible. This saves the hydrogen export business unnecessary investment costs by rather paying known wheeling charges. This additional revenue stream for the transmission and distribution networks also benefits other grid customers, as it enables not only ongoing transmission maintenance but also grid strengthening.

The approach in Europe is that there is a role for both electrolysers directly connected to RE plants and electrolysers connected to the grid. For grid connected electrolysis, the instruments available to ensure the renewable character of the electricity are guarantees of origin (GO) for renewable electricity and power purchase agreements (PPA). The view is that hydrogen producers should be allowed to match their production with GOs and have PPAs with multiple RE producers in order to have a flexible and workable business case. For the supply of Powerfuels

---

[22] India: ~50% of SA export coal is purchased by India, an annual market worth R33 billion in 2018 [96]. India's Coal Ministry plans to cut coal imports by one-third (85-million tonnes) by 2024 [97]. It is the intention of the Indian government that any increased coal demand be fulfilled by domestic coal in the long term [98]

[23] 13% of SA export coal is purchased by Pakistan. In December 2018, the Energy Minister of Pakistan's Punjab province expressed a wish to convert the new Sahiwal coal power plant from imported to domestic coal [98]

[24] South Korea is the 3rd largest purchaser of SA coal. South Korea's total coal imports from South Africa declined 5.5% in 2018. The South Korean government aims to encourage a switch from coal to LNG and renewables with significantly increased taxes on coal imports [98]

[25] A zero-carbon argument is made here to be safe.

by South Africa to Europe, it will be important to have an aligned approach across stakeholders on this [15].

Also, in the EU, the question of additionality, as well as temporal and geographical correlation are concepts being used in legislation [15]. While temporal correlation is reasonable, for South Africa a geographical correlation would be overly restrictive. South Africa is a large country without navigable inland waterways. Thus, transport of Powerfuels to the coast would involve road, rail or pipeline transport, increasing costs and making South Africa less competitive. Transport economics therefore dictates that Powerfuels should be produced at or near the port of shipping. The best renewable resources are not necessarily at the ports, necessitating wheeling of the renewable electricity via the grid.

2.4 Water costs

For the hydrogen to qualify as sustainable, the water source must also be sustainable: using water for fuel production must not negatively affect communities, agriculture or the environment. This is a particular concern under the German National Hydrogen Strategy, which states *"the sustainable supply of water in arid regions of these countries must not be impaired by the production of hydrogen"* [40].

South Africa is ranked as the 30th driest country in the world. Extreme climate and rainfall fluctuations make it a highly water-stressed country. By 2030, severe water shortages are expected in Gauteng, Mpumalanga, KwaZulu-Natal, and the Western Cape (

Figure 12) [55].

The use of potable water for hydrogen generation is therefore not sustainable. Fortunately, the cost of desalination of saline or non-potable water makes up a near-negligible fraction of hydrogen production cost. As mentioned in Section 1.5.1, the Japanese cost targets for hydrogen are \$3/kg in 2025 and \$2/kg in 2050. Compared with these values, the desalination cost component has been calculated to vary between 0.005-0.020 \$/kg of hydrogen produced [56], which is less than 1% of the 2025 target price[26]. From this, it may be seen that a hydrogen production industry can *contribute* to water resilience rather than *detract* from it, as it is in a far better position to carry the costs of desalination than communities or agriculture, who by necessity must rely on other cheaper water abstraction sources and treatment processes.

For these reasons, treated non-potable water is the preferred feedwater supply option for bulk hydrogen production in South Africa. In order to produce bulk hydrogen competitively, transport economics dictate that road transport costs must be kept to a minimum.

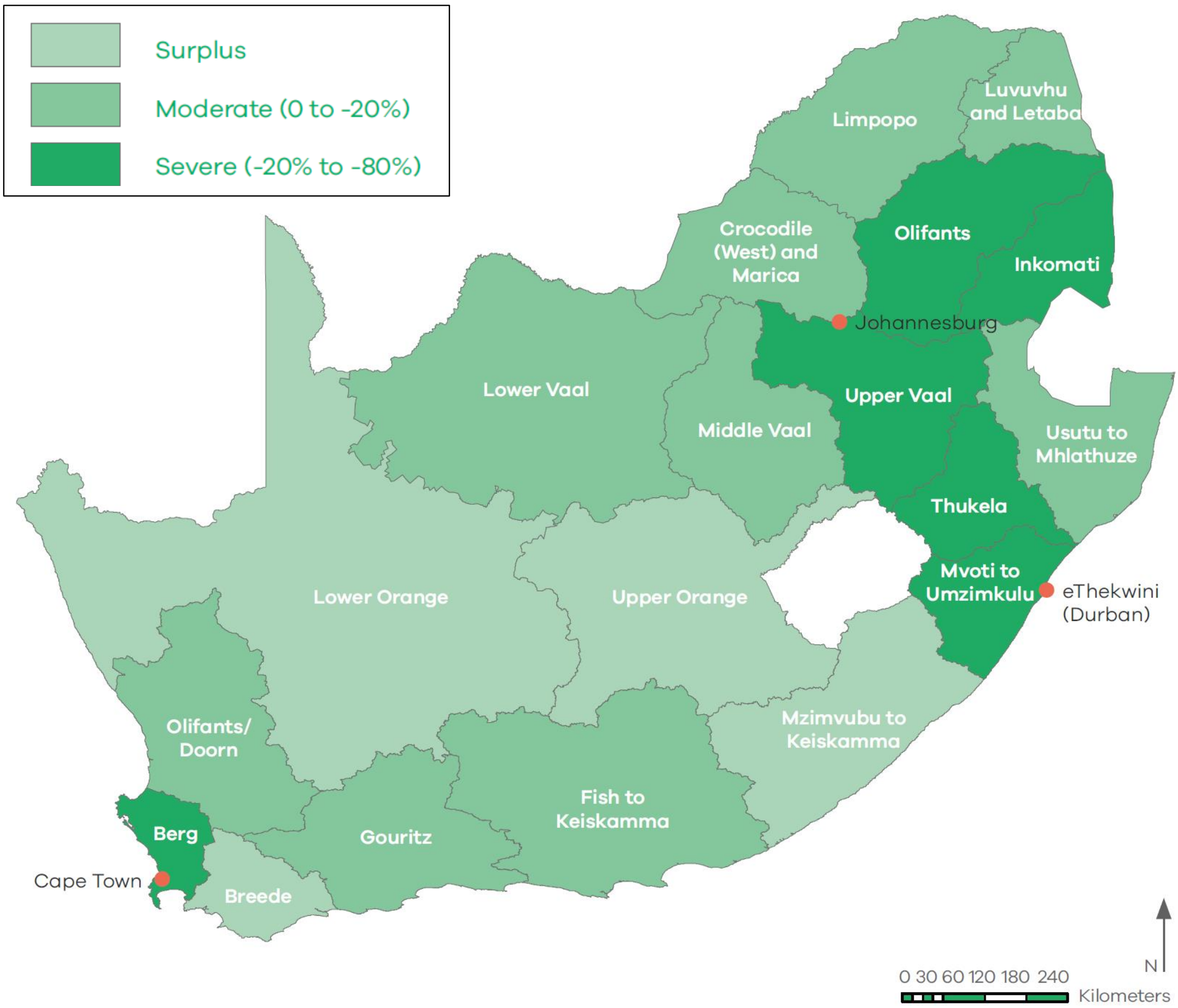
A distinction is therefore made between inland and coastal markets. For the production of hydrogen for export and coastal use, the feedwater should be desalinated seawater. Export hydrogen should be produced at or near the port of shipment.

For the production of hydrogen for inland domestic use, the feedwater should be desalinated/treated water from heavily contaminated sources not treatable by municipal wastewater treatment plants i.e. mine water, acid mine drainage and industrial wastewater. Municipal

[26] The principal reason desalination is such a small fraction of the hydrogen cost is the low specific energy cost of desalination (3-5 kWh/m^3 of desalinated water) compared with the energy cost of electrolysis (about 50 kWh/kg of hydrogen, or ~5 500 kWh/m^3 of water electrolyzed).

wastewater should only be used when these other sources are fully exhausted, as industry may need this water source in the future.

Figure 12: The projected gap between water supply and demand by 2030 in SA catchment areas



Source: [55]

As part of the "social licence to operate", it is recommended that desalination plants supplying the electrolysis plants for bulk hydrogen production be oversized to be at least 300% the capacity required for the electrolysis plant alone. The extra CAPEX costs should be carried by the project and built into the hydrogen price (which, as demonstrated, will not be greatly affected).

For coastal hydrogen production (for export and coastal use), the proposed approach is that in times of good rains and full dams, the desalination plants operate at reduced capacity, supplying only the electrolyser plant. In times of drought, however, the desalination plants operate at full capacity. The local water utility then buys the excess water, paying only for the electricity component: the capital repayment costs are paid for by the hydrogen business.

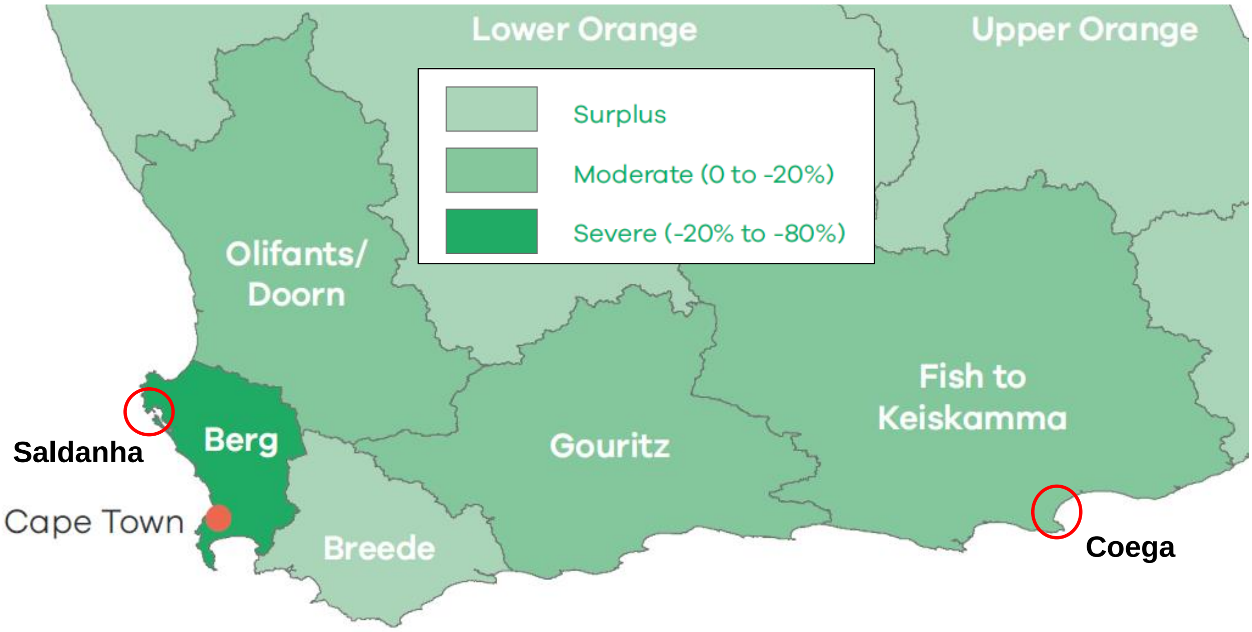
For inland hydrogen production, it is recommended that the oversized desalination plants permanently operate at full capacity. This supports the capacity of the state to treat contaminated water issuing from public sources such as acid mine drainage from abandoned mines without owners, as this burden normally falls to the fiscus. For operating industries that produce contaminated waste water, such as mines and factories, it provides opportunities for partnerships with hydrogen businesses to treat their effluent water.

The above approach will have two beneficial effects. Firstly, it directly addresses the concerns in the German National Hydrogen Strategy, and even increases the water resilience and water treatment capacity of the municipalities and metros involved. Secondly, it makes it easier to secure buy-in from South African public sector stakeholders, as public water infrastructure is difficult to finance, and desalination infrastructure particularly so. Under this approach, coastal water utilities in regions of hydrogen export production now only need to procure base-demand operating desalination plants to meet growth-related additional demand, for which the offtake can be known with greater certainty, making them easier to finance. Capacity to meet seasonally variable and drought-related additional demand is procured by the hydrogen export business.

Two ports in particular are considered attractive for the manufacture of hydrogen for export. Firstly, the Port of Saldanha Bay is attractive for shipments to Europe, as it is South Africa's deepest port and is on the Western seaboard. It has a 365 m long tanker berth for liquid bulk cargo with a permitted draught of 21.25 m alongside[27] [57]. It is also geographically close to good combined solar and wind resources. It is in the Berg catchment, severely affected by water stress (Figure 13).

Figure 13: Close-up of

Figure 12, showing location of proposed hydrogen export ports



Secondly, the Port of Coega makes most sense for shipments to Japan and South Korea, as it is an underutilised deep-water port designed to accommodate vessels of 14 m draught on the Eastern seaboard [58]. It is close to good wind resources, but unfortunately the local solar

[27] In addition to an 874 m long multipurpose quay for breakbulk cargo with max. permitted draughts of 12 m and 13.4 m, and a 630 m iron ore jetty with a permitted draught of 21.25 m on either side

resourse is not strong. That said, it may be connected to good solar regions via the national electricity grid. It is in the "Fish to Keiskamma" catchment with Moderate water stress expectations (Figure 13).

2.5 Cost of hydrogen storage

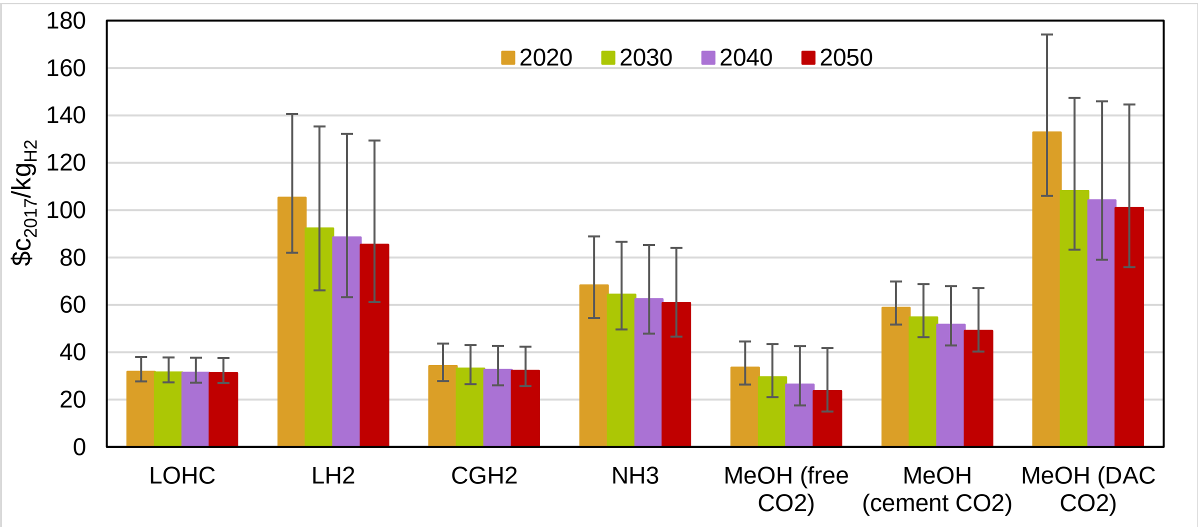
Before hydrogen can be delivered to markets, it must first be stored in a suitable form. Two options exist for storing pure hydrogen: as compressed gaseous hydrogen (CGH_2) at 300 to 700 bar in pressurised tanks, or as cryogenic liquid hydrogen (LH_2) at -253 °C.

Hydrogen may also be stored chemically, either in a chemical compound with high hydrogen content such as ammonia (NH_3) or methanol (MeOH), or else by means of reversible reactions in liquid organic hydrogen carrier (LOHC). If stored as MeOH, the cost is dependent upon the cost of the CO_2 feedstock, which is inversely proportional the concentration of CO_2 in the source gas mixture:

- At lowest cost from highly concentrated steams, such as from a water-gas shift reactor of a Fischer-Tropsch synthesis plant (such as Sasol or PetroSA).
- At moderate cost from the high concentration flue gases of cement plants or steel plants
- At higher cost from flue gases of coal-fired boilers
- At highest cost from direct air capture (DAC)

It has been calculated that renewable hydrogen is generated at lowest cost in South Africa using approximately equal capacities of single axis tracking PV and wind generated electricity [56, 59] [28]. Figure 14 compares the levelised cost of storage (LCOS) of hydrogen using electricity from this RE configuration.

Figure 14: LCOS of hybrid wind/SAT PV-generated H_2 from 2020 to 2050, in 7 different storage options



Source: [59]

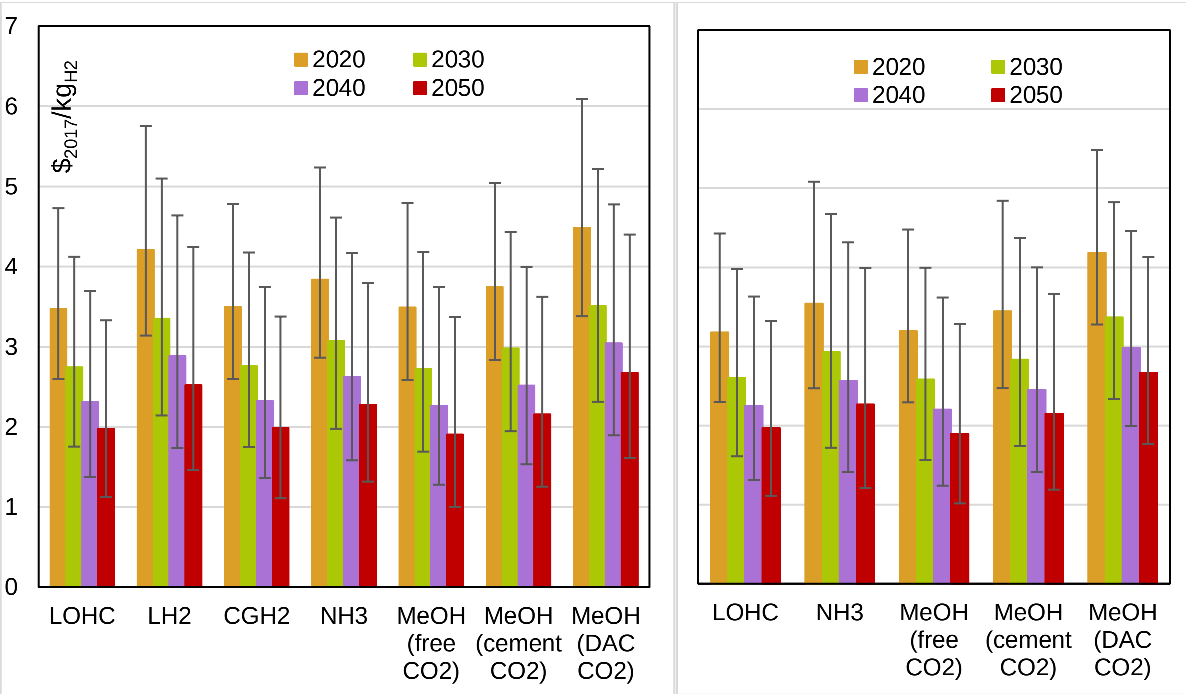
The lowest LCOS values are achieved for LOHC, compressed gaseous storage and MeOH using CO_2 obtained at zero cost. The error bars indicate the range in costs between the most

[28] For comparison, a European study on the costs of hydrogen generation, storage and transport is [99]

optimistic scenario (representing the combined effect of the lowest values for WACC and CAPEX for both RE and electrolysis) and the most pessimistic (representing the combined effect of the highest values for RE and electrolysis CAPEX and WACC) scenarios. The bars indicate the results under the reference scenario, representing the most likely values.

Figure 15 shows the combined cost of hydrogen generation and storage for low temperature electrolysis (left) and high temperature electrolysis (right). The storage of hydrogen generated by high temperature electrolysis in SOECs only makes sense for the exothermic processes: LOHC, NH_3 and MeOH, where the heat released by the exothermic process may be productively used by the SOEC. Therefore, LH_2 does not appear in Figure 15 (right).

Figure 15: **Cost of hybrid wind/SAT PV-generated H_2 from 2020 to 2050, stored as 7 different options: Left - From low-temperature electrolysis, Right - From high-temperature electrolysis**



Source: [59]

2.6 Cost of hydrogen transport by ship

In the study mentioned in the previous section, the preliminary costs of shipping renewable hydrogen in the different carriers was determined from Coega to Kobe, Japan [56, 59]. The transport distance by sea from Coega to Kobe is 14 300 km, whilst the equivalent distance from Saldanha to Rotterdam is 11 200 km (80% of the distance), allowing comparisons to be made regarding shipping costs to Europe.

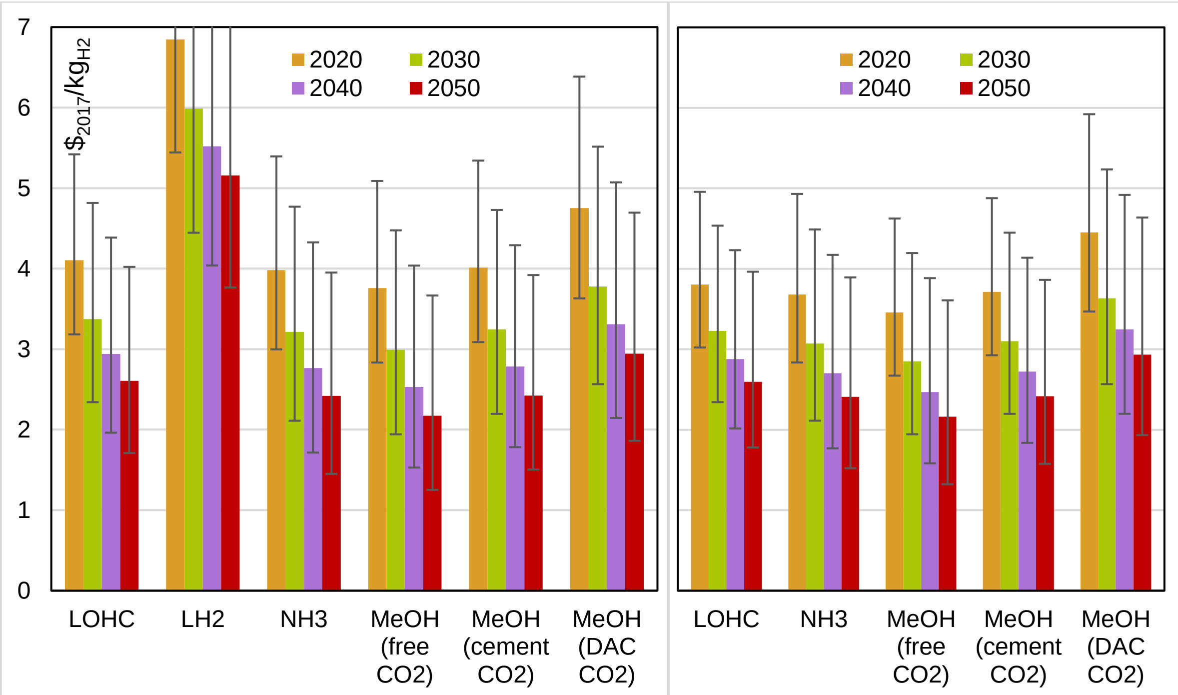
The calculated trip cost of transport of hydrogen from Coega to Kobe is given in Table 1. Long-distance transport of compressed hydrogen by sea was ruled out, as it was considered infeasible in existing ships, and unattractive due to its low energy density. While transport of hydrogen as LH_2 is technically feasible, it is far more expensive than the other carrier options analysed. The cost of hydrogen generated, stored, transported and delivered in Japan is shown in Figure 16.

Table 1: LCOT values for CLH_2, GCH_2 and LOHC in US$/kg by ship

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

Source: [56]

Figure 16: Cost of hybrid wind/SAT PV-generated H_2, stored as 7 different options and transported by ship to Japan from 2020 to 205: Left - low-temperature electrolysis, Right - high-temperature electrolysis



Source: [56, 59]

The following cost conclusions can be made:

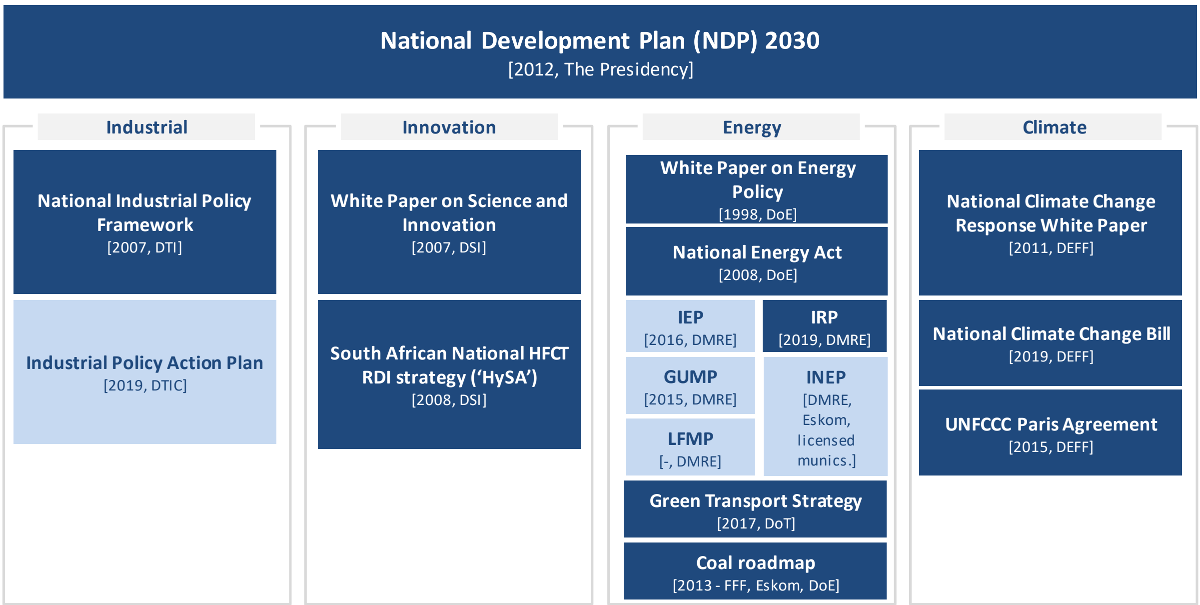
- For CGH_2, transport by ship is not feasible.
- For CLH_2, the transport costs cannot be justified compared with the other carriers
- the costs for LOHC, NH_3 and MeOH (Excluding using CO_2 from DAC) are comparable
- Up to 2040, a cost advantage may be obtained using SOEC compared with low temperature electrolysis

3 South African Legislative and Policy Overview

3.1 Overarching policy environment

The nexus of climate change policy, industrial policy, energy policy and innovation policy informs the role of green hydrogen and Powerfuels in South Africa. This context is provided in Figure 17 and will be summarised in the sub-sections that follow but all are guided by the overarching National Development Plan (NDP) Vision 2030 as published in 2012 [60].

Figure 17: South African policy context (specifically focussed on green hydrogen and Powerfuels)



Note: Light shades indicate draft policy or policy updated periodically. DEFF – Department of Environment, Forestry and Fisheries; DTI/DTIC - Department of Trade, Industry and Competition; DMRE/DoE - Department of Mineral Resources and Energy; DSI - Department of Science and innovation; DoT - Department of Transport; HFCT – Hydrogen and Fuel Cell Technologies; RDI – Research, Development and Innovation; IEP – Integrated Energy Plan; IRP – Integrated Resource Plan; GUMP – Gas Utilisation Master Plan; INEP – Integrated National Electrification Programme; LFMP – Liquid Fuels Master Plan

Chapter 4 of the NDP envisions an energy sector that promotes:

1) Economic growth and development through adequate investment in energy infrastructure. The sector should provide reliable and efficient energy service at competitive rates, while supporting economic growth through job creation.

2) Social Equity through expanded access to energy at affordable tariffs and through targeted, sustainable subsidies for needy households

3) Environmental sustainability through efforts to reduce pollution and mitigate the effects of climate change.

Chapter 5 of the NDP also speaks clearly to the need for sustainability and an equitable transition to a low-carbon economy. As part of this, investments into skills, technologies and institutional capacity are highlighted as part of an envisioned shift away from the existing carbon intensive economy to one that utilises but diversifies natural resource and mineral usage sustainably (including PGMs) with renewable energy at the core of enabling this transition.

From this, the role of hydrogen as an energy carrier, feedstock or for end-use directly is clear especially if produced via low-carbon and clean energy sources like renewable energies. More specifically, the ability to produce hydrogen and Powerfuels for domestic and export markets, to produce energy from hydrogen, to enable energy access via hydrogen and to improve environmental sustainability via reduced pollution when producing hydrogen and Powerfuels is clear.

3.2 Industrial policy

The National Industrial Policy Framework [61] provides for the development of a rolling action plan in South Africa called the Industrial Policy Action Plan (IPAP). The latest iteration of South Africa's Industrial Policy Action Plan (IPAP) for 2019/20 – 2020/21 [62] includes a renewed focus on particular focus areas as well as transversal focus areas. The need to create and maintain a tightly coordinated and supportive environment that provides and enables policy certainty, stakeholder consultation, state-owned companies' (SOCs) renewal and commitment to a sustained war on corruption and collusion is articulated. These are necessary conditions for investment and growth as part of South Africa's much needed re-industrialisation.

IPAP 2018/19-2020/21 includes six (6) transversal focus areas as follows:

- Public procurement and local content
- Industrial financing
- Developmental trade policy
- African integration and industrial development
- Special Economic Zones (SEZs)
- Innovation and technology

Most relevant for green hydrogen and Powerfuels would be the positioning of public procurement and local content where parts of particular value-chains in 23 sectors/products are currently designated for local content whilst simultaneously being subject to public sector preferential procurement policies. Designations for further sectors/products are also continuously under consideration for localisation and should be tracked accordingly. Current requirements are not currently explicit on green hydrogen or Powerfuels infrastructure directly but will at least be indirectly affected in sectors/products including:

- Electrical/telecommunication cables
- Valves/actuators
- Working vessels
- Powerline hardware and structures
- Transformers
- Solar PV components
- Steel products and components for construction
- Pumps and MV motors

On industrial financing, incentives exist for including historically disadvantaged individuals, local supplier development requirements, industrial parks and the promotion of public-private partnerships (PPPs) in manufacturing.

On developmental trade policy, South Africa's technical infrastructure institutions are well respected and collaborate internationally to pool expertise for common standards and wider developmental challenges mandated through legislation. These include the South African National Certification Accreditation System (SANAS), the National Regulator for Compulsory Specification (NCRS) and South African Bureau of Standards (SABS). Particular focus areas for these institutions are in re-industrialisation and technology-intensive production whilst ensuring international norms and standards are established and maintained but in some cases require investment and recapitalisation (SABS).

Integration in the Southern African region as well as African continent has also become a transversal focus area with South Africa heavily involved establishing the Tripartite Free Trade Area (TFTA) and ultimately the Continental FTA. This is also seen as key to industrialisation in the region as current regional trade is only 12% and is expected to increase in future. This can be seen as an opportunity for green hydrogen and Powerfuels in South Africa as a springboard into the region and onto the continent, considering South Africa's established capital markets, long established developmental finance institutions (DFIs), and deep engineering and industrial capabilities.

SEZs have shown to be an effective tool for industrialisation but require focussed attention on priority sectors and disciplined implementation. South Africa has undertaken to invest in SEZs with particular focus on their effective design, planning, development and management. Packaged incentives for particular sectors setting up within SEZs can provide for favourable conditions for investment in green hydrogen and Powerfuels (whether in already existing SEZs or new SEZs being planned).

A listing of the twelve (12) focus areas of the IPAP 2018/19-2020/21 is as follows:

- Automotive
- Clothing, textiles, leather and footwear
- Metal fabrication, capital and rail transport equipment
- Agro-processing
- Forestry, timber, pulp, paper and furniture
- Plastics, pharmaceuticals, chemicals and cosmetics
- Minerals beneficiation
- Green industries
- Business process services
- Marine manufacturing and associated services
- Aerospace and defence
- Electro-technical industries

In relation to hydrogen and Powerfuels, focus areas of relevance include automotive, minerals beneficiation, metal fabrication, green industries and electro-technical industries.

South African industrial policy is focussed on industrialisation and the country is well aware of the small domestic market relative to international markets. Thus, South Africa has an intentional focus on export opportunities across focus areas. This is no different in the focus areas listed and the automotive sector is a good demonstration of this as most vehicles manufactured in South Africa are for export markets (with a 40% local content being achieved thus far but seems to be saturating).

As part of minerals beneficiation focus, intentionally creating demand for PGMs as part of a hydrogen economy is a clear area of growth for export markets as it relates to green hydrogen and Powerfuels in South Africa. South Africa has more than 80% of the world's known Platinum reserves and houses the three largest PGM miners in the world. The IPAP is clear on the intention to expand PGM beneficiation industries including those in mobility and stationary application for energy production and end-use e.g. fuel cell public commuter busses. In this, an immediate focus on commercialising fuel cell components and localising assembly, fuel cell components and complete fuel cell systems manufacturing to become embedded in global value chains is acknowledged.

Metals production and fabrication in South Africa could allow for increased local content as part of hydrogen and Powerfuels related infrastructure development but input costs constrain existing operations making it increasingly difficult for some to compete internationally (energy, logistics and raw materials).

On green industries, following the successful Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) amongst other renewable energy focussed interventions, further localisation is being sought in green industries' value chains for South Africa. There is no explicit positioning of green hydrogen production or Powerfuels at this stage in IPAP but the opportunities for green hydrogen and Powerfuels production, domestic use and export to international markets is clear in terms of value-add for South Africa and international partners.

Although it seems clear that most infrastructure and skills directly linked to potential green hydrogen and Powerfuels production in South Africa would be initially imported, particular electro-technical industries could be nurtured if localisation and skills development is prioritised to enable exports in future (regionally and internationally). However, IPAP recognises that local production costs relative to international competitors could make the domestic market relatively uncompetitive in this sector.

3.3 Climate change policy

The South African government recognises climate change as one of the greatest threats to sustainable development and that South Africa along with developing country peers will be most vulnerable to its impacts. Thus, the South African National Climate Change Response White Paper [63] was published in 2011 as a response to this threat and outlines two objectives:

1) Effectively managing inevitable climate change impacts through interventions that build and sustain South Africa's social, economic and environmental resilience and emergency response capacity; and

2) Make a fair contribution to the global effort to stabilise greenhouse gas (GHG) concentrations in the atmosphere at a level that avoids dangerous anthropogenic interference with

the climate system within a timeframe that enables economic, social and environmental development to proceed in a sustainable manner

South Africa realises the need to be part of the global effort to curb GHG emissions but needs to remain cognisant of developmental and poverty eradication challenges. Thus, the principles applied in South Africa's climate change response include common but differentiated responsibilities and respective capabilities, equity, special needs and circumstances, uplifting the poor and vulnerable, intra- and inter-generational sustainability, precautionary, polluter pays, informed participation and the economic, social and ecological pillars of sustainable development.

As part of the South African mitigation response, the reduction of GHG emissions dominated by the energy sector is a clear focus area considering existing dependence on coal for direct end-use, the large majority of electricity generation and the production of one-third of liquid fuels (via coal-to-liquids). South African GHG emissions are relatively high on a per capita basis (CO2eq/person) and an intensity basis (CO2eq/unit of GDP). The expected growth of South Africa's population combined with increasing levels of urbanisation is expected to result in significantly increased energy demand and significantly increased levels of GHG emissions making the imperative of decoupling this growth from GHG emissions increasingly important. As part of South Africa's fair contribution to limiting anthropogenic warming to below 2°C above pre-industrial levels, a peak-plateau-decline trajectory is used to measure against mitigation efforts (peaking between 2020-2025, plateau for 2025-2035 and declining from 2035 onwards towards 2050).

A further commitment to this came in 2015 when South Africa became a signatory to the Paris Agreement on climate change [2], [64] as an international framework to guide limiting GHG emissions and to meet challenges posed by climate change.

3.4 Energy policy

The White Paper on Energy Policy published in 1998 remains the existing guiding document for energy policy in South Africa and outlines South Africa's energy context, objectives and priorities for energy policy following the end of Apartheid and the need for greater emphasis on transparency, inclusiveness and accountability in the energy sector [65].

The National Energy Act of 2008 aims to ensure diverse energy resources are available in affordable quantities to the South African economy to support economic growth and poverty alleviation whilst accounting for surrounding environments and economic sectors [66]. It established the need for energy supply optimisation and utilisation, integrated energy planning, setting up of institutions (e.g. SANEDI) and security of supply.

Universal energy access predominantly enabled by an intentional Integrated National Electrification Programme (INEP) at a national level has enabled near 90% electricity access in South Africa from a very low base since 1994.

As part of integrated energy planning, the need for a long-term Integrated Energy Plan (IEP) is defined and is a key strategic planning document to deal with the supply, demand, transportation, transformation and storage of energy. Although an IEP has yet to be finalised, various drafts have been published on previous occasions in 2003, 2005, 2012 and 2016 with varying degrees of detail and public consultation. Similarly, other strategic energy planning documents that are intended to feed into the IEP as part of South Africa's strategic energy planning framework include the Gas Utilisation Master Plan (GUMP) and Liquid Fuels Master Plan (LFMP). Neither of these strategic planning documents have been finalised thus far.

The Electricity Regulation Act of 2006 [67] and linked *Electricity regulations on new generation capacity* [68] explicitly require the development, publication and updating of the national level long-term electricity sector plan known as the Integrated Resource Plan (IRP). Amongst other aspects, the IRP establishes long-term planning scenarios relative to a least-cost base plan to meet electricity demand requirements whilst considering government policy objectives for a diverse generation mix.

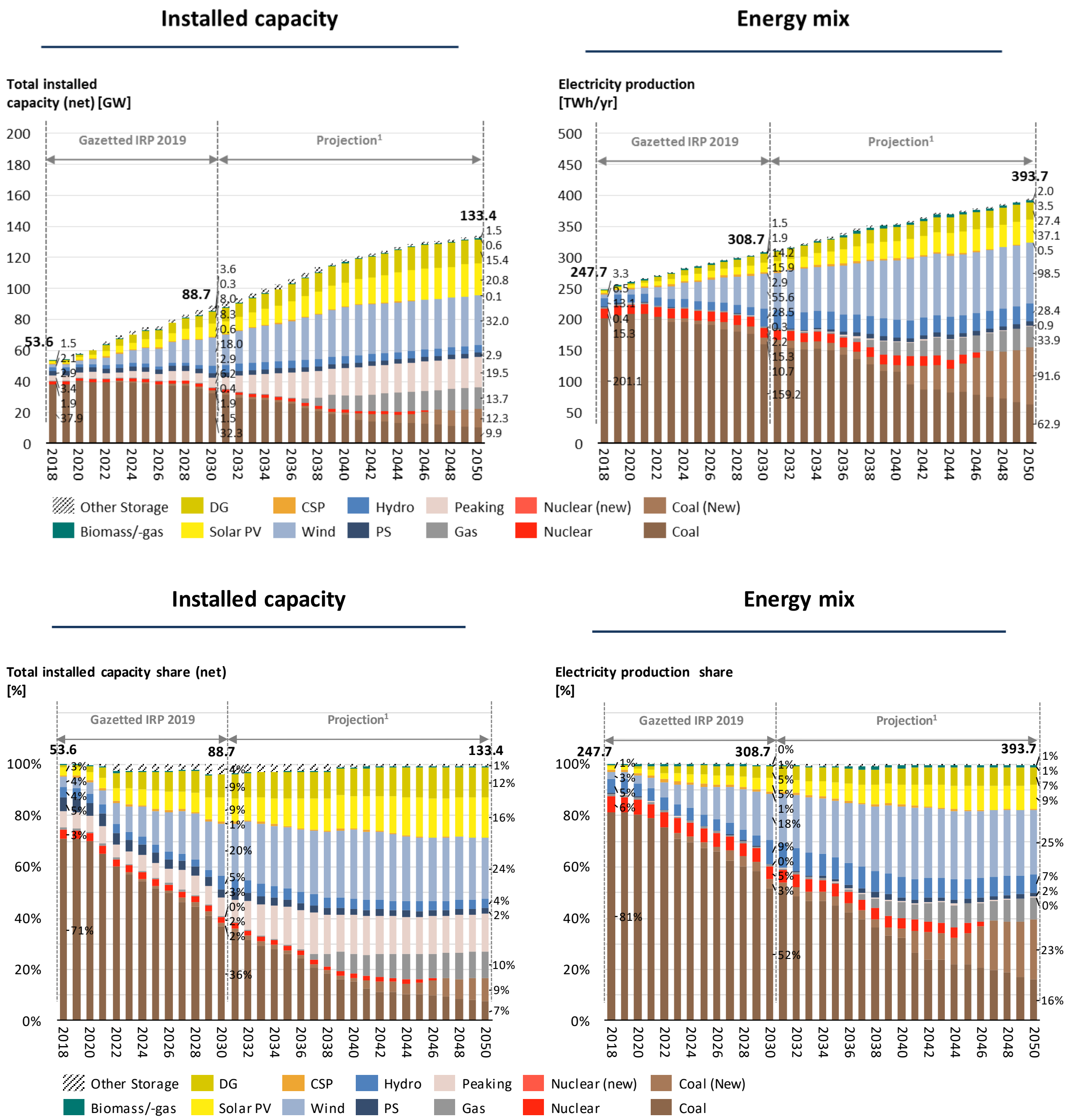
The latest iteration of the IRP is the IRP 2019 [54]. The electrical energy mix expected from the IRP 2019 by 2030 is summarised in Figure 18. Coal is still expected to play a significant but decreasing role in the energy mix by 2030 (~55%). The expected growth in demand combined with a decommissioning coal fleet will mean that even though a sustained renewables new-build deployment is expected towards 2030, renewables are only expected to contribute ~39% to the energy mix by 2030 (driven by wind and solar PV).

In order to drive green hydrogen production and Powerfuels in South Africa, dedicated infrastructure may be necessary to enable hydrogen production from renewables but significant new-build renewables allocations in the IRP 2019 in the form of solar PV and wind enables significant new-build capacity for this to happen.

Liquid fuel production in South Africa is predominantly undertaken via large-scale oil imports or refined liquid fuel imports complemented by synthetic liquid fuel production (coal-to-liquids and gas-to-liquids). About one-third of South Africa's liquid fuel demand is met by synthetic liquid fuel production predominantly by the private sector (Sasol) and the balance coming from the public sector (PetroSA). A prospective opportunity for securing South Africa's national energy security whilst addressing relatively high energy sector GHG emissions would be the displacement of liquid fuel refining with synthetically produced Powerfuels. This is not yet considered or integrated into national policy or strategic planning documents like the IEP, IRP, LFMP or GUMP.

As part of a low-carbon energy sector contributing to South Africa's GHG emissions reductions, the displacement of carbon intensive electricity with low-carbon energy sources including renewables has a significant role to play. However, when considering the overall energy mix, it is clear that there is a distinct opportunity for sector-coupling of transportation and industrial process heating into electricity where relatively cheap renewables-based electricity could directly or indirectly provide fuels and storage. Domestically, however, it seems that there is only so much of a role that hydrogen and related energy carriers could initially play in doing this. It seems that hydrogen and related energy carriers for export markets would initially play a much bigger role where the international market opportunities are immediate.

Figure 18: Installed capacity and electrical energy mix expected in South Africa by 2030 (from IRP 2019)



Note: Projection based on optimisation of 2030-2050 energy mix utilising input assumptions from DMRE IRP 2019 (not unconstrained least-cost); DG = Distributed Generation; PS = Pumped Storage; NOTE: Energy share is a best estimate based upon available data.

Sources: IRP 2019, CSIR Energy Centre analysis

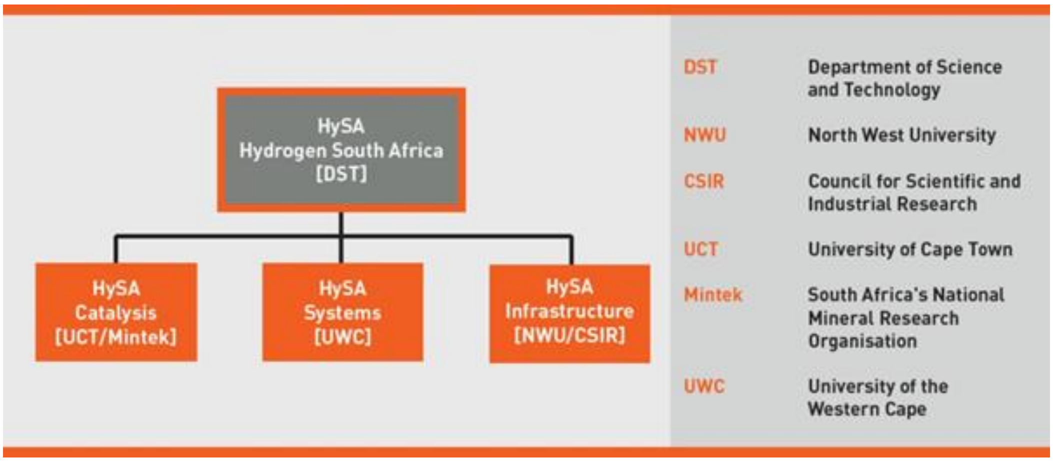
3.5 Innovation policy and HySA

The White Paper on Science and Technology from [69] and 10-year Innovation Plan towards a knowledge-based economy for South Africa (2008-2018) [70] informed the establishment of the South African National Hydrogen and Fuel Cells Technologies (HFCT) Research, Development and Innovation (RDI) Strategy [71]. For reference, a new White Paper on Science, Technology and Innovation was published by the Department of Science and Innovation (DSI) for public comment in 2019 [72].

The South African National HFCT RDI strategy, more commonly known as the Hydrogen South Africa (HySA) strategy, was established in 2008. HySA was established to stimulate and guide innovation of the hydrogen value chain in South Africa in developing South African intellectual property, knowledge, human resources, products, components and processes in a rapidly changing world of hydrogen as an energy carrier and feedstock for industrial processes. As shown in Figure 19, HySA is structured into three centres of competence including HySA Infrastructure (led by North West University - NWU - and the Council for Scientific and Industrial Research - CSIR) [73], HySA Catalysis (led by University of Cape Town - UCT - and MINTEK) and HySA Systems (led by University of the Western Cape - UWC) [74]. The ultimate goal of the HySA strategy is to enable South Africa to achieve 25% share of global hydrogen and fuel-cell catalysts market using PGM catalysts, components and systems by 2020.

HySA is generally focussed on research, development and innovation with assumed crowding in by the private sector to scale-up and reach overall goals of HySA. Some level of private sector investment has scaled initial research, development and innovation funding as well as research outputs via Anglo American Platinum as well as Impala Platinum. However, although contributions have been made towards achieving the HySA overarching goal of 25% of global supply of PGM based fuel-cell industry, this goal has not yet been achieved as of 2020.

Figure 19: Structure of three centres of competence of HySA and stakeholders



3.6 Hydrogen focussed policy roadmap

The Department of Science and Innovation (DSI) is currently developing a policy roadmap to inform and enable all relevant parties on deploying large-scale hydrogen technologies in South Africa. A specific focus is expected to be placed on green hydrogen (hydrogen produced by renewable electricity) whilst also sourcing other sources of hydrogen production including grey hydrogen (hydrogen derived from natural gas), blue hydrogen (hydrogen derived from natural gas with CCS) and brown hydrogen (hydrogen derived from coal).

3.7 Conclusion

The combination of South Africa’s platinum group metals (PGMs) reserves, historical experience in industrial scale Fischer-Tropsch infrastructure and world-class wind and solar resources combined with extensive land area forms a strong case for domestic green hydrogen and Powerfuels production in South Africa.

An overview has been given of the South African legislative and policy environment with respect to renewable electricity and Powerfuels. This includes focussed discussions on industrial policy, climate change policy, energy policy and innovation policy. The requisite policy environment across these areas is shown to be supportive of Powerfuels. However, there is a definitive need to shift from an already existing supportive policy environment in most of these areas to one that is enabling and ambitious. This would empower South Africa to realise the Powerfuels opportunity via initial pilot implementation and roll-out at scale thereafter.

4 Summary of Workshop – Outcomes, Barriers and Recommendations

4.1 Background

As mentioned in Section 1.1, the aims of the Powerfuels technical workshop in December 2019 were to explore the potential of the Powerfuels economy, and to identify hurdles that could hinder the establishment of South Africa as a major supplier. The workshop targeted three sectors – aviation, industrial uses and road transport.

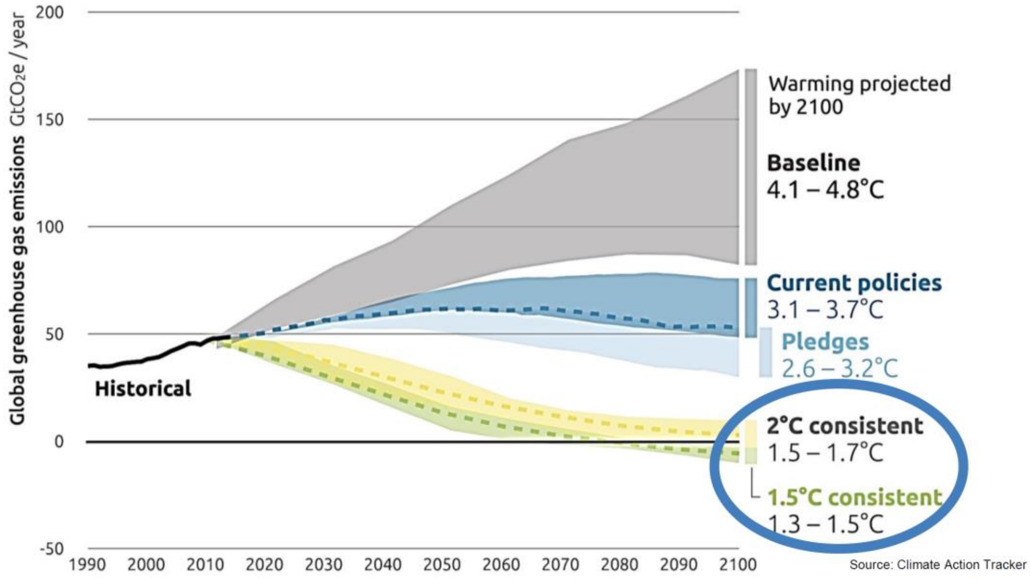
This chapter will review the presentations, and summarise the outcomes, barriers and recommendations.

4.2 Stefan Siegemund (dena: Head of Department): Electrons and molecules: Powerfuels as a missing link for the energy transition

The presentation began pointing out the significant disconnect between the trajectories of annual GHG emissions required to meet the goals of the Paris Agreement, and the trajectories currently achievable by the global community (Figure 20), either:

- Under policies in place in the different countries, or
- If the carbon reduction pledges made by all 196 signatories to the Paris Agreement all come to fruition.

Figure 20: Comparison of trajectories of global annual GHG emissions under different scenarios



Source: [48]

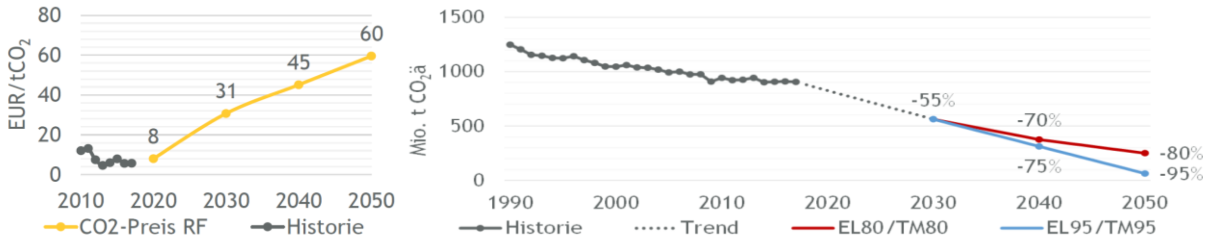
Under an integrated energy study for Germany, dena modelled five scenarios:

- The Reference (RF) scenario reflects an ambitious projection of past and current trends in politics and technology. The scenario assumes that no binding climate goals are imposed, but rather that a CO_2 price is applied in all sectors, which increases over time in a near-linear fashion from historical cost to 60 €/t in 2050 (Figure 21, left).

- Electrification (EL) involves quick and extensive electrification of most energy uses in buildings, industry and mobility; at two different ambition levels (80 % and 95 %)
- Technology Mix (TM) involves a broad variation of energy carriers, infrastructures and applications in all sectors, again at ambition levels of 80 % and 95 %

The climate paths are illustrated in Figure 21 (right).

Figure 21: **Left - CO_2 price applied under RF scenario, Right – Climate paths for Germany under EL and TM scenarios**



Source: [48]

The impact on each of the three pillars of the energy transition (renewable electricity, energy efficiency and Powerfuels) was explored for Germany under the five scenarios:

- Renewables: The installed RE capacity in Germany, which was 94 GW in 2015, will:
  - have doubled by 2030 (184 – 192 GW) under all scenarios,
  - have trebled by 2050 under the TM scenarios (318 and 325 GW) and quadrupled for the EL scenarios (385 and 392 GW). This capacity will be dominated by onshore wind energy (in all scenarios at least 170 GW) and photovoltaics (at least 114 GW).
- Energy efficiency: Total energy demand, which was 2518 TWh in 2015, will decrease:
  - Under all scenarios:
    - Least under the RF scenario, by 2030 by about 9% to 2285 TWh, and by 2050 by about 22% to 1964 TWh
    - More under the TM scenarios, by 2030 by about 12% to 2217 TWh (80% scenario), and by 2050 by about 34% to 1674 (80% scenario) and by about 37% to 1597 TWh (95% scenario)
    - Most under the EL scenarios, by 2030 by about 23% to 1948 TWh (80% scenario), and by 2050 by about 38% to 1551 (80% scenario) and by about 41% to 1477 TWh (95% scenario)
  - And under all sectors:
    - Industry: to 26-33% of 2015 levels
    - Buildings: to 47-64% of 2015 levels
    - Transport: to 43-52% of 2015 levels
- Powerfuels:
  - While starting as only an element of the mix for transport in 2030, Powerfuels becomes essential from 2040.

- In the 95% scenarios, Powerfuels's share of final energy consumption in transport in 2050 will be 50 % to 65 %.
- As H_2 demand increases, it should be met from renewable sources to help reduce GHG emissions. From 2040 at the latest, however, all CH_4 applications and liquid fuels would also have to be defossilised.
- Powerfuels demand data were only given by sector for the 95% scenario, for which the main demand sectors are Transport and Industry in 2030 and 2040, with Energy and Buildings only becoming significant demand drivers approaching 2050.

Table 2: Powerfuels demand per sector in Germany under different scenarios

Year	Transport		Industry		Energy		Buildings	
	EL95	TM95	EL95	TM95	EL95	TM95	EL95	TM95
2030	27	27	20	27	0	2	0	0
2040	84	53	32	48	2	15	0	0
2050	170	262	154	325	207	170	1.4	151

Source: from data in [48]

In addition to renewable power and energy efficiency, therefore, the above shows that a successful energy transition requires Powerfuels as a third pillar. Under all scenarios, there will be a significant need for Powerfuels from 2030 onwards. Table 3 summarises the total for different years and under the EL and TM scenarios (no Powerfuels demand under the RF scenario). In addition to the Powerfuels annual energy (in TWh), the equivalent annual volumes of hydrogen (in Mt per year) are also supplied for the reader's convenience.

Table 3: Powerfuels demand for Germany under different scenarios

Year	TWh/year				Hydrogen equivalent in Mt/year			
	EL80	TM80	EL95	TM95	EL80	TM80	EL95	TM95
2020	4	5	?	?	0.12	0.15	?	?
2030	47	46	47	56	1.41	1.38	1.41	1.68
2040	117	118	128	143	3.51	3.54	3.84	4.29
2050	155	294	533	908	4.65	8.83	16.0	27.27

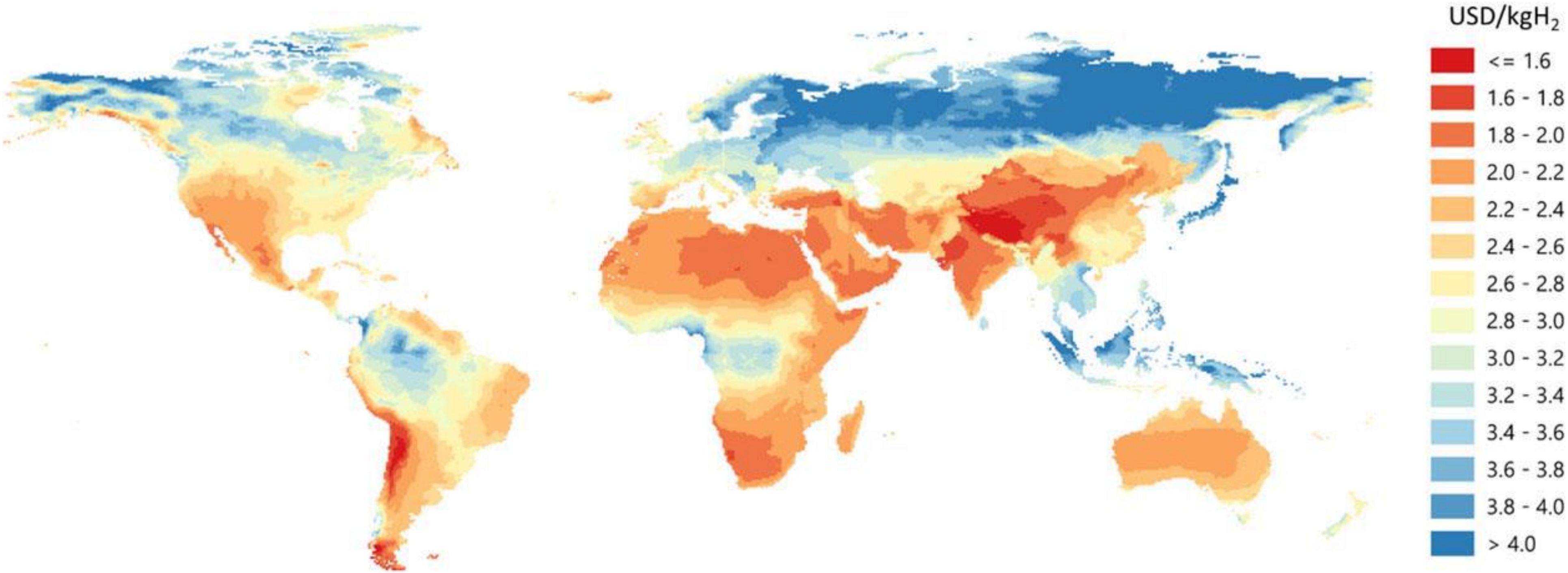
Source: from data in [48]

Powerfuels will be produced in Germany, but mostly imported from European and non-European countries. The presentation suggested that Germany would produce a maximum of about 160 TWh, and a maximum of 200 TWh would be imported from EU countries, equivalent to 4.8 Mt and 6.0 Mt of hydrogen respectively.

To indicate renewable hydrogen costs, the global long-term hydrogen cost map of Figure 6 (repeated in

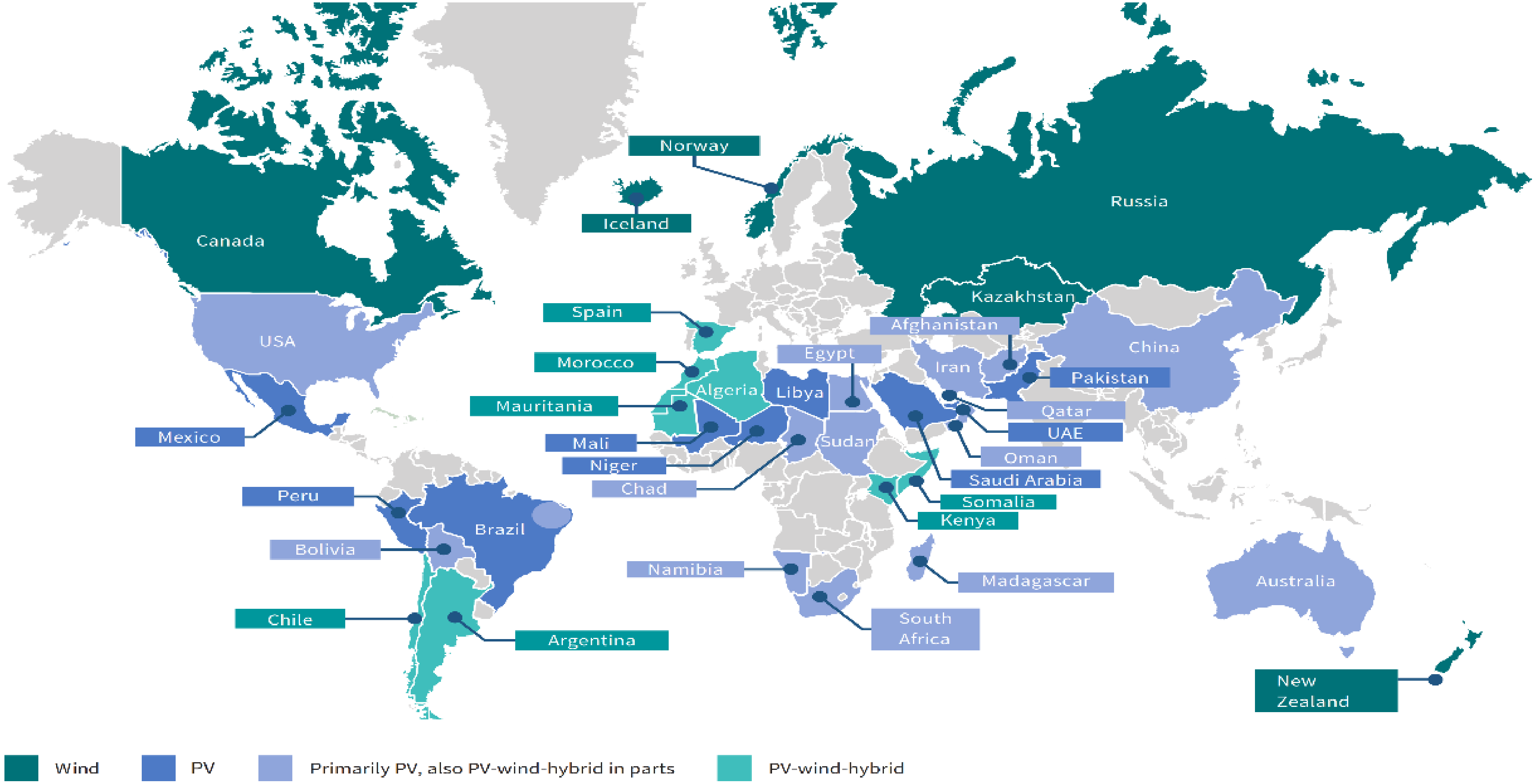
Figure 22) was contrasted with a global map by Frontier Economics (Figure 23) colour-coded to indicate the strongest renewable potentials: PV, wind, primarily PV with PV-wind-hybrid in parts, and PV-wind hybrid.

Figure 22: **Hydrogen costs from hybrid solar PV and onshore wind systems in the long term**



Source: [48]

Figure 23: **Countries with strongest renewable potentials scenarios**



Note: Illustrative presentation of the strongest RES potentials only, not an exhaustive list of all countries

Source: [48] (from Frontier Economics)

While renewable costs are the key factor for competitive Powerfuels production, additional factors determine whether a country emerges to be a significant Powerfuels producer and exporter:

- Is there political stability and investment security?
- Is the requisite technological know-how present in the country?
- Does the necessary transport infrastructure, such as pipelines and tanker shipping, exist?

Powerfuels provide different business opportunities for different players:

- Fossil fuel importers: Can produce RE energy carriers locally, and decrease import dependency
- Oil & gas exporters: Can develop a future-proof business model beyond fossil fuels
- Countries with abundant RE resources: Can become Powerfuels exporters and benefit from global market access
- Technology providers: Can supply technologies and business services facilitating Powerfuels production

Challenges for Powerfuels are (expanded in [75]):

- High investment (CAPEX) costs, but lower running costs (OPEX)

  Powerfuels are currently a relatively new product with high investment costs (CAPEX) that offer great potential to reduce the cost of the final product. If renewable power generation is considered part of the plant, operational costs (OPEX) are comparably low.
- Trade-off: avoided infrastructure investments versus additional costs

  Powerfuels are currently more expensive than other renewable options. However, they can reduce the need for infrastructure investments in the overall system. This trade-off is difficult to quantify and communicate in the energy policy debate.
- Reduction of production costs

  Powerfuels are at a very early market stage. They have a very high cost reduction potential, which can only be achieved through economies of scale and scope in combination with applied research.
- New global renewable energy perspective

  Some of the best Powerfuels production spots are in markets that are not relevant fuel demand markets today and can still be considered developing markets in terms of renewable investments.
- Investment risks

  Some of the best potential Powerfuels production sites are located in countries with relatively unstable investment conditions. It is important to initiate dialogue with decision makers in such countries to identify the potential for local benefit and to reduce investment risks.

Global Alliance Powerfuels, initiated by dena in September 2018, comprises the corporate members shown in Figure 24 (left). In addition, the International Partners Network is a collaboration amongst global initiatives, think tanks, associations and research institutions to further enhance the discussion and development of Powerfuels globally, and comprises the institutions shown in Figure 24 (right), as well as CSIR, LUT university, UCLovain, DECHEMA, Empa Materials Science and Technoloy, Energy Saxony and Hydrogen Valley.

Figure 24: Global Alliance Powerfuels: Left - corporate members; Right - International Partners Network

Source: [48]

In summary:

- Global GHG-emission reduction needs energy efficiency, RE electricity and Powerfuels to succeed.
- Energy efficiency and Powerfuels are not a contradiction. They complement each other.
- Powerfuels offer a business opportunity in a growing market, and create beneficiation and employment
- To bring down costs of Powerfuels, stable demand markets must be created today to scale up production.
- Market development of Powerfuels can start in regions like the EU, but should quickly become a global issue.

4.3 Cédric Philibert (former IEA senior analyst): Electrification and hydrogen in the energy transition

The presentation explored lessons from [11] (discussed in Section 1.4: Hard-to-abate sectors) highlighting the challenge of hard-to-abate sectors of heavy industry (cement, steel and plastics) and heavy-duty transport (heavy road transport, shipping and aviation), pointing out that solutions are possible:

- Technically: technologies are either commercial or in the research phase
- Economically: Implementation will cost less than 0.5% of global GDP

Overall, renewable electricity can replace fossil fuels in many areas, referred to as "direct electrification". Where direct electrification is infeasible, however, producing an electrolysis-based fuel will be necessary. Direct electrification covers:

- Electro-magnetic technologies for heating, hardening, melting
- Heat pumps/mechanical vapour recompression
- Cheap resistances in boilers or furnaces taking advantage of cheap "surplus" power when available (which would otherwise have to be curtailed)

Electric technologies can be cost-competitive when they are twice as efficient (as in the case of heat pumps), thus compensating for the cost difference compared with direct fossil-fuel use. It also helps to integrate more renewables.

Electric drive trains (both battery electric and fuel cell electric) will be expected to dominate in heavy road transport, and short-haul shipping and aviation. Long-distance aviation will probably rely either on bio jet fuel or synthetic jet fuel, while long-distance shipping will likely use ammonia or (to a lower extent) biodiesels.

The lessons from [12] are that the momentum currently behind hydrogen is unprecedented, with progressively more policies, projects and plans by governments and companies in all parts of the world. Hydrogen can help overcome many difficult challenges, to:

- Integrate more renewables, including by enhancing storage options and "exporting sunshine and wind" from places with abundant resources
- Decarbonize "hard to abate" sectors – steel, chemicals, trucks, ships & planes
- Boost energy security by diversifying the fuel mix & providing flexibility to balance grids

Challenges remain, however: costs need to fall; infrastructure needs to be developed; cleaner hydrogen is needed; and regulatory barriers persist.

Low-cost renewables are a game changer, as average auction prices for onshore wind and solar PV have dropped to below 50 USD/MWh, and offshore wind to about 80 USD/MWh (2017 data). Africa has the largest combined RE resource of the continents, predominantly solar.

Green hydrogen from electrolysis can compete with hydrogen from European natural gas: beyond an electrolyser capacity factor of about 30%, the price of electricity dominates the cost of electrolysis hydrogen.

The most relevant areas for green hydrogen use are:

- Green ammonia and methanol for their industrial uses
- Refineries (to upgrade and clean fuels)
- Direct iron reduction in steelmaking
- H_2/NH_3 storable/shippable fuels in power systems
- H_2 or synthetic CH_4 in gas grids, trucks and other vehicles
- NH_3 as fuel for shipping and industrial furnaces
- Methanol and synthetic hydrocarbons as electrofuels or feedstocks for chemical industry and aviation. These are sustainable if the carbon is taken from the air
- Combining hydrogen with the production of biofuels

A case study was presented on the production of hydrogen, ammonia, methanol and Fischer-Tropsch fuels in China. The best solar and wind resources in China are in the North and West, so ammonia, methanol and synthetic crude could be pipelined eastward to consumption centres and industrial facilities. Modelling based on hourly solar and wind data resulted in a levelised cost of \$130 – \$190 per barrel of oil equivalent.

For Fischer-Tropsch fuels for aviation and chemical industries, the carbon from biomass is more abundant than energy, but it is not unlimited. Assuming 100 EJ/y of available biomass gives 33 EJ as biofuels and about 4 Gt CO_2 per year. This annual CO_2 supply will allow Fischer-Tropsch synthesis to deliver enough fuel and feedstock for aviation and chemicals. Possible alternatives are Direct Air Capture and the extraction of CO_2 from seawater. Unfortunately, CCU from fossil-based emissions is not a sustainable solution, but it does makes sense during the transition.

Ultimately, only aircraft propulsion really needs the greater energy density of hydrocarbons. Other fuel choices should be made for long-distance shipping (such as ammonia), and for trucking. Fischer-Tropsch fuels may cost several times more than fossil equivalents. The one sector which seems able to support the costs of technology deployment is aviation. In this case, incorporation mandates would be a better policy option than taxation of air travel or jet fuel. This would eventually require a global policy framework.

Finally, opportunities to convert Sasol plants were discussed. Existing, large Fischer-Tropsch plants in excellent renewable resource areas offer unique opportunities for the production of carbon-neutral, renewable jet fuel. The injection of RE-based H_2 into the process can eliminate the upstream CO_2 emissions, which are larger in the coal-to-liquids process than the emissions from the combustion of the fuel.

Arguments against this approach are:

- Larger CO_2 reductions would be achieved in South Africa if the RE instead displaced coal-based electricity beyond what is published in the IRP, assuming it were possible to do.
- The resultant jet fuel will at best be only marginally greener than oil-based jet fuel.
- It is not clear who would agree to pay the higher price for this fuel if it is not green.

Alternatively, arguments for this approach are:

- Jetfuel decarbonisation will not take place overnight, so a start should be made ASAP
- The injection of green hydrogen is a necessary first step towards greening fuels
- Carbon from biomass could replace coal as feedstock, while RE electrolysis hydrogen replaces coal as energy source.

4.4 Dr. Tobias Bischof-Niemz (CEO, ENERTRAG South Africa): Liquid fuels from wind: Turning South Africa into the Saudi Arabia of the sustainable energy era

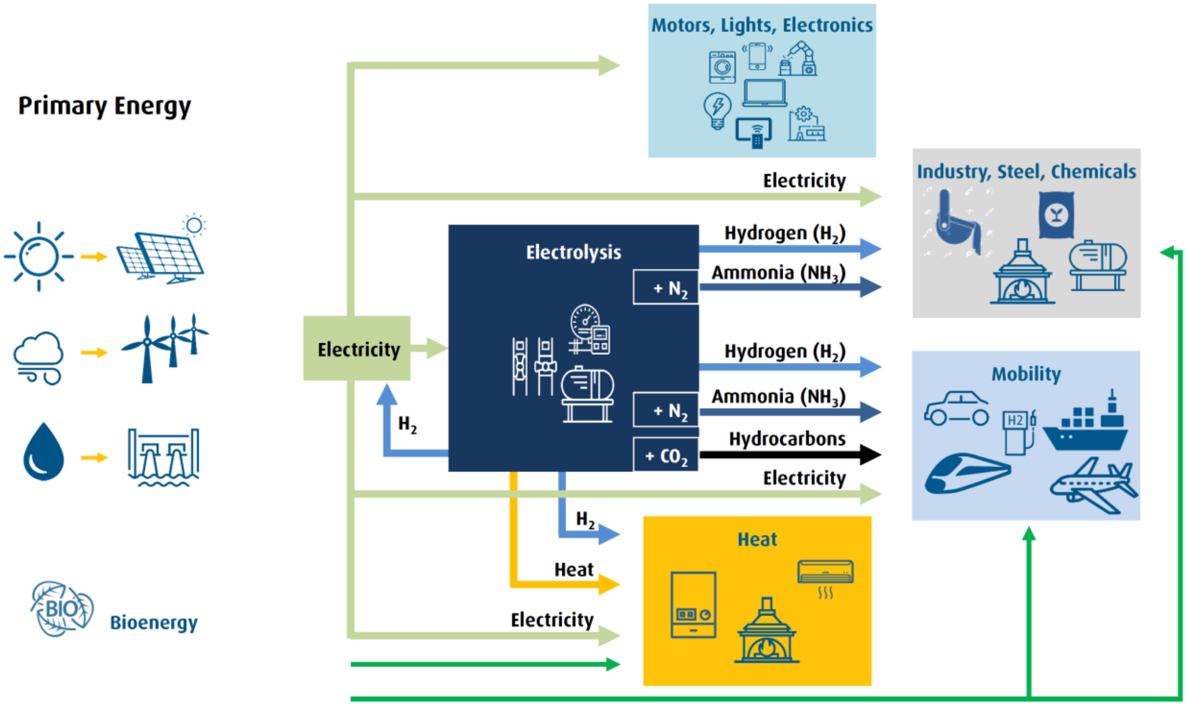
The opening argument of this presentation, concerning the economics of renewable electricity both globally and in South Africa, has been covered in Section 0. The entire energy system could be based on electricity and hydrogen in the future, driven exclusively by renewables (Figure 25).

The argument was further built out, showing what the ongoing roll-out of renewable capacity could look like. An actual South African grid hourly load profile for a week was illustrated graphically under four renewable capacity scenarios. In the first scenario, the impact of 5 GW installed capacity of wind and solar PV each was shown. The residual load profile was similar to the demand profile, but displaced about 5 GW below.

In the second scenario, titled "IRP: Cost-optimised solar/wind mix for electrical load only", 50 GW installed capacity of wind and solar PV each was modelled. No residual load remains during daylight hours, but between 20 GW and 35 GW of power is curtailed over midday. At night-time, the residual load varies between about 5 GW and 20 GW in the early evening to between about 5 GW and 15 GW in the early morning.

In the third scenario, titled "Additional renewable electricity produces hydrogen", 80 GW solar PV and 100 GW wind installed capacity was modelled. Residual load was only visible at night time, and then during only two nights of the week. 45 GW electrolyser capacity was also installed, and the excess power available was able to achieve high capacity factor for the electrolyser. Lastly, 20 GW direct electricity heat production was possible every day for a few hours during daytime. Curtailment occurred for three days of the week, only during daylight hours.

Figure 25: Energy system based on electricity and hydrogen, driven by renewables



Source: [10]

In the last scenario, titled "Beyond electricity: RSA as exporter of hydrogen-rich products", 300 GW each of wind and PV installed capacity was assumed, with electrolyser capacity of 250 GW. The electrolyser capacity factor was reasonable, but not as high as in the previous scenario. Residual load had completely disappeared. 50 GW of direct electricity heat production was possible every day of the week for several daylight hours. Significant curtailment occurred for three days of the week, only during daylight hours.

Finally, four scenarios were played out for Sasol Fischer-Tropsch synthesis of kerosene for aviation, progressively adding more amounts of renewable energy. In each case, for 1 t of kerosene produced, 1.3 t of water is produced as a by-product. When the kerosene fuel is burnt by aircraft engines in flight, 4t of CO_2 is produced.

In the first scenario titled "Status Quo", to produce 1 t of kerosene, 2 t of coal, 1.7 t of oxygen (O_2) and 2.6 t of water are consumed. All the coal and O_2 and some of the water is consumed in the coal gasification process, producing hydrogen (H_2) and carbon monoxide (CO). Additional H_2 is generated in the water-gas shift reactor (to obtain the desired H_2/CO ratio), where some of the CO is reacted with the remainder of the water. 4 t of CO_2 is produced and emitted. The H_2 and the remaining CO passes into the into Fischer-Tropsch synthesis reactor to make the 1 t kerosene.

In the 2nd scenario, titled “Interim 1”, 50% of the coal-based hydrogen is displaced by 0.1 t of green H_2. This is obtained by the electrolysis of 0.9 t of the water, using 5 MWh of green electricity. Coal and oxygen consumed in the coal gasification process drop to 1.5 t and 1.3 t respectively, and CO_2 emissions from the water-gas shift reactor drop 43% to 2.3t.

In the 3rd scenario, titled “Interim 2”, the water-gas shift reaction is completely bypassed, and the CO_2 process emissions drop to zero. 100% of the water-gas shift-based H_2 is displaced by 0.24 t of green H_2 (obtained by the electrolysis of 2.24 t of the water, using 12 MWh of green electricity). The coal gasification step consumes the remaining 0.36 t of water, and the coal and O_2 consumption drop to 0.85 t and 0.75 t respectively.

In the final scenario, titled “End-state”, coal consumption drops to zero. Instead, 3 t of CO_2 are obtained from the atmosphere by Direct Air Capture. The coal gasification is completely replaced by an RE-powered electrolyser, which electrolyses the full 2.6 t of water, producing H_2. The water-gas shift reactor is replaced by a reverse water-gas shift reactor. Some of the H_2, and all the carbon dioxide, are routed to the reverse water-gas shift reactor, producing CO and water. The CO and H_2 proceed to the FT reactor to produce the 1t of kerosene. In this scenario, Sasol has become carbon negative, and the kerosene has become carbon neutral.

In the final remarks, the case was made that Green Fuel is a huge export opportunity for South Africa, as renewable electricity here will always be cheaper than in most other countries, as the combined solar, wind and land resources are better than in most other parts of the world. This cheapest renewable electricity is a competitive advantage that will never go away.

Further, South Africa has vast experience in creation of synthetic liquid fuels (8 billion litres/year). A third of the country’s liquid fuel demand is obtained from Coal-to-Liquid. This existing asset and experience base can be repurposed for Green Fuel production. As an example, for the daily Lufthansa flight from Johannesburg to Frankfurt to be powered by Green Fuels would requires 100 MW of electrolyser capacity. For South Africa to supply 20% of the global aviation fuel demand would require 250 GW of electrolyser capacity, 300 GW of wind capacity and 300 GW of solar PV capacity. This would require 2.5% of RSA land area for wind farms (which would leave most of the land undisturbed) and 0.5% of the land area for solar PV farms.

A global initiative has been started by the German Energy Agency (dena) to connect off-takers with suppliers https://www.powerfuels.org/home/

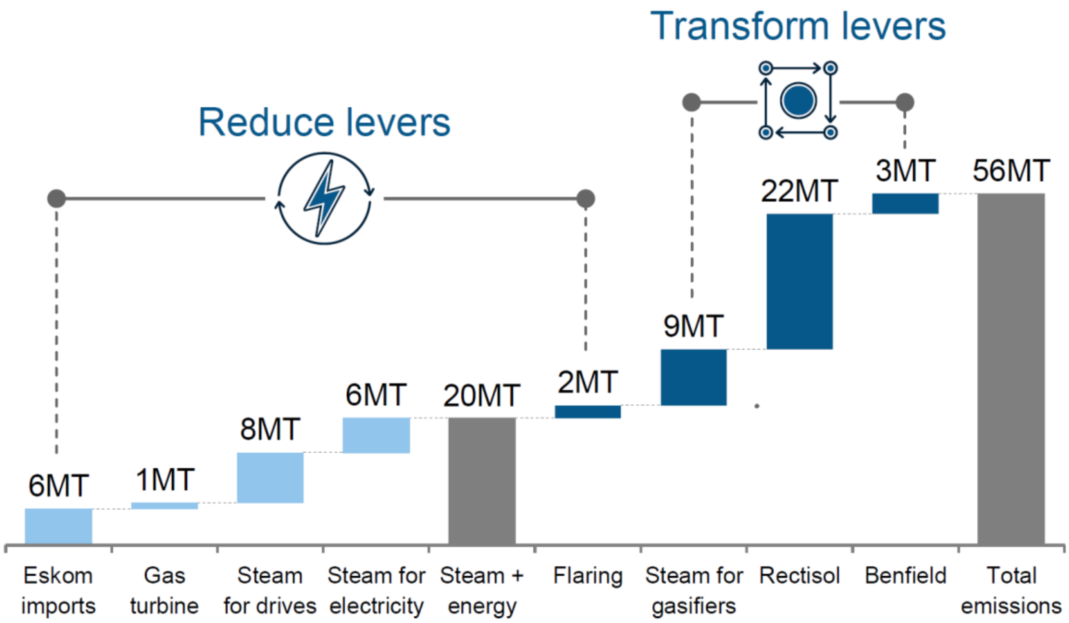
4.5 Theo Pretorius (SASOL, Vice President: Technology Management), A Sasol perspective on Sustainability and Powerfuels

The Fischer-Tropsch facility at Secunda currently accounts for more than 80% of Sasol’s global GHG emissions. Sasol is committed to reduce its greenhouse gas emissions, using an approach based on three pillars:

- Reduce emissions through efficiency and cleaner energy sources
- Transform the coal-based operations
- Shift Sasol’s portfolio towards less carbon-intensive businesses

Figure 26 shows the different sources of the 56 Mt annual CO_2 emissions at the Secunda facility.

Figure 26: **Distribution of CO_2 emissions at Secunda (Mt per Year)**



Source: [76]

The light blue bars represent utilities: steam for drives (fired by fine coal) and electricity from three sources: imports from Eskom, a 280 MW combined cycle gas turbine (fired by natural gas), and steam turbine generation plant (fired by fine coal). Sasol aims to reduce CO_2 emissions from these sources by renewable energy and process and energy efficiency[29].

The dark blue bars represent process emissions:

- Flaring
- Raising gasifier steam (fired by fine coal)
- Rectisol process removing CO_2 and H_2S from the synthesis gas upstream of the synthesis reactor
- Benfield process, removing CO_2 from the tail gas downstream of the synthesis reactor.

To reduce the process emissions, the operations need to be transformed away from coal, either by sourcing green hydrogen or by moving towards a hydrogen-rich feedstock.

The largest of the process-related CO_2 emission sources is the Rectisol process, and arises in the following manner. The CTL process converts coal into hydrocarbons. The coal is gasified in a Lurgi gasifier, where coal undergoes incomplete combustion in an oxygen-poor environment in the presence of steam. The stoichiometry of the gasification of the carbon fraction of the coal is as follows:

$$3C + O_2 + H_2O \rightarrow H_2 + 3CO$$

The molar ratio of hydrogen to carbon in the coal used by Sasol is about 0.67, so the equation becomes:

[29] In line with this, in May 2020 Sasol issued an RFI (Request for Information) for potential bidders, with respect to procuring 600 MW of renewable electricity capacity

$$3(C + 0.67H) + O_2 + H_2O \rightarrow 2H_2 + 3CO$$

The required hydrogen-to-carbon molar ratio of hydrocarbons is a little above 2, but the ratio available in the synthesis gas (syngas) from the equation above is 1.3-1.4. Additional hydrogen therefore needs to be added to the feedstock. Additional steam is injected, allowing some of the carbon monoxide above to strip oxygen from the water molecules, releasing extra hydrogen in the water-gas shift reaction:

$$CO + H_2O \rightarrow H_2 + CO_2$$

The combined equations therefore become:

$$6(C + 0.67H) + 2O_2 + 3H_2O \rightarrow 4H_2 + 6CO + H_2O \rightarrow 5H_2 + 5CO + CO_2$$

This yields the desired hydrogen to carbon monoxide ratio of 2. The CO_2 produced is removed from the gases leaving the gasifier through the Rectisol process, providing a concentrated CO_2 stream. It is this step which gives rise to the largest process emissions stream.

For Sasol to achieve Paris-aligned emission reductions, the source of the hydrogen and carbon of the process must change, which requires either:

- Renewables-based green hydrogen to be sourced, or
- The coal feedstock must be changed to gas

If the feedstock is changed to natural gas, the standard gas-to-liquids approach may be followed. The steam reforming of natural gas is an endothermic reaction, so energy is required to drive it. This is achieved using an autothermal reformer, where the partial oxidation of some of the gas drives the reforming reaction. For complete stoichiometry, the reaction equation is:

$$4CH_4 + O_2 + 2H_2O \rightarrow 10H_2 + 4CO$$

To achieve the required ratio of hydrogen to carbon monoxide, however, Sasol applies a different ratio of natural gas, oxygen and steam. The syngas is converted into hydrocarbons in a Sasol low temperature Fischer-Tropsch reactor, which after product upgrading gives a range of products: LPG, GTL naphtha, GTL diesel, GTL kerosene, drilling fluids, paraffins and base oils.

Apart from natural gas, syngas can be generated from a range of other potential feedstocks: green hydrogen, CO_2, refuse gasification and biomass gasification. In addition to autothermal reforming, electric reforming and solar reforming are also possible.

Haldor Topsoe have developed an electric steam methane reformer. The specific energy consumption is about 1 kWh/Nm^3_{H2}, or 11 kWh/kg_{H2} which has significantly lower power consumption than electrolysis. This eSMR technology is being employed in a Biogas to MeOH demonstration plant in Denmark producing 700 kg/day.

The Topsoe Re-Shift technology allows methane to be reformed with CO_2 rather than steam, producing a more CO-rich syngas and consuming CO_2.

Sasol believes feasible demonstration opportunities would be using CO_2-rich process streams from the Secunda facility:

- combined with hydrogen from RE electrolysis, or
- combined with steam reforming integrated with renewable electricity

Sasol could supply Cobalt based FT-catalyst for suitable applications anywhere in the world, converting syngas generated from other CO_2 and green hydrogen. Otherwise, Sasol could potentially participate in technical reviews to assist other players in the Global Alliance Powerfuels.

Hybrid solutions, drawing on the strengths of both the traditional GTL technology offering and green hydrogen or excess CO_2, could potentially provide attractive solutions.

4.6 Jens Baumgartner (sunfire, Business Development Manager Electrolysis), From Plans to Plants: Towards Commercial Viability

The presentation began by emphasising that in 2050, even in scenarios with large future increase in direct electrification, liquid and gaseous energy carriers will remain necessary to cover the global energy needs, requiring renewable solutions for e-fuels, e-gases and e-chemicals.

The SOEC electrolysers (see Section 2.3) produced by the company sunfire operate at an efficiency of 82%, compared with the 50-60% efficiency of the more commonly-used low temperature PEM and AEC electrolysers. Put another way, the sunfire SOECs require 3.7 kWh of AC electricity to produce one normal cubic metre of hydrogen (or 41.2 kWh/kg) compared with the range of 5-6 kWh/Nm^3 (55.6 – 66.8 kWh/kg) required by low temperature electrolysis.

Apart from pure hydrogen for rail transport, industries and steelmaking, other Powerfuels production pathways involve exothermic reactions which can provide the steam for the SOEC electrolyser:

- Methanation, providing methane for light and heavy vehicle transport, industry and residential heating
- Fischer-Tropsch synthesis, providing:
  - Petrol and diesel for light and heavy vehicle transport, rail transport and shipping
  - Jet fuel for aviation
  - Wax for chemicals
- Methanol synthesis, providing methanol and olefins for chemicals
- Ammonia synthesis, providing ammonia for chemicals and fertiliser

Two EU Framework projects for Green Industrial Hydrogen (GrInHy from 2016-2019 and GrInHy 2.0 from 2020), electrolysis hydrogen for steel has been showcased at Stahlwerk Salzgitter.

For the production of green synthetic hydrocarbon fuels, Fischer-Tropsch synthesis requires hydrogen (H_2) and carbon monoxide (CO) as building blocks to create the longer-chain molecules. H_2 is obtained by electrolysis, while CO must be obtained by splitting the CO_2 molecule.

If use is made of low temperature electrolysis, a three-step process must be followed:

- Hydrogen is obtained by electrolysing water
- Some of the H_2 must be reacted with CO_2 in the reverse water-gas-shift (RWGS) reaction, producing CO and water vapour
- The CO and the remaining H_2 are converted to longer-chain hydrocarbons in the Fischer-Tropsch reactor

The overall efficiency of this process lies in the 40 - 48% range. If the exothermal heat of the Fischer-Tropsch reaction is recuperated, and used to raise steam for steam electrolysis using a sunfire SOEC, the efficiency improves to the 50 – 58% range. If use is made of an SOEC instead of low temperature electrolysis, further improvements may be obtained by moving from the three-step process to a two-step process, by dispensing with the RWGS reactor and co-electrolysing the CO_2 with the steam in the SOEC. In that case, the efficiency of the process improves to the 55 – 63% range.

Renewable E-Crude for fuels and chemicals has been showcased with Audi using steam and CO_2 as feedstocks, powered by renewable electricity. More than three tonnes of renewable e-crude have been produced, comprising e-fuels (diesel and petrol) and e-wax. The fuel has been verified by Audi to possess premium properties: it is ASTM certified and is drop-in capable, in blends up to 50%. E-Jetfuel for aviation has been tested within the Demo-SPK project.

In the Kopernikus (2019) and Kopernikus 2 (2020) projects, the CO_2 required for fuel production is obtained by direct air capture (DAC), and the CO_2 is co-electrolysed in the SOEC as described above for increased conversion efficiency.

At Rotterdam The Hague Airport, a study is underway to produce a 1000 litres per day renewable fuel facility, using sunfire SOEC electrolysers and ClimeWorks DAC technology. The first fuel is expected to be available in 2022.

Larger scale facilities are being planned in Norway by Norsk e-Fuel, a consortium comprising sunfire, Climeworks, EPC company Paul Wurth, and green investor Valinor. The first facility is planned for construction at the Heroya Industry Park in Porsgrunn, with commissioning in 2023. It will have the capacity to produce 10 million litres (8000 tonnes) of renewable fuel per year, from 20 MW of electrolyser capacity. There are plans to expand it to 100 million litres annually by 2026, using 100 MW electrolyser capacity.

In the e-CO_2Met R&D project, Sunfire will provide a megawatt-scale high temperature SOEC electrolyser for use in the industrial-scale production of synthetic methanol from renewables and industrial concentrated CO_2 at the Mitteldeutschland refinery of Total near Leipzig.

4.7 Kilian Crone (dena, Vice President: Team Lead International Cooperation Hydrogen & Powerfuels Management), Review statement of Powerfuels workshop

Powerfuels are being discussed around the world as an important option for the future energy system: They can help to reduce emissions in all consumption sectors and can also be a central component of energy security and innovation strategies of countries and industries. Together with WITS Business School and the European Chamber of Commerce and Industry in Southern Africa, the Global Alliance Powerfuels held a workshop in Johannesburg on 9 December 2019. The aim of the event was to bring together key players and to exchange views on existing and future technology approaches. About 60 participants followed the invitation as evidence of a high level of interest especially from business and science.

The workshop demonstrated the relevance of Powerfuels in industrial policy considerations: Could Powerfuels be an opportunity for the transformation of industry and society in areas currently dependent on coal mining? Could Powerfuels be an opportunity to create new export markets, and so additional beneficiation in South Africa? Could exports help to lead Powerfuels out of a niche application in South Africa in the medium term?

The questions were intensely discussed in light of the continuing difficulties in reliable electricity generation and increasing electricity prices. There was broad consensus among the participants that green hydrogen as the base of all powerfuels can contribute to the development of South African wind and solar energy. Tobias Bischof-Niemz, Head of Business Development at wind developer Enertrag, highlighted the outstanding renewable potential in the country compared to other parts of the world. The existing know-how in fuel processing and catalysis is also an important argument for South Africa's future as a technology provider for hydrocarbon Powerfuels.

Jens Baumgartner, Business Development Manager Electrolysis with the Global Alliance Powerfuels member sunfire, presented the company's highly efficient technology and upcoming projects in the European market. Several ideas were discussed to get Powerfuels "from plans to plants". One of them was a proposal to use and modify the existing Fischer-Tropsch fuel production plants in South Africa towards the production of kerosene as a sustainable aviation fuel, which could be sold as a high-value product internationally. Other ideas, such as hydrogen buses and hydrogen long-distance transport vehicles, were also discussed.

As a conclusion, participants expressed the need to continue and deepen Powerfuels discussion in South Africa and to start a moderated market development process with politics, industry and science.

The Global Alliance will further contribute to raising awareness of South Africa's potential as a key player in Powerfuels and actively support project development in the region. An extensive documentation of the workshop results will be published in the next weeks on the website of the Global Alliance Powerfuels.

4.8 Analysis

Market driver: The dena and IEA presentations agree that to meet the Paris agreement goals, Powerfuels are an absolute necessity to decarbonise sectors that are difficult or impossible to abate using direct electrification with RE electricity.

SA opportunity: The dena and Enertrag presentations, as well as the dena review, highlight the opportunity presented to SA to export Powerfuels, by virtue of above-average RE resources in SA.

Product of choice: the IEA, Enertrag and Sasol presentations each identify the reconfiguring of Sasol's process away from pure CTL to make Powerfuels aviation fuel as the major opportunity, as the Fischer-Tropsch equipment and expertise exist.

Enertrag advocates introducing, and progressively increasing, green H_2. This will have the effect of decreasing the amount of H_2 obtained from the water-gas-shift reactor, reducing the amount of coal required. Finally, the carbon feedstock is to be supplied by direct air capture from the atmosphere. This approach appears consistent with what would be acceptable under the RED.

The presentation of sunfire shows the efficiency benefits of high temperature SOEC electrolysis, particularly when using co-electrolysis of CO_2 for the production of syngas for Fischer-Tropsch synthesis of longer-chain hydrocarbons. High temperature SOEC electrolyser units are available in the megawatt range.

From an economic feasibility perspective Sasol's preference appears to be:

- Replacing the coal feedstock with natural gas
- Using an electrical reformer rather than a combustion-based auto-reforming process
- Reforming some natural gas with CO_2 rather than steam. This has the benefit of "consuming" CO_2 as a feedstock.

It is unlikely that a fuel manufactured in this manner could be marketed in Europe as "clean", however, as pointed out by Cédric Philibert. Under the RED, the energy to make the fuel must be renewable and the CO_2 must be captured from a waste process. The Sasol approach on their existing operations will reduce upstream emissions, but will not become a carbon sink, as it continues to use "ancient" fossil carbon as feedstock rather than "current" emitted carbon.

Use of the CO_2-rich streams from the Rectisol and Benfield processes would qualify under the RED, as long as the H_2 is obtained by RE electrolysis.

Sasol refers to the CO_2-rich streams from the water-gas shift reactor at Secunda as "potential demonstration opportunities", where the title of the slide in question is "Sasol is keen to work with industry to find low carbon solutions for the future".

Sasol was approached for clarity concerning its decarbonisation preferences. At this point, Sasol is pursuing a low-cost partial decarbonisation approach, rather than adopting green electrolysis hydrogen at scale, because:

1) A climate-related premium is required to compensate adequately for the higher cost of production of completely green hydrocarbons. Sasol believes that while customers may be willing to pay such a premium in the short to medium term, it does not believe that customers (either airline carriers operating out of ORTIA[30] purchasing aviation fuel, or domestic or foreign liquid fuel customers) will pay premiums for green jetfuel in the longer term. Sasol believes technology and cost reduction forces will drive low cost solutions. It believes that to make significant capital investments, to produce a further inherently expensive product, puts Sasol at great risk, as the elevated premiums required to finance the investments may not endure for the full period required for payback.
2) While there may be market for green aviation fuel, the Fischer-Tropsch process does not produce a kerosene as a single product[31] but rather a "product slate" of hydrocarbons products ranging from short chains such as methane (C1) to long chains such as waxes (as long as C50). Significant additional processing is required with the associated losses in product, efficiency and capital expenditure to convert chains of undesired length to maximise jetfuel production. This has apparently been shown in the past to be very expensive. Alternatively, a market with equivalent premiums is required for the other chain lengths so that the capital investments may achieve payback.
3) Sasol is not in a position to initiate significant capital expenditure projects owing to its weakened financial position caused by low oil prices and the Lake Charles project which has consumed significantly more funds than planned.

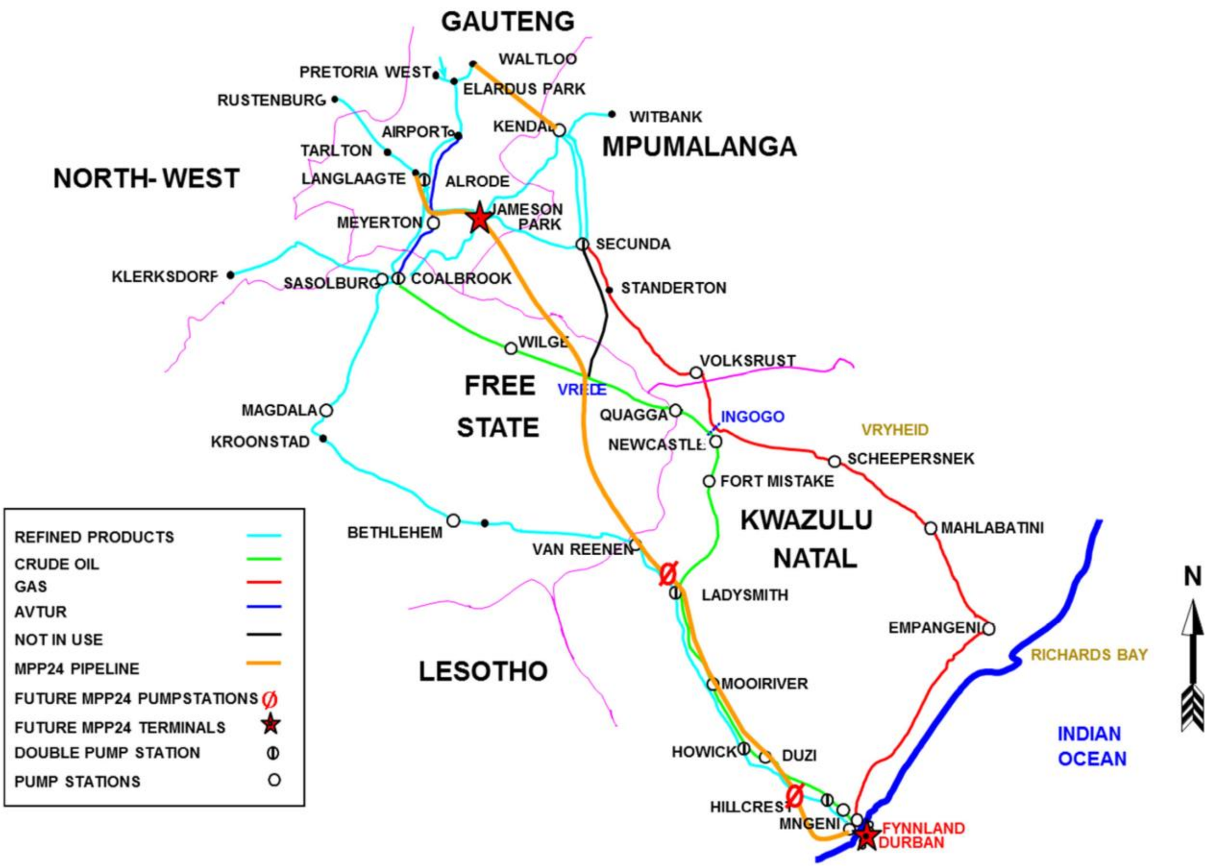
[30] O.R. Tambo International Airport

[31] Aviation kerosene or JET A1 comprises a complex mixture of hydrocarbons consisting of paraffins, cyclo-paraffins, aromatic and olefinic hydrocarbons with carbon numbers predominantly in the C9 to C16 range **Invalid source specified.**

No pipeline is currently available to convey green liquid product from Sasolburg or Secunda to the coast, as the liquid pipelines run in the other direction. Green liquid product would have to be transported to ports by road tanker or by rail, further increasing costs.

4) Figure 27 shows the existing Transnet pipelines:

Figure 27: **Transnet pipeline network**



Source: [77]

a. AVTUR: A dedicated 94km pipeline (dark blue in figure) with an annual capacity of 1.3 billion litres transports aviation turbine fuel (Avtur) from the Natref refinery in Sasolburg to ORTIA.

b. DJP: the multi-product 12-inch Durban Johannesburg Pipeline (cyan blue in figure), with an annual capacity of 3.72 billion litres, transports petrol from Durban to the inland network, and both petrol and diesel to Ladysmith, Bethlehem and Kroonstad. The DJP can transport jet fuel to ORTIA if required. It has reached the end of its technical and economic life.

c. MPP24: The 825km new 24-inch Multi-Product Pipeline, with an annual capacity of 8.76 billion litres, is replacing the DJP. It currently transports 500ppm diesel from Durban to Jameson Park. Petrol will be introduced when the Coastal (TM1) and Jameson Park (TM2) terminals are commissioned.

d. Lily: A 600km 16-inch pipeline with an annual capacity of 8.76 billion litres conveys methane-rich gas from Secunda, with off-take points at Newcastle, Empangeni/Richards Bay and Durban. The maximum capacity of this pipeline is 23 million GJ per year.
e. COP: A 580km Crude Oil Pipeline transports crude oil from Durban to the Natref refinery in Sasolburg. It consists of a 16-inch section and an 18-inch section, and has an annual capacity of 7.3 billion litres.

This dilemma will be discussed in the chapter Barriers to Powerfuels.

Sasol's interest in pursuing green hydrogen at pilot plant scale as part of its longer-term goals has been repeated recently by the CEO Fleetwood Grobler [78].

5 Industries in South Africa most likely to benefit from Powerfuels

5.1 Petrochemicals and refineries

There are four oil refineries and two synthetic fuel (synfuel) refineries in South Africa. The capacities and locations of these refineries are shown in Table 4 and Figure 28.

Table 4: Capacities of oil and synfuel refineries in South Africa

Refinery class	Name	Location	Company	1997 data **[79]**		Capacity data **[80]**	
				Crude processed		1997	2016
				t/mo	bbl/d	bbl/d	bbl/d
Oil	Engen	Durban	Engen	425 000	105 000	105 000	135 000
	Sapref	Durban	Shell & BP	668 000	165 000	165 000	180 000
	Natref	Sasolburg	Sasol & Total	344 000	85 000	86 000	108 000
	Caltex	Cape Town	Caltex	445 000	110 000	100 000	100 000
	Total			1 882 000	465 000	456 000	523 000
Synfuel	Sasol	Secunda	Sasol	648 000	160 000*	150 000*	150 000*
	PetroSA	Mossel Bay	Central Energy Fund	142 000	35 000*	45 000*	45 000*
	Total			790 000	195 000*	195 000*	195 000*

Source: [79, 80]

Figure 28: Location of the four oil refineries and two synfuel refineries

Source: [81]

Oil refineries: Conventional oil refineries use hydrogen to lower the sulphur content of diesel fuel. While refineries also produce some by-product hydrogen from the catalytic reforming of naphtha into higher value high-octane products, that source meets only a fraction of their hydrogen needs. The balance is made up either by hydrogen generated onsite by steam methane reforming, or else purchased from 3rd party suppliers [82].

If the conventional oil refineries were instead to make use of green hydrogen to desulphurise diesel, the upstream emissions of the resultant diesel would be greatly reduced. This would provide an early customer for green hydrogen, but the impact upon the cost of the resultant diesel would have to be evaluated.

Synfuel refineries: The Sasol CTL plant has a production capacity of 160 000 barrels per day. For reasons discussed earlier, Sasol is not in a position to supply green Powerfuels for export for the foreseeable future. That said, it is prepared to collaborate with other parties on a pilot plant to convert the concentrated CO_2 stream at Secunda to green Powerfuels for the inland South African market, possibly including aviation fuel for OR Tambo International Airport, if all the product (not only the aviation fuel) could be sold at a premium to cover the additional capital costs required.

While uncertainty exists regarding Sasol's ability to switch to green Powerfuels, a possible shorter term opportunity may lie with PetroSA, a smaller state-owned synthetic fuels producer. PetroSA is located at the coast at Mossel Bay, and is a gas-to-liquids Fischer-Tropsch synthesis plant using offshore natural gas as feedstock. It is a 45 000 bbl/day facility with annual emissions of about 2 Mt of CO_2 per year. This makes it a convenient size for repurposing to produce Powerfuels aviation fuel for the European market: most of the 94 refineries in Europe are larger than PetroSA, only 10 are smaller. PetroSA is state-owned enterprise facing difficulties in continuing operations, as the gas wells supplying it are becoming depleted[32]. Converting PetroSA operations to sell green Powerfuels to Europe on a long-term offtake contract, using the existing refinery and South African renewable resources should prove cheaper than European business building a new refinery or repurposing an existing refinery, with European renewable resources. Preliminary discussions with PetroSA and the CEF (Central Energy Fund, of which PetroSA is a subsidiary) concerning switching to PtX for aviation fuel have been very favorably received.

5.2 Underground mining

One sector already pursuing Powerfuels (at least hydrogen) in South Africa are the mining houses, who are moving towards replacing diesel engines with hydrogen fuel cells as prime movers for underground operations. Diesel fumes are carcinogenic, so mine ventilation systems must limit the concentration of diesel fumes to acceptable levels [83]. As much as 20% of all electricity consumption in underground mines is due to ventilation, and the replacement of diesel with fuel cell vehicles means ventilation costs can be reduced by 20%. While hydrogen fuel and fuel cell systems are more expensive than diesel fuel and engines, the entire system cost is cheaper when the ventilation burden is considered [84].

Anglo American has been developing fuel cell-powered vehicles for underground operation: a locomotive and an ultra-low profile fuel cell bulldozer [85]. As of June 2019, the locomotive

[32] PetroSA is currently operating at 10% capacity as a result **Invalid source specified.**

was still undergoing trials on the surface, while the bulldozer had proceeded to underground testing [84].

Impala Platinum (Implats) is using a prototype hydrogen forklift at the enclosed dispatch area of their Base Metals Refinery (BMR). Apart from releasing noxious fumes, diesel forklifts are noisy, while fuel cell forklifts are silent and operators do not need to wear respirators [86]. The forklift and hydrogen refueling station was developed by HySA Systems [87]. In addition to avoiding exposing underground workers to diesel fumes, an additional driver (for at least platinum mining houses) is to reduce carbon emissions for reputational reasons. Anglo American has committed to reducing its global greenhouse gas emissions by 30% by 2030. At the Mogalakwena platinum mine, Anglo American is developing the world's largest hydrogen powered mine truck, which is an existing mine haul truck using a fuel cell module paired with a lithium-ion battery system [88].

5.3 Banks

The REIPPPP programme provided investment opportunities for the South African banking community. Nedbank hosted a Hydrogen Fuel Cells conference in Cape Town in July 2019, in response to questions from its corporate clients regarding the future of hydrogen and fuel cells in South Africa. Electrolysis infrastructure, and the RE infrastructure to power it, would be financed by the banking community (local and international), so the banking sector would have a vested interest in understanding developments in the sector to ensure a sufficiently risk-adjusted approach.

5.4 Renewable power developers

As a result of the REIPPPP, many international (including European) renewable power companies have established a presence in South Africa, including developing supplier and community relationships. A bulk green hydrogen and Powerfuels export programme would require significant additional RE infrastructure build and would enable significant investments to be made by renewable power developers into further RE infrastructure over and above what is already defined in the IRP 2019.

5.5 Hydrogen infrastructure companies

There are several fuel cell-related companies operating in South Africa. Mitochondria Energy Company is partially owned by the Industrial Development Corporation and is an energy project developer using fuel cells. Isondo Precious Metals produces fuel cell components, as does Hyplat (which grew from HySA). Chem Energy SA (the South African subsidiary of the CHEM Group, based in Taiwan) is building a factory in Dube Tradeport (near King Shaka Airport), to produce fuel cells for the telecoms industry. Bambili Energy is the energy arm of Bambili investment firm, and is involved in creating a Hydrogen Valley in South Africa [89].

There may be an opportunity to partner with EU businesses to drive localisation of fuel cell, electrolyser and ancillary infrastructure where it makes sense.

5.6 Gas handling companies - Air Liquide, Afrox and Air Products

Air Liquide is a French multinational company. South African operations have been in business for more than 60 years, currently employing about 750 people. It supplies industrial gases, specialty gases and related services to various industries, and operates the world's largest air separation unit supplying 5 000 tonnes of oxygen per day to Sasol at their Secunda operations for the manufacture of synthetic fuels. Air Liquide B-BBEE (Broad Based Black Economic Empowerment) contributor ratings are level 8 (Air Liquide Large Industries) and level 3 (Air Liquide Healthcare). No information is available for Air Liquide Engineering and Construction.

Afrox (African Oxygen Limited) is part of the Linde Group, a global (originally German) industrial gases and engineering company. Afrox has over 3000 staff and is listed on the JSE and the Namibian Stock Exchange. Afrox provides engineering services and atmospheric gases, welding and safety products and LPG to customers. Afrox is a level 1 B-BBEE contributor.

Air Products is a US-based industrial gases multinational corporation which operates in 50 countries. Air Products South Africa is a level 4 B-BBEE contributor, with about 500 employees. It manufactures, supplies and distributes industrial and specialty gas products to the Southern African region.

5.7 Transnet Port Terminals (TPT) and Coega Development Corporation (CDC)

TPT is a division of Transnet, South Africa's state-owned freight transport company. It owns and operates 16 terminal operations situated across seven South African ports. The bulk export of green hydrogen would provide a source of revenue for the ports concerned (currently envisaged as Saldanha and Coega). The Port of Rotterdam have had prior engagement with Transnet and would like to develop relationships further [90].

CDC has been engaged by CSIR concerning the possibility of exporting Powerfuels and is interested in further investigations surrounding feasibility.

5.8 Urban bus transport

Moving urban public bus transport from diesel to electrically-driven variants (either battery or fuel cell) improves urban air quality, and reduces CO2 emissions (depending on the source of the electricity charging the batteries or generating the hydrogen). As mentioned in Section 1.4, hydrogen buses have some advantages over battery buses: they are lighter, have better range and shorter refueling times. If powered by green hydrogen, they allow cities to achieve emissions reductions towards climate goals.

Fewer hydrogen refueling stations are required for hydrogen-powered urban bus transport compared with other hydrogen-powered transport modes, as the routes are periodic and the buses return to the same place several times per day. A possible candidate for early adoption of hydrogen buses is the Gautrain bus network providing last-mile service to Gautrain commuters, as the passengers are generally middle-class and better able to afford the fares than working-class commuters.

5.9 Long-distance trucking

As part of the Hydrogen Valley mentioned in Section 5.5, hydrogen refueling stations are planned along the N3 highway connecting Gauteng Province with Durban, to allow hydrogen fuel cell-powered trucks to begin decarbonising heavy goods transport along this busy corridor.

5.10 Steelmaking

Saldanha Steel is a mothballed steel plant, owned by ArcelorMittal, located at Saldanha. The steelworks could be converted to a DRI steel plant, supplied by green hydrogen generated at or near the port, producing “green steel” that could be shipped to Europe. This would provide a new business model for a plant that was unable to compete with cheap Chinese steel supply, and would be synergistic with a Saldanha port reconfigured for green hydrogen and Powerfuels production and export.

The Vanderbijlpark steelworks of ArcelorMittal is one of the world’s largest inland steel mills and sub-Saharan Africa’s biggest supplier of flat steel products, and produces about 2 million tonnes of liquid steel per year [91]. Since the company as a whole (also comprising steelworks at Newcastle and Saldanha) has scope 1 emissions of 2.03 tonnes of CO_2 equivalent per tonne of liquid steel [91], it is fair to assume about 4 Mt of CO_2 is emitted annually from the Vanderbijlpark facility. It is unlikely that ArcelorMittal South Africa will implement direct reduction of steel with green H_2 at Vanderbijlpark in the short term, but may end up doing so over the medium to long term. Until then, its CO_2 emissions may provide a source of CO_2 feedstock for carbon-neutral hydrocarbon Powerfuels production (such as aviation fuel or methanol), possibly by Sasol. The sale of CO_2 will offset losses due to the South African carbon tax, which are expected to increase over time. The capture of CO_2 is cheaper from steel plants than from coal-fired power stations, due to the higher concentration of CO_2 in their flue gases.

One company well positioned to assist in the transformation of both PetroSA and ArcelorMittal towards green product development is ThyssenKrupp. While it is a European company, the South African division has Level 3 B-BBEE certification. ThyssenKrupp have experience as EP or EPC in delivering large electrolyser units for industry (Table 5). Alongside electrolysis, ThyssenKrupp can implement carbon capture technology, as well as methane, methanol and ammonia synthesis. A pilot CO_2 capture plant has been installed at ThyssenKrupp Steel in Duisberg as part of the Carbon2Chem project, together with a 2 MW electrolysis plant.

Table 5: ThyssenKrupp EP/EPC projects involving electrolysis

Electric capacity	Customer	Location	Product capacity
120 MW	KEM ONE	Lavera, France	400 kt/a Cl_2
100 MW	Tessenderlo	Belgium	272 kt/a Cl_2, 306 kt/a NaOH
80 MW	Vestolit	Marl, Germany	210 kt/a Cl_2, 236.9 kt/a NaOH
20 MW	PCC Rokita SA	Brzeg Dolny, Poland	62.285 kt/a Cl_2
6 MW	Serba/Junaco	Msufini, Tanzania	15 kt/a Cl_2, 16.8 kt/a NaOH

Source: [92]

5.11 Cement plants

There are 20 cement plants located in South Africa, as shown in Table 6.

Table 6: Cement plants located in South Africa

Province	Location	Facility name	Company name	Group name
Gauteng	Randfontein	Randfontein	Lafarge Industries SA (Pty) Ltd.	LafargeHolcim Ltd.
	Pretoria	Hercules	PPC Ltd	Public Investment Corporation
	Johannesburg	Jupiter		
	Roodepoort	Roodepoort	AfriSam (South Africa) (Pty) Ltd	
	Vanderbijlpark	Vanderbijlpark		
Mpumalanga	Delmas	Delmas	Sephaku Cement (Pty) Ltd	Dangote Cement South Africa
North West	Lichtenburg	Aganang		
		Lichtenburg	Lafarge Industries SA (Pty) Ltd.	LafargeHolcim Ltd.
		Dudfield	AfriSam (South Africa) (Pty) Ltd	Public Investment Corporation
	Slurry (near Mahikeng)	Slurry	PPC Ltd	
Limpopo	Limpopo	Dwaalboom		
	Krokodilkraal	Limpopo	Mamba Cement Co	Tangshan Jidong Cement (Group)
KwaZulu – Natal	Durban	Durban	Natal Portland Cement Co (Pty) Ltd	InterCement Portugal, S.A.
	Newcastle	Newcastle		
	Port Shepstone	Simuma		
Northern Cape	Ulco (near Barkly West)	Ulco	AfriSam (South Africa) (Pty) Ltd	Public Investment Corporation
	Lime Acres (near Postmasburg)	De Hoek	PPC Ltd	
Western Cape	Riebeeck Kasteel	Riebeeck		
	Saldanha	Saldanha		
Eastern Cape	Coega, EC	Coega Slag Mill	OSHO Cement (Pty) Ltd	Osho Group of Companies

Source: [93]

As described in Section 1.4, decarbonisation is difficult for cement manufacturers, as CO_2 is an inevitable product of the process of converting limestone to calcium oxide. The only available options are to:

- Emit the CO_2 and pay the carbon tax, which is expected to increase into the future
- Sequester the emitted CO_2, which is expensive and has no economic return; or
- Capture the CO_2 for re-use by creating a marketable product.

Following the third option is similar to the position faced by the steel industry. Captured CO_2 may provide a source of CO_2 feedstock for carbon-neutral hydrocarbon Powerfuels production (such as aviation fuel or methanol), possibly by Sasol. The sale of CO_2 will offset losses from the South African carbon tax. Again, as with steel plants, the capture of CO_2 is cheaper from cement plants than from coal-fired power stations, due to the higher concentration of CO_2 in flue gases.

6 Barriers to South African and EU businesses seizing Clean Powerfuels win-win opportunities

6.1 Legal/Regulatory

6.1.1 Construction of renewable electricity infrastructure

To create green hydrogen in the volumes needed to create a Powerfuels export industry, large amounts of renewable electricity are required. In South Africa, the addition of electricity generation capacity larger than 1 MW is only possible in accordance with the Integrated Resource Plan (IRP) 2019 and resulting Ministerial Determinations.

The IRP, however, was not written considering the large increase in renewable electricity demand which would arise from of a significant rollout of hydrogen electrolyser capacity to meet green hydrogen export demand. Therefore, using renewable allocations under the IRP for hydrogen generation effectively removes current or planned future renewable supply from conventional grid demand, slowing down grid decarbonisation and aggravating energy security concerns. This also runs directly counter to the German National Hydrogen Strategy:

- "Here, it is important to ensure that local markets and a local energy transition in the partner countries are not impeded, but are fostered by the production of hydrogen."
- "In developing countries in particular, it is vital to ensure that the export of hydrogen will not be detrimental to possibly inadequate energy supply systems in the exporting countries concerned and thus incentivise local investment in even more fossil fuels. Therefore, the production of green hydrogen is to act as a stimulus for these countries to rapidly expand their capacities for generating renewable energy – these will, after all, also benefit local markets."
- "Here, attention will be paid to ensuring that an import to Germany of green hydrogen or energy sources based on it takes place on top of domestic energy production in the respective partner countries and does not impede the supply of renewable energy, which is inadequate in many cases, in the developing countries."

Further, since a municipality may not currently contract an independent power producer (IPP) directly under current South African legislation, neither will a potential hydrogen producer be able to do so.

These constraints must be resolved to allow the development of a large-scale Powerfuels export market, particularly to Germany.

6.1.2 Aviation and maritime fuel

Unlike terrestrial transport, which takes place within defined jurisdictions and may be subjected to national or regional policies (such as mandatory blending of biofuels or CCU fuels, like RED II), aviation and maritime transport takes place over international airspace or waters, making jurisdiction and compliance management more difficult. In his presentation, Cédric Philibert stated regarding aviation that incorporation mandates would be a better policy option than taxation of air travel or jet fuel, eventually requiring a global policy framework. Until then, possible options are:

- Optional purchase by air carriers of aviation fuel containing a Powerfuels fraction (obviously more expensive). This has the disadvantage that adopters operate at a financial disadvantage compared with non-adopters.
- Airports imposing a certain Powerfuels fraction to aviation fuel sold (equivalent to landing fees). It is not clear whether this would be subjected to legal challenge, and may have the unintended consequence of driving customers to other airports, where the Powerfuels fraction obligation is not applied.
- Nations imposing aviation fuel of a certain Powerfuels fraction to be supplied at airports within their territory. This requires policy change, and may impact tourism and other sectors.

Ammonia has been touted as a maritime fuel which, if manufactured using green hydrogen, results in no CO_2 emissions. For this to be financially viable for ports to supply, it would have to be adopted as a fuel by a significant fraction of shipping visiting the ports concerned. Bilateral agreements between the EU and SA could assist in developing this market.

6.2 Market conditions

Powerfuels products will be more expensive than equivalent fossil-based products for the foreseeable future. Also, products from early Powerfuels plants will be more expensive than products produced by plants built later. To address both issues, there must be certainty that the green Powerfuels produced will be sold at prices high enough to recoup the renewable power and electrolysis investments required.

Europe has committed to Powerfuels imports, so exports to Europe present less of a problem. Solutions may take the form of long-term offtake agreement contracts for different Powerfuels products: hydrogen, ammonia, methanol and/or aviation fuel.

For domestic consumption, the problem becomes more difficult. If Sasol, possibly in collaboration with partners, were to produce hydrocarbon Powerfuels from green hydrogen and captured CO_2, a range of carbon chains will be produced. Some of these carbon chains may be used as aviation fuel. Short of building a pipeline to the coast, or re-engineering an existing pipeline, which will add to the infrastructure costs to be recouped, the fuel will have to be sold at nearby inland airports: O R Tambo International Airport, Lanseria, Wonderboom and Waterkloof Air Force Base. This gives rise to the question as to whether Powerfuels aviation fuel will be mandated, as discussed in Section 6.1.2.

Apart from the aviation fuel fractions, the light and heavy fractions also need to be sold at premium prices, alternatively they must be converted to chains of the required length, incurring additional infrastructural cost which must be recouped. Light gaseous fractions could be blended into the natural gas Sasol supplies to Gauteng customers. The heavy fractions be used for the making of plastics.

6.3 Human and technical capacity

It is not believed that capacity presents an insurmountable challenge. The REIPPPP created a renewable electricity market in South Africa, and international companies invested in the local market, creating supply chains and developing human capital. Human capacity in electrolysis is being developed at HySA (amongst others). Chemical engineering capacity exists in various industrial sectors.

6.4 Infrastructure

While PetroSA and Sasol can generate green Powerfuels using their own CO_2 process emissions, a wholesale shift towards green Powerfuels would require an enduring separate CO_2 supply. Most CO_2 emitted in South Africa is generated inland at all the coal-fired power stations (mostly in Mpumalanga province), Sasol, ArcelorMittal and the majority of the cement works (15 of the 20 are located inland). Pipelines might deliver CO_2 from these to Sasol, and from there a single pipeline could transport CO_2 to PetroSA. These pipelines do not currently exist.

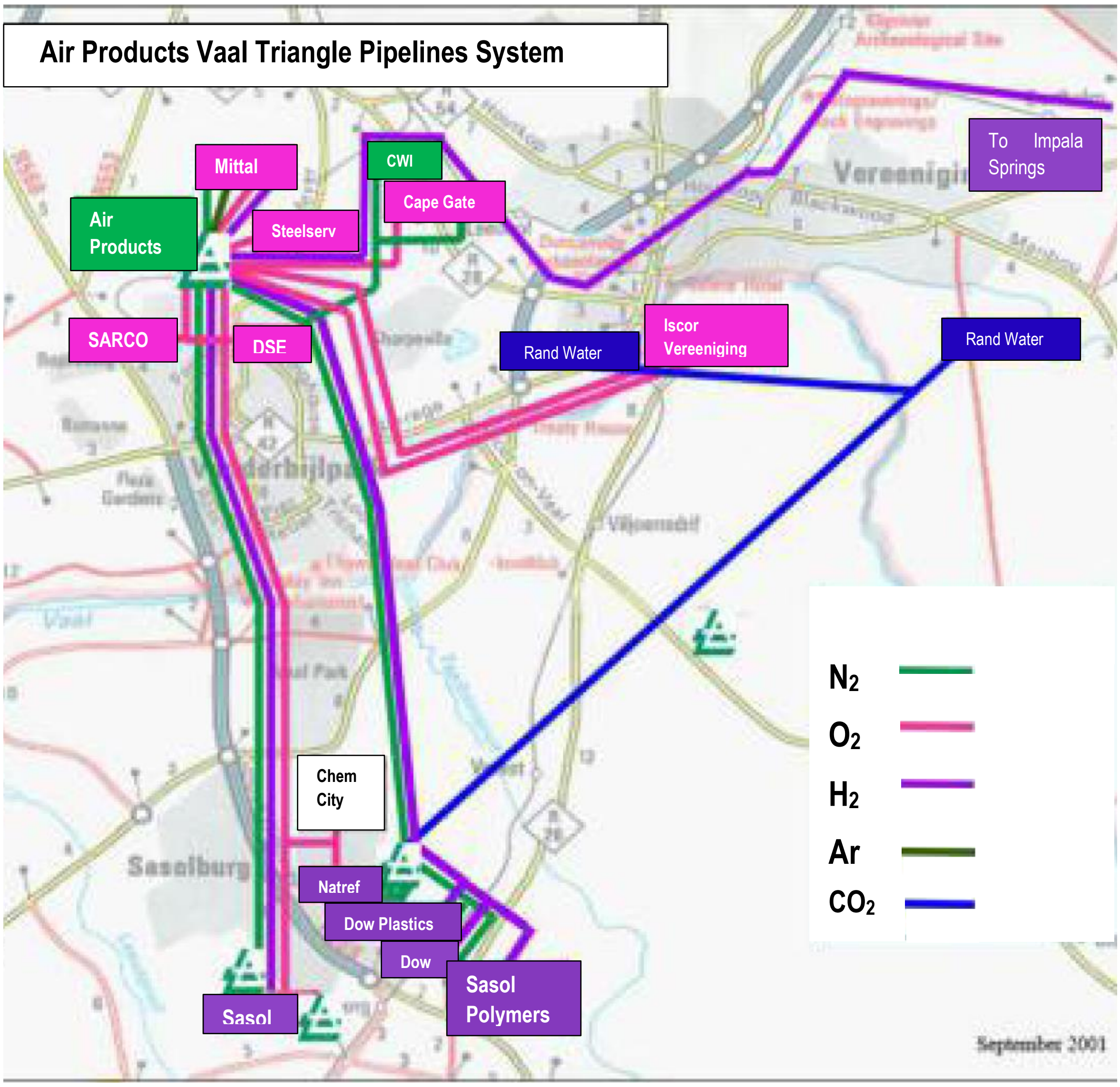
CO_2 pipelines are also a well-known technology with 2591 km of pipelines in existence in the USA with a capacity for 49.9 $MtCO_2$/y, mostly delivering CO_2 for enhanced oil recovery (Figure 29).

Figure 29: CO_2 pipelines in North America

Source: [94]

The gas pipeline network of Air Products in South Africa is shown in Figure 30.

Figure 30: Air Products Vaal Triangle Pipeline System



Source: [95]

Reference list

[1] Global Alliance Powerfuels, "What are Powerfuels?," [Online]. Available: https://www.powerfuels.org/powerfuels/. [Accessed 6 September 2020].

[2] UNFCCC, "The Paris Agreement," 2020. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. [Accessed 5 June 2020].

[3] European Parliament, "European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP))," 15 January 2020. [Online]. Available: https://www.europarl.europa.eu/doceo/document/TA-9-2020-0005_EN.html. [Accessed 9 June 2020].

[4] European Commission, "Submission by Croatia and the European Commission on behalf of the European Union and its Member States," 6 March 2020. [Online]. Available: https://unfccc.int/sites/default/files/resource/HR-03-06-2020%20EU%20Submission%20on%20Long%20term%20strategy.pdf. [Accessed 4 August 2020].

[5] European Commission, "A hydrogen strategy for a climate-neutral Europe," 8 July 2020. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf. [Accessed 5 August 2020].

[6] IPCC, "2014: Technical Summary," in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014.

[7] IEA, "World Energy Outlook 2019," 2020. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2019. [Accessed 8 June 2020].

[8] IEA, "Africa Energy Outlook 2019," 2020. [Online]. Available: https://www.iea.org/reports/africa-energy-outlook-2019. [Accessed 8 June 2020].

[9] M. P. Blimpo and M. Cosgrove-Davies, "Electricity Access in Sub-Saharan Africa: Uptake, Reliability, and Complementary Factors for Economic Impact," World Bank, Washington, DC, 2019.

[10] T. Bischof-Niemz, "Liquid fuels from wind: Turning South Africa into the Saudi Arabia of the sustainable energy era," in *Workshop: The Potential for Powerfuels, 9 December*, Johannesburg, 2019.

[11] Energy Transitions Commission, "MISSION POSSIBLE: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century," 2018.

[12] IEA, "The Future of Hydrogen: Seizing today's opportunities," Report prepared by the IEA for the G20, Japan, 2019.

[13] McKinsey, "Decarbonization of the industrial sector: the next frontier," 2018.

[14] Nikola, "Nikola Motor Company," 2020. [Online]. Available: https://nikolamotor.com/motor. [Accessed 10 June 2020].

[15] A. Floristean, *Private communication (representing Hydrogen Europe),* Hydrogen Europe, 2020.

[16] B. Biebuyck, *Private communication (representing FCH JU),* 2020.

[17] B. Biebuyck, "FCH JU - Making fuel cells and hydrogen an everyday reality," in *African Hydrogen Parnership conference and first meeting, February*, Addis Ababa, 2020.

[18] D. Hart, "Keynote address," in *Nedbank Hydrogen and Fuel Cell Conference, July*, Waterfront, Cape Town, 2019.

[19] Shift2Rail, "Study on the use of fuel cells and hydrogen in the railway environment," Publications Office of the European Union, Luxembourg, 2019.

[20] World Coal Association, "How is Steel Produced?," 2020. [Online]. Available: https://www.worldcoal.org/coal/uses-coal/how-steel-produced. [Accessed 10 June 2020].

[21] Wikipedia, "Blast furnace," 10 June 2020. [Online]. Available: https://en.wikipedia.org/wiki/Blast_furnace. [Accessed 10 June 2020].

[22] IEA and CSI (Cement Sustainability Initiative), "Technology Roadmap: Low-Carbon Transition in the Cement Industry, IEA,," International Energy Agency, Paris, 2018.

[23] Wikipedia, "Petrochemical," 20 April 2020. [Online]. Available: https://en.wikipedia.org/wiki/Petrochemical. [Accessed 15 June 2020].

[24] Wikipedia, "Steam cracking," Wikipedia, 24 April 2020. [Online]. Available: https://en.wikipedia.org/wiki/Steam_cracking. [Accessed 15 June 2020].

[25] Wikipedia, "Fluid catalytic cracking," Wikipedia, 10 May 2020. [Online]. Available: https://en.wikipedia.org/wiki/Fluid_catalytic_cracking. [Accessed 15 June 2020].

[26] Creative Commons, "Haber-Bosch-En.svg," 2019.

[27] Index Mundi, "Coal Imports by Country," Index Mundi, 2020. [Online]. Available: https://www.indexmundi.com/energy/?product=coal&graph=imports&display=rank. [Accessed 17 June 2020].

[28] Wikipedia, "List of countries by natural gas imports," Wikipedia, 18 April 2020. [Online]. Available: https://en.wikipedia.org/wiki/List_of_countries_by_natural_gas_imports. [Accessed 17 June 2020].

[29] Wikipedia, "List of countries by oil imports," Wikipedia, 17 March 2020. [Online]. Available: https://en.wikipedia.org/wiki/List_of_countries_by_oil_imports. [Accessed 17 June 2020].

[30] METI, "METI has compiled a Strategic Road Map for Hydrogen and Fuel Cells," Ministry of Economy, Trade and Industry, 24 June 2014. [Online]. Available: https://www.meti.go.jp/english/press/2014/0624_04.html. [Accessed 17 June 2020].

[31] METI, "Provisional Translation of Basic Hydrogen Strategy," 26 December 2017. [Online]. Available: https://www.meti.go.jp/english/press/2017/1226_003.html. [Accessed 17 June 2020].

[32] M. Sugano, "Japan’s Path towards the Hydrogen Society," in *1st African Hydrogen Partnership Conference and Preparation Meeting, 19 and 20 February*, Addis Ababa, 2020.

[33] IRENA, "Hydrogen: A renewable energy perspective," International Renewable Energy Agency, Abu Dhabi, 2019.

[34] European Commission, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC," *Official Journal of the European Union,* vol. L 140, pp. 16 - 62, 5 June 2009.

[35] A. Mohr and S. Raman, "Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels," *Energy Policy ,* vol. 63, p. 114–122, 2013.

[36] European Commission, "Directive (EU) 2015/1513 of the European Parliament & of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol & diesel fuels & amending Directive 2009/28/EC on the promotion of use of energy from renewable sources," *Official Journal of the European Union,* vol. L 239, pp. 1 - 29, 15 September 2015.

[37] European Commission, "DIRECTIVE (EU) 2018/2001 of the European Parliament & of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)," *Official Journal of the European Union,* vol. L 328, pp. 82-209, 2018.

[38] European Commission, "The European Green Deal," 11 December 2019. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. [Accessed 9 June 2020].

[39] F. Simon, "EU Commission unveils 'European Green Deal': The key points," EURACTIV.com, 11 Dec 2019. [Online]. Available: https://www.euractiv.com/section/energy-environment/news/eu-commission-unveils-european-green-deal-the-key-points/. [Accessed 17 June 2020].

[40] BMWi, "The National Hydrogen Strategy," 17 June 2020. [Online]. Available: https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html. [Accessed 21 June 2020].

[41] Government of the Netherlands, "Government Strategy on Hydrogen," 6 April 2020. [Online]. Available: https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen. [Accessed 20 June 2020].

[42] M. Swanson, *Private Communication,* Rotterdam: Business Manager, New Business & Portfolio/International, Port of Rotterdam, 2020.

[43] Port of Rotterdam, "Rotterdam boosts hydrogen economy with new infrastructure," Port of Rotterdam, 7 May 2020. [Online]. Available: https://www.portofrotterdam.com/en/news-and-press-releases/rotterdam-boosts-hydrogen-economy-with-new-infrastructure. [Accessed 20 June 2020].

[44] Port of Antwerp, "Hydrogen Economy: On course together towards a circular future," 9 April 2019. [Online]. Available: https://www.fch.europa.eu/sites/default/files/201-MI_Antwerp-H2_Valleys-Port_of_Antwerp.pdf. [Accessed 18 September 2020].

[45] FuelCellWorks, "TWEED Cluster, Publishes its Strategic Vision for the Development of Hydrogen in Wallonia, Belgium," FuelCellWorks, 27 December 2018. [Online]. Available: https://fuelcellsworks.com/news/tweed-cluster-publishes-its-strategic-vision-for-the-development-of-hydroge/. [Accessed 18 September 2020].

[46] Port of Antwerp, "Port of Antwerp brings different players together to produce sustainable methanol," 22 March 2019. [Online]. Available: https://www.portofantwerp.com/en/news/port-antwerp-brings-different-players-together-produce-sustainable-methanol. [Accessed 18 September 2020].

[47] Politico, "France cooks up new green recipe: Nukes and hydrogen," Politico, 9 September 2020. [Online]. Available: https://www.politico.eu/article/france-green-hydrogen-vision/. [Accessed 14 September 2020].

[48] S. Siegemund, "Electrons and molecules: Powerfuels as a missing link for the energy transition," in *Workshop: The Potential for Powerfuels, 9 December*, Johannesburg, 2019.

[49] Agora Verkehrswende, Agora Energiewende and Frontier Economics, "The Future Cost of Electricity-Based Synthetic Fuels," Agora Verkehrswende, Agora Energiewende and Frontier Economics, translated from the German by WordSolid, Berlin, Cologne, 2018.

[50] Global Solar Atlas, "Map and data downloads," 23 October 2019. [Online]. Available: https://globalsolaratlas.info/download/world. [Accessed 6 July 2020].

[51] Global Wind Atlas, "Download high resolution poster maps (limited selection)," 2019. [Online]. Available: https://globalwindatlas.info/downloads/high-resolution-maps/World. [Accessed 15 September 2020].

[52] E. Lantz, O. Roberts, J. Nunemaker, E. DeMeo, K. Dykes and G. Scott, "Increasing Wind Turbine Tower Heights: Opportunities and Challenges," National Renewable Energy Laboratory. NREL/TP-5000-73629., Golden, CO, 2019.

[53] S. Fakir, "The political economy of South Africa's energy transition for outsiders," Daily Maverick, 22 June 2020. [Online]. Available: https://www.dailymaverick.co.za/opinionista/2020-06-22-the-political-economy-of-south-africas-energy-transition-for-outsiders/?utm_source=Ince_FirstThing#gsc.tab=0. [Accessed 22 June 2020].

[54] DMRE, "Integrated Resource Plan (IRP 2019)," Department of Mineral Resourcecs and Energy, South Africa, 17 October 2019. [Online]. Available: http://www.energy.gov.za/IRP/2019/IRP-2019.pdf. [Accessed 4 September 2020].

[55] GreenCape, "Water - 2019 Market Intelligence Report," GreenCape, Cape Town, 2019.

[56] T. Roos, "Renewable Hydrogen Generation and Transport Costs," CSIR Energy Centre Report, 2020.

[57] Africa Ports and Ships, "Port of Saldanha Bay," [Online]. Available: https://africaports.co.za/saldanha-bay/. [Accessed 23 June 2020].

[58] Africa Ports and Ships, "Port Of Ngqura (Coega)," Africa Ports and Ships, [Online]. Available: https://africaports.co.za/coega/. [Accessed 23 June 2020].

[59] T. Roos, "The Cost of Production, Storage and Transport of Renewable H2 from South Africa up to 2050 Under Different Scenarios," in *HYPOTHESIS XV, 3-5 June*, Cape Town, 2020.

[60] NPC, "National Development Plan 2030 - Our Future-make it work," National Planning Commission, 2012. [Online]. Available: https://www.gov.za/documents/national-development-plan-2030-our-future-make-it-work. [Accessed 4 September 2020].

[61] DTI, "National Industrial Policy Framework," Department of Trade and Industry, South Africa, 2007. [Online]. Available: https://www.gov.za/sites/default/files/gcis_document/201409/national-industrial-framework-policy04032008.pdf. [Accessed 4 September 2020].

[62] DTI, "Industrial Policy Action Plan (IPAP), 2018/19-2020/21: Economic sectors, employment and infrastructure development cluster," Department of Trade and Industry, South Africa, 2018. [Online]. Available: https://www.gov.za/sites/default/files/gcis_document/201805/industrial-policy-action-plan.pdf. [Accessed 4 September 2020].

[63] DEA, "National Climate Change Response White paper," Department of Environmental Affairs, South Africa, 2011. [Online]. Available: http://www.gov.za/sites/www.gov.za/files/national_climatechange_response_whitepaper.pdf. [Accessed 4 September 2020].

[64] DEA, "South Africa signs Paris Agreement on Climate Change in New York," Department of Environmental Affairs, South Africa, 22 April 2016. [Online]. Available: https://www.environment.gov.za/mediarelease/southafricasignsparisagreementonclimate. [Accessed 4 September 2020].

[65] DME, "White Paper on the Energy Policy of the Republic of South Africa," Department of Minerals and Energy, South Africa, December 1998. [Online]. Available: http://www.energy.gov.za/files/policies/whitepaper_energypolicy_1998.pdf. [Accessed 4 September 2020].

[66] The Presidency, "National Energy Act 34 of 2008," *Government Gazette,* vol. 521, no. 31638, pp. 1-13, 24 November 2008.

[67] The Presidency, "No. 4 of 2006: Electricity Regulation Act," *Government Gazette,* vol. 493, no. 28992, pp. 1-17, 5 July 2006.

[68] DoE, "Electricity Regulation Act, 2006: Electricity regulations on new generation capacity," *Department of Energy, South Africa; Government Gazette,* vol. 721, no. 32378, pp. 3-11, 5 August 2006.

[69] Department of Science and Technology (DST), "White Paper on Science and Technology," Government Gazette, 1996.

[70] DST, "INNOVATION TOWARDS A KNOWLEDGE-BASED ECONOMY Ten-Year Plan for South Africa (2008-2018)," Department of Science and Technology, South Africa, 2008. [Online]. Available: http://www.foresightfordevelopment.org/library/55/1373-innovation-towards-a-knowledge-based-economy-ten-year-plan-for-south-africa-2008-2018. [Accessed 4 September 2020].

[71] DST, *National Hydrogen and Fuel Cell Technologies Research, Development and Innovation Strategy (#95306),* Department of Science and Technology, South Africa, 2007.

[72] DST, "White Paper on Science, Technology and Innovation," Department of Science and Technology, South Africa, March 2019. [Online]. Available: https://www.dst.gov.za/images/2019/WHITE_PAPER_ON_SCIENCE_AND_TECHNOLOGY_web.pdf. [Accessed 4 September 2020].

[73] D. Bessarabov, G. Human, A. J. Kruger, S. Chiuta, P. M. Modisha, S. P. du Preez, S. P. Oelofse, I. Vincent, J. van der Merwe, H. W. Langmi, J. Ren and N. M. Musyoka, "South African hydrogen infrastructure (HySA infrastructure) for fuel cells and energy storage: Overview of a projects portfolio," *International Journal of Hydrogen Energy,* vol. 42, no. 19, p. 13568–13588, 2017.

[74] B. G. Pollet, Pasupathi, Sivakumar, G. Swart, K. Mouton, M. Lototskyy, M. Williams, P. Bujlo, S. Ji, B. J. Bladergroen and V. Linkov, "Hydrogen South Africa (HySA)

Systems Competence Centre: Mission, objectives, technological achievements and breakthroughs," *International Journal of Hydrogen Energy,* vol. 39, no. 8, p. 3577–3596, 2014.

[75] Global Alliance Powerfuels, "Guidelines for Market Development," Deutsche Energie-Agentur GmbH, 2019.

[76] T. Pretorius, "A Sasol perspective on Sustainability and Powerfuels," in *Workshop: The Potential for Powerfuels, 9 December*, Johannesburg, 2019.

[77] Transnet, "Chapter 5 Pipeline Development Plan - Long Term Planning Framework 2017," 2017. [Online]. Available: https://www.transnet.net/BusinessWithUs/LTPF%202018/5.%20LTPF%202017_Pipeline.pdf. [Accessed 14 August 2020].

[78] Mining Weekly, "Sasol pins low-carbon ‘reset’ hopes on gas, renewables and green hydrogen," 11 November 2020. [Online]. Available: https://www.miningweekly.com/article/sasol-pins-low-carbon-reset-hopes-on-gas-renewables-and-green-hydrogen-2020-11-11. [Accessed 23 November 2020].

[79] K. Pearce and D. Whyte, "NATSURV 15: Water and Wastewater Management in the Oil refining and Re-refining Industry," Water Research Commission, WRC Report No. TT 180/05, 2005.

[80] SAPIA, "2016 Annual Report," South African Petroleum Industry Association, 2017.

[81] SAPIA, "South African fuel industry," 2018. [Online]. Available: http://www.sapia.org.za/overview/south-african-fuel-industry. [Accessed 25 October 2018].

[82] EIA, "Hydrogen for refineries is increasingly provided by industrial suppliers," US Energy Information Administration, 20 January 2016. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=24612#:~:text=Hydrogen%20for%20refineries%20is%20increasingly%20provided%20by%20industrial%20suppliers,-Source%3A%20U.S.%20Energy&text=Refineries%20use%20hydrogen%20to%20lower%20the%20sulfur%20content%20of%2. [Accessed 3 September 2020].

[83] D. Bessarabov, "Update from HySA," in *DST-led Solar Study Tour to Germany*, 2019.

[84] G. Mouton, *Private Communication,* 2019.

[85] P. Valicek and F. Fourie, "Fuel cell technology in underground mining," in *The 6th International Platinum Conference, ‘Platinum–Metal for the Future’, The Southern African Institute of Mining and Metallurgy,*, 2014.

[86] Implats, "Proto-type Fuel Cell Forklift and Hydrogen Refuelling Station at Refineries," [Online]. Available: https://www.implats.co.za/pdf/sustainable-development/fact-sheets/other/fuel-cell-proto-type-fact-sheet.pdf. [Accessed 4 September 2020].

[87] UWC, "HySA and Implats Introduce First Hydrogen Fuel Cell Forklift Prototype," 4 April 2016. [Online]. Available: https://www.uwc.ac.za/News/Pages/HySA-and-Implats-Introduce-First-Hydrogen-Fuel-Cell-Truck-Prototype.aspx. [Accessed 6 September 2020].

[88] Industry Europe, "The world's largest hydrogen powered mining truck," 17 February 2020. [Online]. [Accessed 4 September 2020].

[89] EK, "South Africa: DSI Invites Bambili Energy to Join the Hydrogen South Africa (HySA) Strategy," 28 July 2020. [Online]. Available: https://ibekachikwu.com/tag/bambili-energy/. [Accessed 23 October 2020].

[90] M. Swanson, *Private communication,* Port of Rotterdam, 2020.

[91] ArcelorMittal, "Integrated report 2019," ArcelorMittal, Vanderbijlpark, 2019.

[92] P. Nellessen, "Potential for a Potential for a hydrogen based economy in South Africa," in *African Hydrogen Parnership conference and first meeting, February*, Addis Ababa, 2020.

[93] Cemnet, "Cement Plants located in South Africa," 2020. [Online]. Available: https://www.cemnet.com/global-cement-report/country/south-africa. [Accessed 5 September 2020].

[94] IPCC, "Transport of CO2, Chapter4 of IPCC Special Report on Carbon dioxide Capture and Storage," Intergovernmental Panel on Climate Change, 2018. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter4-1.pdf. [Accessed 10 September 2020].

[95] P. M. Modisha, C. N. M. Ouma, R. Garidzirai, P. Wasserscheid and D. Bessarabov, "The Prospect of Hydrogen Storage Using Liquid Organic Hydrogen Carriers," *Energy Fuels,* vol. 33, p. 2778−2796, 2019.

[96] South African Market Insights, "South Africa's coal exports to India as a percentage of total coal exports," South African Market Insights, 6 December 2018. [Online]. Available: https://www.southafricanmi.com/sa-coal-exports-india-6dec2018.html. [Accessed 22 June 2020].

[97] Engineering News, "Transnet sees slump in export coal volumes as ‘cyclical not structural’," Engineering News, 30 September 2019. [Online]. Available: https://m.engineeringnews.co.za/article/rail-utility-sees-slump-in-export-coal-volumes-as-cyclical-not-structural-2019-09-30. [Accessed 22 June 2020].

[98] Mining Review Africa, "Demand for SA coal exports declining," Mining Review Africa, 30 January 2019. [Online]. Available: https://www.miningreview.com/top-stories/demand-for-sa-coal-exports-declining/. [Accessed 22 June 2020].

[99] European commission, "Hydrogen generation in Europe: Overview of costs and key benefits," Publications Office of the European Union, Luxembourg, 2020.

Annex: Agenda of Powerfuels workshop

9:00	**Registration**		
9:30	**Welcome address** Prof. Rod Crompton, Director of the African Energy Leadership Centre at Wits Business School		
9:40	**Welcome address** Thabo Molekoa, Board Member, EU Chamber of Commerce and Industry in South Africa and CEO Sub-Saharan Africa Region, thyssenkrupp		
9:50	**The Role of Powerfuels in the Energy Transition** **Electrons and molecules: Powerfuels as a missing link for the energy transition** Stefan Siegemund, Head of Department, German Energy Agency **The need for electrification and hydrogen in the global energy transition** Cédric Philibert, formerly International Energy Agency **Renewable potentials in South Africa and Europe** Tobias Bischof-Niemz, Head of Corporate Business Development, Enertrag **A Sasol perspective on Sustainability and Powerfuels** Theo Pretorius, Vice President: Technology Management, SASOL **Beneficiation of South African renewables: Industrial policy perspective** TBD, Department of Trade and Industry (Requested) Moderation: Prof. David Walwyn, University of Pretoria *Discussion*		
12:30	**Lunch break**		
13:40	**From plans to plants: towards commercial viability** Jens Baumgartner, Business Development Manager Electrolysis, sunfire *Discussion*		
14:15	**Powerfuels applications & projects in the European-South African context** *Workshop Session*		
	Group 1 **Powerfuels in industrial uses** Co-Chairs: Benoit Decourt, UCL Sarushen Pillay, SASOL	Group 2 **Powerfuels in aviation** Co-Chairs: Tjasa Bole-Rentel, WWF Kilian Crone, dena	Group 3 **Powerfuels in Road Transport** Co-Chairs: Gaylor Montmasson-Clair, TIPS (tbc) Stefan Siegemund, dena
16:00	**Coffee Break**		
16:15	**Criteria for project development in the European-South African perspective** Presentations of main results by the workshop chairs Moderation: Cédric Philibert, formerly International Energy Agency *Discussion*		
17:00	**Conclusion & Outlook** Cédric Philibert, formerly International Energy Agency Stefan Siegemund, Head of Department, German Energy Agency Prof. Rod Crompton, Director of the African Energy Leadership Centre at Wits Business School		
17:30	**Networking Reception**		
19:00	**End**		