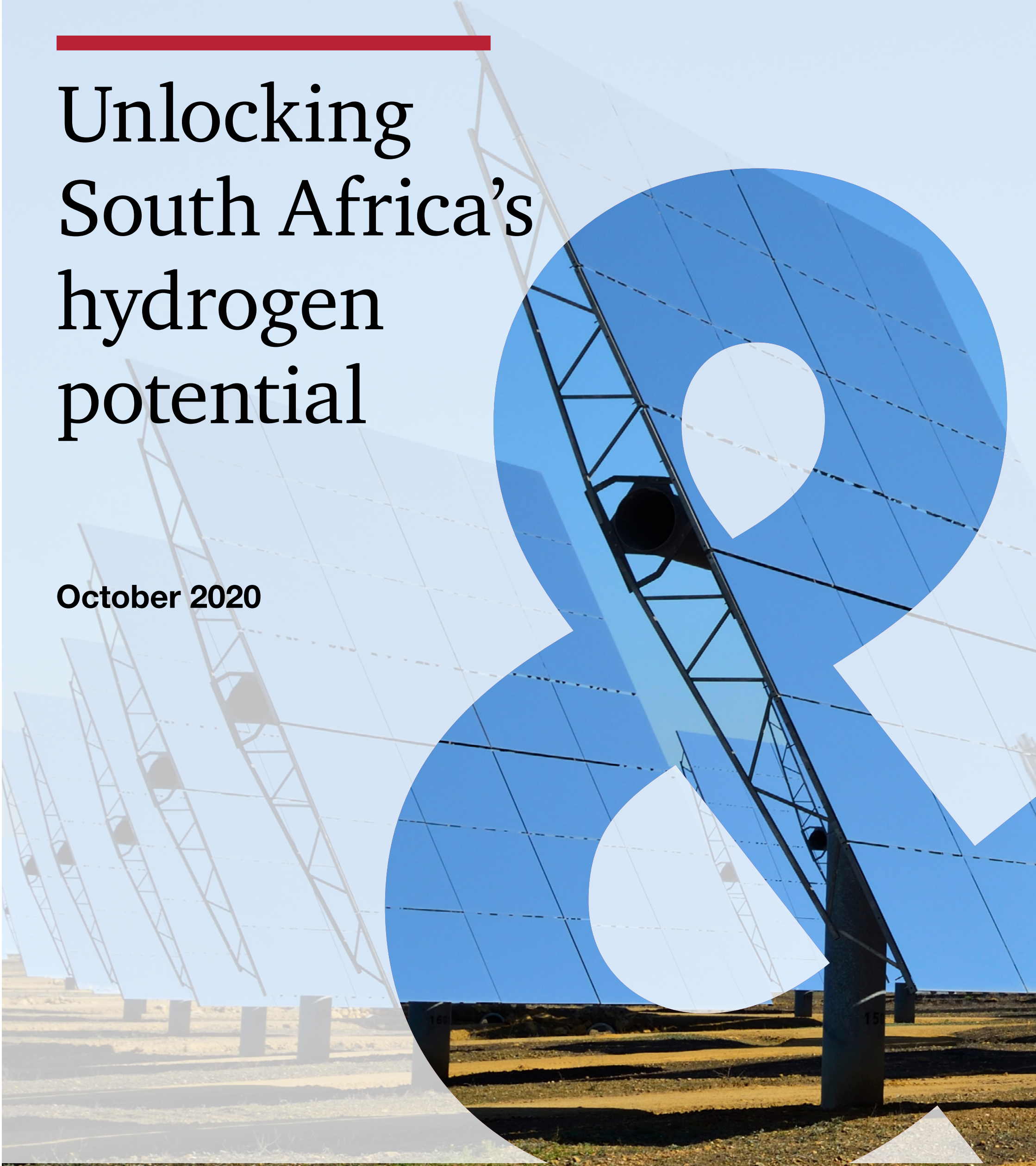
strategy&
Part of the PwC network

Unlocking South Africa's hydrogen potential

October 2020



Contacts

South Africa

Kalane Rampai
Africa Consulting Leader
PwC Africa
+27 (0) 11 797 5395
kalane.rampai@pwc.com

Ricardo Rosa
Africa Advisory Clients &
Market Leader
PwC Africa
+27 (0) 11 797 5602
ricardo.rosa@pwc.com

Andries Rossouw
Africa Energy, Utilities &
Resources Leader
PwC Africa
+27 (0) 11 797 4060
andries.rossouw@pwc.com

Wayne Jansen
Africa South Market Lead —
Energy, Utilities & Resources
Strategy&
+27 (0) 11 059 7209
wayne.jansen@pwc.com

Simon Venables
Head of Origination,
Sub-Saharan Africa
PwC Africa
+27 (0) 11 797 5660
simon.venables@pwc.com

About the authors

Jonathan Metcalfe has a core focus on the development of Southern Africa's hydrogen economy. Jonathan has extensive experience in mining and resources, particularly in cost optimisation, market entry strategy and infrastructure development. Jonathan is an economist by training and has considerable knowledge in financial and risk modelling.

Le Riche Burger has extensive experience in the oil & gas sector, with particular focus on the augmentation of Southern Africa's fuel sourcing strategies. Le Riche has an engineering background with an emphasis on infrastructure development, logistics optimisation, energy strategy and cost optimisation.

James Mackay is a multidisciplined engineer and CA(SA) who has over 20years' diverse experience in infrastructure development and finance. James leads the PwC energy transition strategy across Africa and is particularly passionate about the positive development impact that can be realised by Africa through the transition to a green economy. James is active across oil & gas as well as power markets.

Contents

Glossary of acronyms

AWE	Alkaline water electrolysis
BEV	Battery electric vehicles
CCUS	Carbon capture, utilisation and storage
CHP	Combined heat and power
DAC	Direct air capture
DRI	Direct reduced iron
EAF	Electric arc furnace
FCEV	Fuel cell electric vehicle
FTP	Fischer-Tropsch process
GM	General Motors
GTL	Gas-to-liquids
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicles
IRP	Integrated resource plan
LCOE	Levelised cost of energy
LNG	Liquified natural gas
PEM	Polymer electrolyte membrane
PGM	Platinum group metal
PV	Photovoltaics
REE	Rare earth elements
SCA	Strategic cooperation agreement
SEZ	Special economic zone
SMR	Steam methane reforming
VLOT	Vertical lift-off taxis

Introduction

The economic worth of any commodity boils down to three things; how well it serves its function, how easy it is to obtain and what externalities are created from its use. Fossil fuels gained popularity in the early 20th century through their effectiveness in producing heat and in providing efficient power in the internal combustion engine. These fuels were relatively easy to access, cheap to exploit and, until recently, the negative externalities of their use were of little concern.

Fast forward to the present day and the global energy economy is facing an unprecedented challenge. Fossil fuels are becoming harder to extract cost effectively. The effects of fossil fuel-based climate change are being felt all over the globe and new renewable energy technologies are proving more efficient than their carbon intensive counterparts. Suddenly the economic worth of a fossil fuel based global energy economy is not looking so promising.

On 12 December 2015, the Paris Agreement, which seeks to limit the global increase in temperatures to less than 2°C this century, was signed by 195 countries. In order to achieve this ambitious target, significant reductions in emissions are required and a paradigm shift in how we source and utilise energy is needed. Unfortunately, at the current global levels of consumption of fossil fuels, the 2°C scenario is looking unattainable.

But hope is not lost. Massive strides have been made into the renewable energy sector, with some countries already achieving carbon-neutrality in certain economic activities. It is estimated that by 2050 more than 50% of primary energy production will come from renewable sources.

However, renewable energy faces some challenges of its own in decarbonising the global economy. Most issues facing large-scale adoption of renewable energy boil down to a simple problem: How can we efficiently store and transport clean energy?

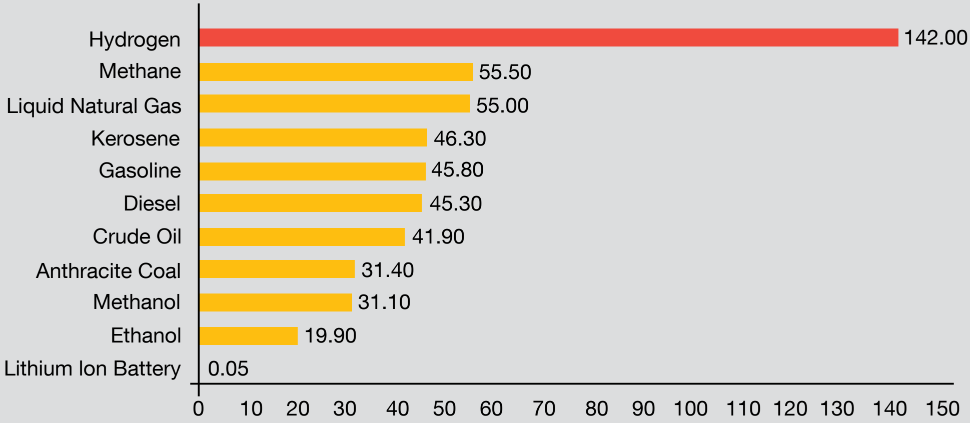
Electrical energy is difficult to store at scale and for long periods of time without unacceptable energy losses and long distance transmission through high-voltage lines also creates inefficiencies. On a more micro-scale, storing electric energy in batteries has received the most attention and investment through the initiative of companies like Tesla in their battery electric vehicles (BEVs) and in their fixed storage solutions. Although batteries provide unparalleled results in certain instances, they also face issues around cost of production, rarity of battery materials and, importantly for the transport sector, power-to-weight ratios. So, this leaves one option; chemical storage. It just so happens that the best option for the chemical storage of clean energy lies with the same element that makes up 75% of the mass of the universe; hydrogen.

Hydrogen is exceptionally energy dense per unit of weight, see Exhibit 1 and Exhibit 2 for a direct comparison to other fuels. It is no more difficult to store and transport than liquified natural gas (LNG). Through its direct combustion, its use in fuel-cells and its use as an industrial feedstock, it can decarbonise a greater range of sectors than renewable electrical energy alone.

Hydrogen can be produced in collaboration with renewable energy almost anywhere in the world. It requires cheap clean energy and one of the planet's most abundant and easy to access resources, water. Importantly, in the context of global climate change, the use of hydrogen that is produced from renewable energy produces no carbon emissions. By every metric through which we measure the economic worth of a commodity, hydrogen offers the most compelling solution to support renewable initiatives and achieve the 2°C scenario by the end of this century. The following sections will discuss in detail the ways in which hydrogen can be produced cost effectively, can support decarbonisation and the opportunities for South Africa in the global hydrogen economy.

Exhibit 1

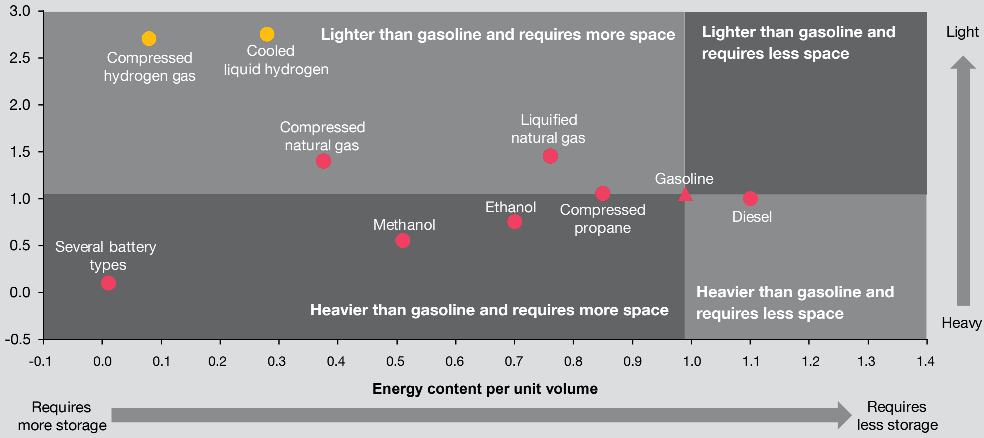
Chemical energy content (MJ/kg)



Source: C. Ronneau – Universitaires de Louvain

Exhibit 2

Fuel energy content per unit weight



Source: US Energy Information Administration, Barclays Research

Five challenges to global decarbonisation

Renewable energy variation	As both solar and wind technology adoption is predicted to exponentially increase in the coming decades, this creates issues around energy variability. Solar solutions can only generate power during the hours of sunlight and wind solutions are dependent on favourable weather conditions. With the limitations of grid storage and the massive cost involved with battery storage at scale, the question remains: **How can we efficiently store the energy created from renewables in order to achieve smooth supply?**
Transportation of energy	As of 2017, 30% of the world's energy trades across borders, and this is likely to increase in the future as countries rich in renewable energy sources increasingly export their energy to those without. However, trading of energy becomes increasingly difficult unless it can be cost-effectively stored and transported. Electrical energy is difficult to store at scale and for long periods of time without unacceptable energy losses. Long distance transmission of electricity also creates significant energy losses. **How best can we provide a storage of this energy that will facilitate the increased global trade in cost-effective clean energy?**
Grid buffering	Globally, there exists an energy capacity buffer of 15%; this absorbs supply chain shocks, strategic reserves and addresses supply/demand imbalances. Most of these reserves are fossil fuels based due to their ability to instantaneously generate power. As electrification increases globally, these reserves will not be adequate. Simultaneously, nations are facing increasing pressure to decarbonise, making these fossil-fuel based grid buffering solutions increasingly less socially acceptable. With current technology, large-scale battery storage is not cost effective. **How can economies provide adequate grid buffering without turning to carbon-intensive solutions?**
Difficult to electrify sectors	In recent years massive strides have been made in the decarbonisation of previously fossil fuel intensive processes. However, in industries such as heavy-duty transport, non-electrified trains, shipping and aviation, it is not feasible to electrify through either the grid or with rechargeable batteries. The significance of these industries' impact on global warming is likely to increase along with the exponential growth in the global population. **How can we decarbonise these industries and not undermine the good work already done in other sectors to tackle climate change?**
Industrial and chemical processes	Much focus had been placed on the decarbonisation of fuels that are used to create primary energy, such as petrol for transport or coal for power stations. However, a huge proportion of carbon emissions come from industrial and chemical processes. These emissions are usually omitted through the creation of heat or through a chemical reaction (e.g. the cement industry). There is currently no feasible way for electricity produced from renewables, on its own to aid in the decarbonisation of these industrial and chemical processes. **How can countries achieve decarbonisation targets in these industrial and chemical industries?**

Producing hydrogen

There are three hydrogen production methods. Although they all produce a chemically identical product, they differ in the quantities of carbon they emit in the process. With the global production of hydrogen being dominated by carbon-intensive methods, the key to driving the hydrogen economy forward will be the transition towards fully carbon-free green hydrogen.

1

Grey hydrogen

Fossil fuel based

Grey hydrogen accounts for vast majority of hydrogen supply and is produced from fossil fuels, mainly coal and natural gas. This produces significant volumes of carbon emissions.

Hydrogen from natural gas is the most common method of production globally. Natural gas is converted into pure hydrogen and carbon dioxide through the process of steam methane reforming (SMR). In SMR, gas feedstock reacts with steam at high temperatures and pressures to produce synthesis gas (syngas), which consists primarily of hydrogen and carbon monoxide. The synthesis gas is then reacted with additional water through a water shift reactor to produce pure hydrogen and carbon dioxide. Although a more environmentally friendly method than production from coal, the process still emits approximately 9.2kg of carbon for every 1kg of hydrogen produced.

In order to create hydrogen from coal, the coal must be passed through a gasifier and converted into syngas. This syngas is a combination of hydrogen and carbon. In grey hydrogen production the syngas is processed into pure hydrogen and the carbon is released into the atmosphere as carbon dioxide. Coal gasification is by far the least environmentally friendly production method, with approximately 18kg-20kg of carbon emitted for every 1kg of hydrogen produced.

2

Blue hydrogen

Fossil fuel based utilising carbon capture and storage

Blue hydrogen is a growing sector, with significant capital being poured into both new blue hydrogen facilities and upgrading grey hydrogen facilities to blue ones. Blue hydrogen production uses the same fossil-fuel based sources as grey hydrogen (coal or natural gas), but uses Carbon capture, utilisation and storage (CCUS) technology at the end of the extraction process, which traps up to 90% of the greenhouse gas emissions.

This CCUS can take many forms, with traditional methods of capture already utilised within the power sector such as ammonia scrubbing. It is far easier to capture the carbon from the natural gas reforming process as the carbon by-product is very pure and therefore easier to capture.

Another promising avenue for carbon storage is through utilising depleted gas fields to store emissions. This solution is already being used in Norway, Australia and the UK.

Blue hydrogen is not a long-term solution as it will not be cost-effective to capture and store carbon indefinitely. However, it may well be the bridge into green hydrogen and the development of downstream hydrogen technologies. It also allows existing high capital grey hydrogen production facilities and their upstream supply structures to continue to be utilised while simultaneously reducing their carbon emissions.

3

Green hydrogen

Renewable energy electrolysis

Green hydrogen is produced in a sustainable way and creates no carbon emissions in its production. The main way of producing green hydrogen is through the electrolysis of water. Utilising a high electrical current, water can be split into its component parts, allowing for the recovery of pure hydrogen gas and oxygen. When the electricity for the electrolysis process is supplied from renewable sources such as solar or wind energy, the hydrogen produced is classified as green.

There are three major electrolysis technologies with different levels of maturity. One technology, alkaline water electrolysis (AWE), is the most basic and mature technology and has a market share of about 70% of the currently very small green hydrogen market. It benefits from low cost, and this process has a long operational life. However, AWE processes need to run continuously or the production equipment can get damaged. The intermittent nature of renewable energy, therefore, rules it out as a single source of power for AWE.

Another technology is polymer electrolyte membrane (PEM) electrolysis, which has a market share of about 30% and is being adopted by most of the leading electrolyser manufacturers. PEM yields higher-quality hydrogen and can be operated intermittently, but is also expensive and has lower production rates than AWE. Currently, PEM electrolysis has an 80-92% efficiency and converts approximately 9kg of water into 1kg of hydrogen, enough to power an FCEV family vehicle for 100km.

A third technology is a solid oxide electrolyser cell, which is still in the development stage. It offers high efficiency at low cost. However, it requires a long start-up time and the components of this process have a short operational life.

There are other green methods of production, including the gasification of biomass and the production of hydrogen from bioreactors. But neither of these technologies are as commercially viable as the electrolysis of water from renewables.

Green hydrogen is receiving the greatest focus from a research and development perspective and the cost of producing it continues to fall. Key to achieving the widescale adoption of green hydrogen production will be continuing investment in renewable energy generation capacity and the construction of large-scale electrolysis plants.

Transition from grey hydrogen to green hydrogen

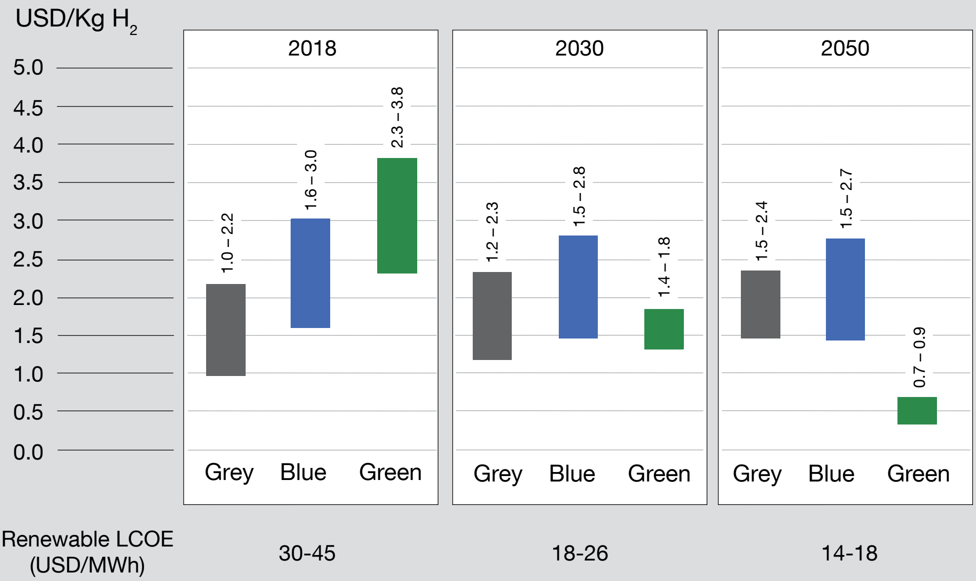
Today, grey and blue hydrogen account for ~96% of total global hydrogen production with 'green' production through electrolysis only accounting for ~4%.

Green hydrogen is currently more expensive than traditional production processes, roughly twice as much as grey hydrogen (see Exhibit 3). However, advances in electrolysis technology, decreasing costs of renewables, and increased economies of scale should significantly reduce its production cost and make it an increasingly economically viable solution.

Exhibit 3

Green hydrogen should become cost competitive compared to grey and blue hydrogen

Hydrogen cost development by production type



Note: Cost assumptions based on greenfield projects, excluding cost for buildings and cost for building cooling requirements.

Source: International Energy Agency, "The Future of Hydrogen: Seizing today's opportunities," June 2019 (https://www.iea.org/reports/the-future-of-hydrogen); Strategy& "The dawn of green hydrogen – Maintaining the GCC's edge in a decarbonized world

Application areas for hydrogen

Transport

The transport sector currently accounts for 23% of global carbon emissions. With the rise in the world's population and increasing levels of globalisation, this sector is expected to continue to grow rapidly. Currently, most of this sector relies on fossil-fuels as its primary energy source due to their high power-to-weight ratios, relative abundance and historical investment. The transport sector is one of the most difficult sectors to decarbonise due to its need for a stable, safe and energy dense fuel source. As you will see in the following sections, hydrogen, in one or other form, can provide a compelling solution to the decarbonisation of this sector.

Road

Hydrogen can be converted to usable energy in two ways; either through direct combustion and the creation of heat or through an electrochemical reaction inside a fuel cell. Internal combustion engine vehicles (ICEVs) have relied on fuels that need to be combusted and, in the process, this combustion creates dangerous by-products, such as carbon dioxide, nitrous oxide and fine particulates. Moreover, the conversion of chemical fossil-fuels to rotary motion requires a significant number of moving parts and produces large amounts of unwanted heat. In comparison, a fuel cell electric vehicle (FCEV) requires no combustion of its fuel and therefore produces far fewer unwanted by-products.

When hydrogen from a vehicle's fuel tank reacts with oxygen from the atmosphere inside the fuel cell it produces electricity that is used to drive the electric motors that power the wheels, with the only by-product exiting the exhaust being water.

In addition, fuel cells have almost no moving parts, making them significantly more reliable than ICEVs. Importantly, when the production of FCEVs reaches significant scale, their production cost should be lower than that of an ICEV due to their need for far fewer components. Additionally, FCEVs run silently, making them ideal for inner city transport where noise pollution is an issue.

As shown in Exhibit 2 and Exhibit 3, the energy density of hydrogen per unit of weight is exceptionally high. However, in its atmospheric state it has an incredibly low density. In order to be practically utilised inside an FCEV, the hydrogen must be stored under high pressure. One of the most common criticisms of this technology has been the safety of such systems and implications of these high-pressure fuel tanks in vehicle collisions. Many automotive manufactures have already launched FCEVs, and in order for these vehicles to be made legal for the road, they have undergone stringent safety testing. For instance, the high-pressure storage tanks inside current FCEVs are double or triple walled and can resist a gunshot at point blank range. Moreover, if a leak in an FCEV were to occur, the hydrogen dissipates very quickly. The systems used in FCEVs are no more dangerous than the liquid natural gas systems utilised on many ICEVs in South America. Even though the pressurised fuel system in FCEVs has been deemed safe for the public roads in most countries, researchers have made significant progress in developing metallic honey-comb storage systems that would nullify the need for such high pressures in the tanks.

Relative to ICEVs, FCEVs have far better power-to-weight ratios.

An average four-door car would require six litres of petrol (4.6kg) to travel 100km. In comparison, an FCEV could reach the same distance on 1kg of hydrogen. Even with low levels of adoption in FCEVs, given the current price per/kg of hydrogen, this would be significantly cheaper for consumers.

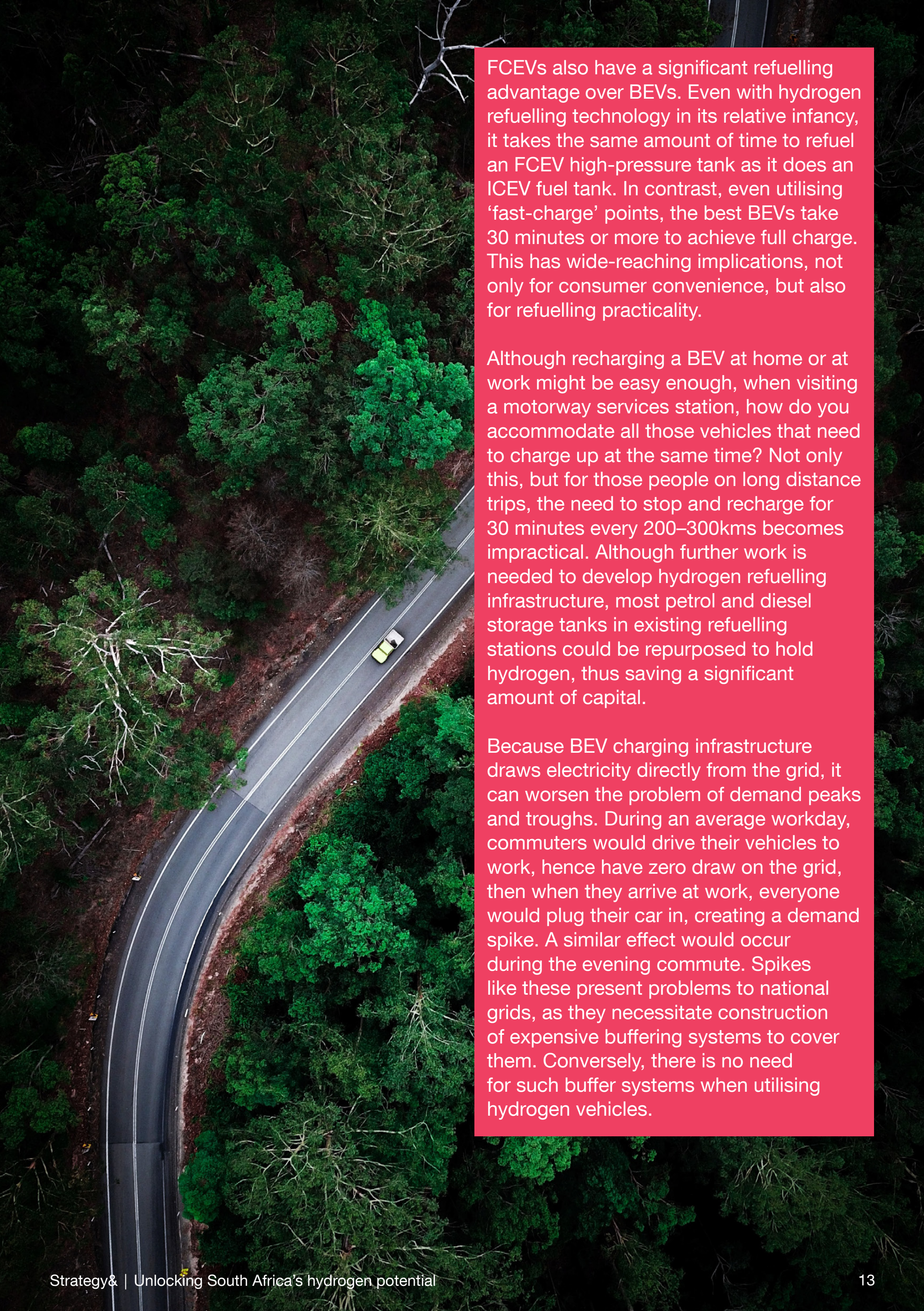
The relative energy density of hydrogen means that even at current technological levels, FCEVs have significantly higher fuel efficiency against both ICEVs and BEVs. A four-door FCEV can hold around 5-6kg of hydrogen in a full tank, thus giving it a range of 500-600km. This is comparable to an average ICEV family car. In contrast, even the market leaders in BEVs (Tesla) can only achieve 200–300km on a single charge. The key issue is simply the power-to-weight ratio. The battery required to power an 85kw motor in a Tesla weighs 530kg, a third of the entire weight of the car. A significant amount of the stored energy is therefore used simply to carry the battery around.

Toyota recently revealed the latest version of its hydrogen FCEV, which is set for launch in late 2020. Since the launch of the first model (Exhibit 4) in 2014, Toyota has sold more than 10 000 Mirai models globally.

Exhibit 4

Toyota Mirai Hydrogen FCEV

Image courtesy/copyright of Toyota Motor Europe



FCEVs also have a significant refuelling advantage over BEVs. Even with hydrogen refuelling technology in its relative infancy, it takes the same amount of time to refuel an FCEV high-pressure tank as it does an ICEV fuel tank. In contrast, even utilising 'fast-charge' points, the best BEVs take 30 minutes or more to achieve full charge. This has wide-reaching implications, not only for consumer convenience, but also for refuelling practicality.

Although recharging a BEV at home or at work might be easy enough, when visiting a motorway services station, how do you accommodate all those vehicles that need to charge up at the same time? Not only this, but for those people on long distance trips, the need to stop and recharge for 30 minutes every 200–300kms becomes impractical. Although further work is needed to develop hydrogen refuelling infrastructure, most petrol and diesel storage tanks in existing refuelling stations could be repurposed to hold hydrogen, thus saving a significant amount of capital.

Because BEV charging infrastructure draws electricity directly from the grid, it can worsen the problem of demand peaks and troughs. During an average workday, commuters would drive their vehicles to work, hence have zero draw on the grid, then when they arrive at work, everyone would plug their car in, creating a demand spike. A similar effect would occur during the evening commute. Spikes like these present problems to national grids, as they necessitate construction of expensive buffering systems to cover them. Conversely, there is no need for such buffer systems when utilising hydrogen vehicles.

A vehicle's carbon footprint is more than just the carbon dioxide it emits while in use — it includes the carbon attributable to its lifecycle. In this respect FCEVs offer a significant advantage over both BEVs and ICEVs. An ICEV creates a significant amount of emissions though the numerous materials needed for its construction, as well as its emissions through use. In a BEV, although it has fewer components, the materials required to produce the vast quantities of lithium-ion batteries to power it are relatively rare and create significant emissions in their extraction. In comparison, an FCEV contains fewer components than an ICEV and utilises an onboard battery a fraction the size of the one needed in BEVs. When looking at the cradle-to-grave carbon impact of all three options, the FCEV has the lowest carbon footprint.

For commercial road transport, FCEVs have significant advantages over BEVs. The increased use of car-sharing applications such as Uber requires cars to be in continuous operation and run for long periods of time in-between refuelling. FCEVs offer significant benefits as they can run for double the distance of BEVs and also refuel far quicker.

These same benefits apply within the trucking industry, where 'on-road' time is a priority. A previous counter to this argument had been that drivers (especially in the trucking industry) need to rest every 200–300 kms, hence recharging a BEV would align to this schedule. However, with the advent of autonomous vehicles in both the ride-sharing and commercial trucking industry, the need for drivers in these vehicles is fast becoming a thing of the past. Investors in these autonomous systems will require high utilisation with minimal time spent refuelling, making the only practical 'green' way of achieving this being with FCEVs.

FCEVs have already seen good penetration in industrial sectors such as materials handling (forklifts). This in mainly due to strict indoor warehouse emissions laws. FCEV buses are also gaining significant traction as concerns over air quality in urban areas escalates.

Within the mining sector, the first FCEV mining trucks are being developed, utilising 'green' hydrogen that is produced on remote mining sites through solar to electrolysis technology (Exhibit 5). 'First motion' of the hydrogen powered mining truck is expected in 2021, followed by a testing and validation programme at Anglo American's Mogalakwena mine in South Africa, after which the trucks are expected to be deployed at other Anglo American operations.

Operational performance of the converted trucks is expected to be the same or better than the diesel trucks they replace, with the additional benefits of cleaner air, less noise and lower maintenance costs. Through regenerative braking, the battery system will be capable of recovering energy as the haul truck travels downhill.

In July, JCB unveiled its 20-tonne 220X excavator, powered by a hydrogen fuel cell, which has been undergoing rigorous testing at JCB's quarry proving grounds for more than 12 months. The development means JCB is the first construction equipment company in the world to unveil a working prototype of an excavator powered by hydrogen, reaffirming its drive in the sector towards zero and low-carbon technologies (Exhibit 5).

Exhibit 5

Anglo Americans haul truck that is being converted into an FCEV and JCB's hydrogen-powered excavator

Image courtesy/copyright of Anglo American

Image courtesy/copyright of JCB

Large potential FCEV uptake is expected from the long-haul and public transport sectors thanks to fuel efficiency 2–3 times better than that of regular diesel ICEVs. Hyundai's H2 Xcient hydrogen FCEV heavy-duty trucks are expected to be on the road in Switzerland in 2020 as part of an order for 1 600 of these trucks being delivered between now and 2025.

The trucks will be leased out through Hyundai hydrogen mobility and are equipped with two hydrogen fuel cell stacks that drive electric motors. The system provides 190kw of power and with seven high-pressure tanks, each carrying 35kg of hydrogen, a range of around 400km is expected — much further that an equivalent BEV heavy load vehicle.

Anheuser Busch has cemented its commitment to reduce emissions by placing an order for 800 hydrogen-FCEV class 8 trucks from Nikola Motors, at an expected price tag of around USD375k. This is a material premium when compared to the USD180k BEV equivalent, the Tesla Semi, and even more so when compared to a normal diesel ICEV equivalent at around USD120k.

First movers in the FCEV transport technology space have gained significant investment attention in recent years. In September 2020, General Motors (GM) announced its acquisition of a USD2bn stake (11% stake) in Nikola. The deal will also see GM manufacturing Nikola's Badger, a fully electric and hydrogen FCEV pickup truck, as well as becoming the exclusive supplier of their fuel cells around the world.

Exhibit 6
FCEV heavy-duty trucks destined for roll-out in 2020

Image courtesy/copyright of Nikola Motor Company

Although FCEVs present significant advantages over both ICEVs and BEVs in certain instances, it is important to note that the future of road transport will not be characterised by a winner takes all technology. There is little doubt that by the middle of this century, with the pressure mounting on decarbonisation, ICEVs will be a thing of the past. But their replacement will likely be a combination of both BEVs and FCEVs.

FCEVs are far more economical in applications that require long ranges, heavy loads or high utilisation. However, for inner-city transport outside of the commercial sector, BEVs will likely be more suitable, as access to plug points is easy and there is no need to travel long distances or carry heavy loads.

The development of both FCEVs and BEVs is likely to be symbiotic, as the technology used in both is largely the same (electric motors), so they can both benefit from each other's research and development initiatives. The future of the 'green' vehicle marketplace will likely see manufacturers selling both FCEVs and BEVs that utilise the same platform (chassis) and drivetrains but have both fuel-cell and battery configurations.

Rail

Decarbonising rail transport would appear simple on the face of it, as all you would need to do is generate energy with renewables and electrify all the trains. Unfortunately, it's not that easy. About 70% of the world's 200 000 locomotives operate on non-electrified rails. The electrification of existing rail infrastructure alone would be an extremely capital-intensive exercise, let alone the new rail infrastructure that is required to support the swelling global population. One proposed solution to the decarbonisation of the rail sector is through utilising hydrogen technology.

The majority of rail infrastructure, especially in the developing world, is used for freight transport and not for passengers. Most of these freight trains utilise diesel-electric locomotives. This means the train combusts diesel through an ICE generator to produce electricity, then uses this electricity to run high-torque electric motors that power the wheels. The configuration of this system provides a unique opportunity for hydrogen technology and for the decarbonisation of rail transport.

If the diesel generator was removed from the locomotive, then essentially all that is needed to power the train is a source of electricity, such as a fuel-cell. The diesel fuel tanks can be replaced by high-pressure hydrogen tanks and the space that was previously occupied by the diesel generator could house the much smaller fuel cell. The fuel-cell would then provide electrical energy to the motors in the same manner the diesel generator would have. This solution has a number of benefits over the electrification of rail networks and it requires no capital expenditure on the existing rail infrastructure, making it a significantly cheaper option.

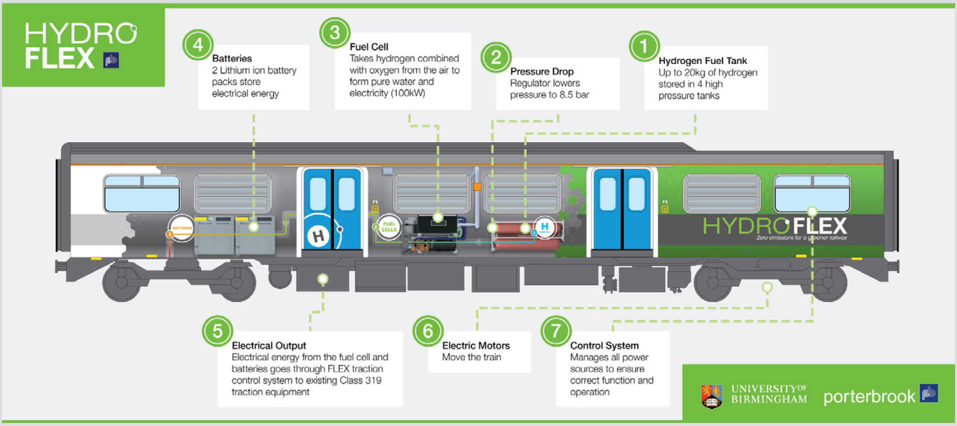
The solution also requires minimal redesign of locomotives, which is especially important in the freight industry, as very few all-electric freight trains or the overhead lines needed to power them currently exist. The system has already been piloted on commuter rail networks in Germany and the UK, with great success (Exhibit 7).

The HydroFlex project in the UK is expected to decarbonise sections of the British railway network by replacing diesel trains with hydrogen ones by 2040.

In 2016, Germany unveiled the Coradia iLint, the world's first hydrogen-powered train, which can run for 965km on a single tank of fuel — on par with the distances that traditional trains achieve on a tank of diesel. The rail industry is in a unique position to be an early adopter of hydrogen technology as, not only is the economic argument for its use compelling, but its centralised refuelling configuration means will not need to rely on significant hydrogen refuelling infrastructure being built.

Exhibit 7

HydroFLEX train concept design



① **Hydrogen Fuel Tank** Up to 20kg of hydrogen stored in 4 high pressure tanks

② **Pressure Drop** Regulator lowers pressure to 8.5 bar

③ **Fuel Cell** Takes hydrogen combined with oxygen from the air to form pure water and electricity (100kW)

④ **Batteries** 2 Lithium ion battery packs store electrical energy

⑤ **Electrical Output** Electrical energy from the fuel cell and batteries goes through FLEX traction control system to existing Class 319 traction equipment

⑥ **Electric Motors** Move the train

⑦ **Control System** Manages all power sources to ensure correct function and operation

Image courtesy/copyright of University of Birmingham

The first zero-emission ‘Hydrail’ project in the US will be in Southern California, where the San Bernardino County Transportation Authority plans to operate a Flirt H2 train from Swiss supplier Stadler from 2024. The first train, with two cars and a rooftop power pack containing fuel cells and hydrogen tanks, will run on a nine-mile commuter rail line between San Bernardino and Redlan.

Widespread adoption of hydrogen would create obvious synergies across the transport sector in having both road vehicles and trains utilise the same fuel source. However, in the rail industry (especially freight) there exists further synergy opportunities. In the long run the most cost-effective way to transport hydrogen long distances on land will be through pipelines, in a fashion similar to natural gas. But in the early adoption years of the hydrogen economy, the only way to move hydrogen across land will either be on tanker trucks or on rail networks. It will create obvious synergies from both a cost and convenience perspective if the very locomotives transporting hydrogen are also being powered by it.

Aviation

The aviation industry is by far the most difficult of all transport sectors to decarbonise. This is due to the need that whatever powers an aircraft has an extremely high power-to-weight ratio. It must also be stable at different pressures and not present an unacceptable safety risk in a crash.

In recent years there has been massive innovation in small-scale aviation technologies, namely drone technology. Drones have seen high uptake both in the personal and commercial sector. Many drones currently run off high-spec lithium-ion batteries that power a propeller array. They perform well in applications where they only need to carry light payloads such as cameras or small deliveries. The highest specification drones have a flight time of 40-minutes, before needing to be recharged. Heavier payloads makes their this flight time shorter. It is this issue of flight time and payload capacity that has led some companies to investigate hydrogen powered drones.

In 2019 a Chinese company built a hydrogen-powered drone that completed and uninterrupted flight of over 12 hours. It is clear that as this technology continues to innovate, hydrogen will play an ever-increasing role. It is once again the energy density of hydrogen compared to batteries that has led to companies developing large-scale drones capable of carrying humans, called vertical lift-off taxis (VLOTs), to pursue hydrogen as a fuel. The first VLOT prototypes are expected in the coming years.

Although, progress has been made into the electrification of small-scale and short-distance aviation, there has been little to no progress made in addressing long-distance aviation decarbonisation. There have been some prototype electric planes, but they have not yet proved to be commercially viable. Once again, the challenge is the power-to-weight ratio. There is no electrical technology that can compete with the performance of a fossil-fuel powered jet engine.

It is theoretically possible to run existing jet engines on liquid hydrogen, but the storage of this fuel in high-pressure cylinders within the aircraft presents some safety concerns. Nonetheless, there are prototype hydrogen-powered planes being piloted on short-haul flights in the north of Scotland.

While there is no clean solution to replace the technology that currently enables long-haul flight, we can take measures to decarbonise the fuel. It is in this regard that hydrogen can play a critical role in addressing the carbon emissions of the aviation industry.

All combustible fossil fuels are comprised of three basic components: hydrogen, oxygen and carbon. For the aviation industry, oil is synthesised into kerosene, a molecule comprised of hydrogen and carbon. This is combined with oxygen and combusted in a jet engine; 1kg of kerosene produces 3kg of carbon dioxide and 3.5kg of water. If we are able to produce hydrogen from a 'green' source, namely renewables, then this hydrogen can be combined with atmospheric carbon to create synthetic kerosene. In fact, this method can be used to produce any number of hydrocarbon-based fuels.

Pilot projects have already been launched in the Netherlands, utilising so-called 'carbon sails'. These sails filter carbon from the atmosphere and combine it with hydrogen produced from the electrolysis of water, using renewable energy. The resultant synthetic fuel still emits carbon when combusted, but importantly does not emit any more carbon into the atmosphere than was already there. It is hoped that this technology can be rolled out to such a scale that the entire aviation fuel market can transition into a closed-carbon loop in which no new emissions are created.

Climeworks is another company utilising direct air capture (DAC) technology to draw in air and bind the carbon dioxide using a filter. The filter is then heated to release the concentrated gas, which can also be used in industrial applications such as a source of carbonisation in the food and beverage industry or in the production of synthetic fuels.

Image courtesy/copyright of thyssenkrupp

Shipping

Global shipping accounts for 3% of total carbon emissions and is set to increase in the coming years. Due to the vast amount of power needed to turn a ship's propeller and the long distances between ports, it is not practical to electrify ships. It is possible to power the engines of smaller ships from natural gas or even through the direct combustion of hydrogen in gas turbines, but the risk presented by the storage of combustible gas on a ship is too high to make it a viable option at this stage.

In order to address the decarbonisation of the shipping industry, in a similar fashion to the aviation industry, we must look to the fuel source. Currently, almost all ships run on forms of diesel. Diesel is a combination of hydrogen and carbon, and when combusted with oxygen emits a significant amount of this carbon into the atmosphere in the form of carbon dioxide. But diesel engines have the unique property that they can combust most flammable liquids and, as in the aviation industry, the answer to decarbonisation lies in the utilisation of a 'green' hydrogen-based synthetic fuel; ammonia.

Ammonia is a molecule containing nitrogen and hydrogen, and when combusted produces nitric oxide and water, but no carbon emissions. Importantly for the shipping industry, ammonia is exceptionally stable and energy dense, making it an ideal fuel. It would require no significant re-design of existing shipping diesel engines in order for them to utilise ammonia as a fuel source.

The key to achieving decarbonisation in shipping will be the creation of synthetic ammonia utilising 'green' hydrogen produced from renewables. An example of how this has been put into practice is illustrated by Norwegian national energy company Equinor having signed an agreement with Eidesvik Offshore for the conversion of the Viking Energy supply vessel to be fuelled by ammonia (Exhibit 8).

The project will test whether the technology can deliver 100% carbon-free power over long distances. According to the project plan, ammonia will meet 60– 70% of the power requirement on board for a test period of one year. Viking Energy will still be able to use LNG as fuel, and the remaining power requirement will be met by a battery. Importantly, this project demonstrates that the technology can be applied to older vessels with minimal modifications.

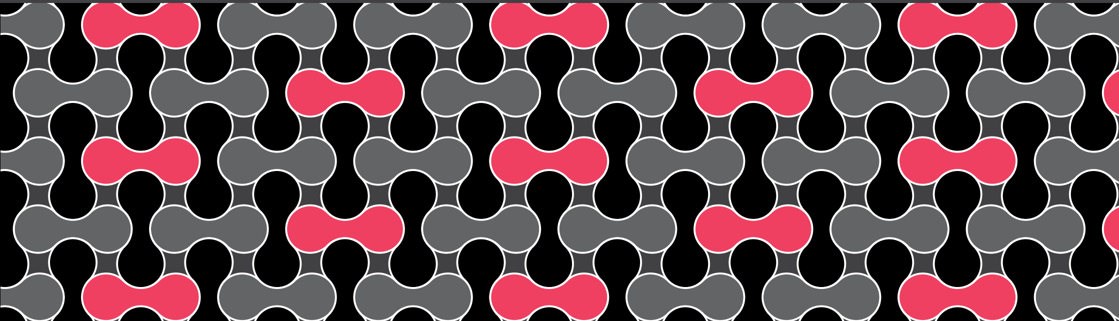


Exhibit 8
Viking Energy supply vessel

Image courtesy/copyright of Eidisvik Offshore

Building heat and power

Building and water heating account for 80% of residential energy consumption, creating 12% of global carbon emissions. This can be reduced through improving building energy/heating/cooling efficiency and using green energy sources. As a green energy source, hydrogen can help decarbonise building heat and power in a number of ways.

In more developed countries, especially those in the northern hemisphere, there exists significant natural gas networks. These networks provide natural gas directly to people's stoves, geysers and central heating systems. If the countries where these natural gas networks exist wanted to transition to renewable energy directly to the home, they would need to decommission these grids and provide electric boilers, geysers, heat pumps and stoves to those homes that previously relied on gas. The capital cost of such an exercise would be tremendous.

Alternatively, hydrogen can be blended with natural gas up to 20% and can be piped through existing infrastructure without any need for upgrades. In Italy, Snam was the first company in Europe to introduce a mix of 5% hydrogen and natural gas in its transmission network in April 2019. The trial involved supplying H2NG (hydrogen-natural gas mixture) for a month to two industrial companies in the area, a pasta factory and a mineral water bottling company. In December 2019, Snam successfully doubled the hydrogen concentration on its existing transmission network to 10%.

It is also an option to upgrade existing grids to run on 100% renewable hydrogen. This would require some capital expenditure to upgrade appliances to run on a more energy-dense fuel. The capital cost involved in upgrading to hydrogen would still be a fraction of the cost of changing to other technologies. In the UK, 100% hydrogen schemes such as the H21 project (Exhibit 9), are already being piloted.

The use of hydrogen in natural gas networks is also advantageous from an energy storage perspective. The H21programme, launched in 2016, is a collaborative gas industry programme led by Northern Gas Networks, the gas distributer for the North of England, focused on demonstrating how converting the UK gas network to carry 100% hydrogen is technically and economically viable as a means tackle the UK's decarbonisation challenges.

The project aims to convert 3.7 million homes and businesses from natural gas to hydrogen over seven years. A further roll-out could mean 12 million additional homes converted to hydrogen by 2050. It is anticipated that the full deployment will utilise SMR with carbon capture in the North Sea.

Exhibit 9

H21 Leeds City Gate Concept view of infrastructure layout to hydrogen conversion of existing natural gas distribution networks

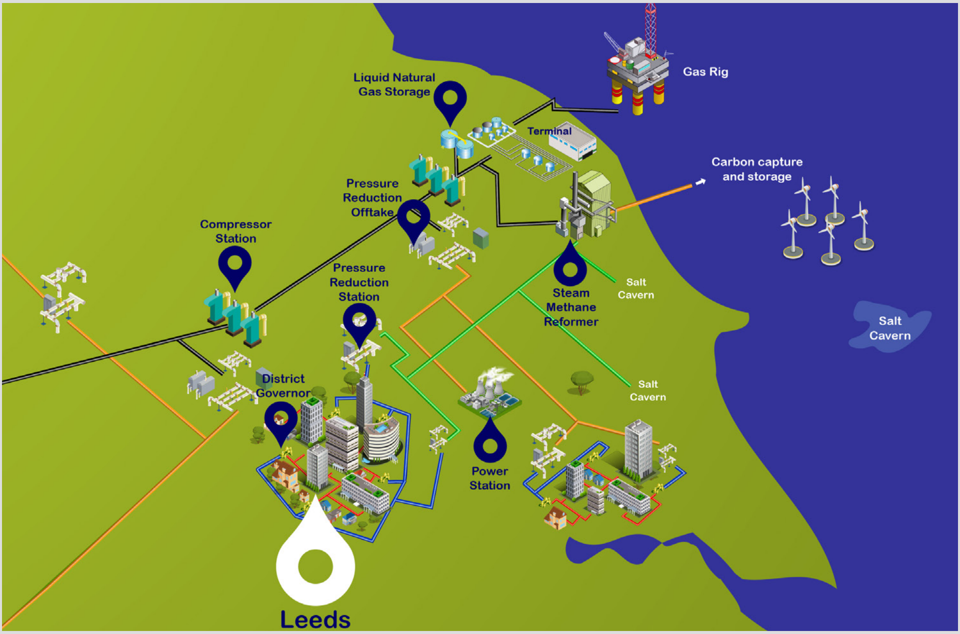


Image courtesy/copyright of H21

Hydrogen can be stored for long periods of time without losing its energy potential and is also unaffected by the cold, unlike batteries. Most European countries have relatively warm sunny summers and cold winters. As is the case with solar photovoltaic (PV) systems, there is usually a surplus of energy produced in the summer months and a shortage of energy in the winter months. If the summer surplus is used to create hydrogen through electrolysis, this hydrogen can be stored very cost effectively and utilised to provide building heat during winter. This solution reduces the need for large buffer systems in the grid and allows for a full utilisation of renewable solar PV in the summer.

When hydrogen reacts with oxygen in a fuel cell and a significant amount of heat is created as a by-product, in FCEVs this heat is unutilised, but can be utilised to heat buildings while simultaneously providing electrical power. Such combined heat and power (CHP) units have been rolled out extensively as part of the Ene-farm project in Japan, to provide both off-grid electricity and heat to warm homes in winter. The use of fuel cells to provide building heat and power is an efficient solution and also provides increased reliability.

In cases where national grid supply is inconsistent or where back-up power is a necessity (hospitals, school), fuel cells offer a clean alternative to diesel generators. The Ene-farm project aims to deploy 1.15 million hydrogen fuel cell CHP units in addition to the 305k that are already operating, with the potential for a future roll-out of 3.9 million units by 2030. The initial cost of a typical unit has seen a significant 75% cost reduction over 10 years. However, the economic viability of the project is still dependent on a government subsidy of 6–10%.

Energy sector

One of the key issues facing the renewable energy sector is how best to efficiently store the energy created in order to achieve smooth supply and maximise asset utilisation. Currently, there is limited capacity to hold energy within grid systems and the massive cost involved with battery storage at scale makes it a poor option. Energy oversupply can be combatted by turning the asset off, but in the case of renewables (wind, solar) this is a highly inefficient utilisation of the asset.

Hydrogen can help solve the intermittent supply issues associated with renewable energy by utilising electrolysis to convert excess electricity into hydrogen during times of oversupply. This hydrogen can then be utilised to generate power through either fuel-cell or direct combustion in gas turbines when it is needed.

Excess hydrogen could also be supplied to the transport, building heat and power or industrial sectors. Hydrogen can help address energy intermittence across long horizons, helping to counter seasonality in renewables such as solar deficits in winter. Hydrogen offers better energy storage per unit of weight and it has no theoretical maximum storage time, unlike batteries. Underground storage (salt caverns) of hydrogen is already a well-established commercial practice. There are also pilot tests underway of storing hydrogen in depleted gas fields.

Over the short term, conversion of electrical energy to hydrogen through electrolysis is more inefficient and loses more energy losses compared to battery storage. However, when looking at the longer term and the cost of hydrogen storage vs. large-scale batteries, the economic argument for hydrogen becomes compelling. Hydrogen's capacity to be multifunctional through its energy storage and ability to provide primary fuel to the transport sector makes it highly appealing.

As global energy production transitions away from fossil fuels towards renewables, power production is going to increasingly become geographically linked. With countries with high solar, wind and hydroelectric potential accounting for a larger proportion of the world's energy production capacity. This will necessitate the transportation of energy from renewable 'rich' countries to renewable 'poor' ones.

One example of this is the relationship between Japan and Australia. Japan has committed to one of the world's more progressive decarbonisation strategies, yet, has relatively low renewable power generation capacity. It has therefore partnered with Australia (a country with vast production potential of both green and blue hydrogen) to supply clean energy. The countries plan to transport this energy through liquified hydrogen via cargo ships developed by Kawasaki heavy industries.

Suiso Frontier, the world's first liquified hydrogen cargo ship was developed to provide a means of transporting liquefied hydrogen at 1/800 of its original gas-state volume, cooled to –253°C, safely and in large quantities over long distances, predominantly from Australia to Japan (Exhibit 10). Kawasaki plans to install a 1 250m³ vacuum-insulated, double-shell-structure liquefied hydrogen storage tank on the ship and complete the vessel's construction by late 2020.

Exhibit 10

SUISO Frontier liquified hydrogen carrier destined to ship liquified hydrogen from Australia to Japan

Image courtesy/copyright of HySTRA

As discussed earlier, hydrogen is exceedingly energy dense and if stored correctly has no theoretical expiration. On land, the most efficient distribution method for hydrogen is through gas pipelines, similar to those currently utilised for natural gas. Before such large capital-intensive pipelines can be built, the most practical method of land transportation will likely be road tanker and rail. Given the significantly higher energy density of hydrogen over fuels already transported such as gasoline (six times denser), it's clear how much more cost-efficient hydrogen would be.

Hydrogen's ability to store energy effectively and for a long time makes it an ideal buffer technology. Current buffer energy generation stands at 15% globally, the bulk of this being fossil fuel-based systems. Both through its direct combustion and use in gas turbines or through fuel-cells, hydrogen can generate instant energy just like fossil fuels. While initial hydrogen infrastructure is more expensive than battery storage, hydrogen infrastructure is far cheaper at scale and does not require significant upscaling of existing electricity grids.

The use of hydrogen in grid buffering not only supports the use of renewables, but can remove the need for large overcapacity in power generation. In times of high energy usage, and in cases where there are other sectors of the economy utilising hydrogen technology, hydrogen could be redirected from the transport sector (temporarily) and be utilised to generate additional energy to the grid, removing the need for expensive buffer generation capacity. Transitions to domestic renewables will reduce the need for this, but hydrogen offers a better long-term solution to provide back-up energy as it requires very little conversion to be immediately utilised. Current buffer power systems such as natural gas turbines can be easily retrofitted to run on hydrogen and thus remove the need for new capital to be spent on 'green' buffering systems.

Fuel cells are increasingly being used to provide off-grid power solutions to remote villages, islands, mountainous areas and telecom sites as they are a more cost-effective solution to grid infrastructure. With the logistics around transportation of liquid hydrogen still technically difficult, most of these off-grid sites run on hydrogen 'rich' liquid fuels such as methanol. These stationary fuel cells are also being deployed in back-up generation systems by the telecommunications sector, hospitals and IT datacentres.

Industrial heat and feedstock

The uptake of hydrogen for use in both industrial heat and feedstock may well be the catalyst for widespread adoption across all sectors. The three major ways to decarbonise industrial usages with hydrogen are using hydrogen for heat, pre-combustion feedstock, and post-combustion feedstock. At present hydrogen is the only alternative in driving decarbonisation in the industrial sector. Furthermore, investment in the use of hydrogen in industrial activities will also drive its adoption in other areas, creating a win-win situation.

Industrial heat

Currently, coal, natural gas, and oil provide the primary energy (usually through direct combustion) for industrial processes, contributing 20% of all global emissions. With the steel industry accounting for the biggest share, followed by non-metallic minerals and the chemical industry.

Industrial processes that require low-cost, high temperatures, are difficult to replace with electric furnaces powered through renewable energy.

Although global steel demand is expected to slow in the coming years, particularly as the automotive sector turns towards lighter materials such as aluminium and carbon fibre, the steel industry will contribute an ever-increasing proportion of global emissions.

Certain processes in the steel-making process require coke to be combusted with the material. It is both this direct 'reductant' process and through the heat needed in smelting of raw iron that the steel industry creates high emissions.

Hydrogen can help combat these emissions both as a direct source of heat in the smelting process and as a chemical 'reductant' inside the smelter, thus replacing the need for carbon-intensive coke.

In Sweden, the HYBRIT initiative has been launched to produce zero-emission steel. The construction of the hydrogen electrolysis and storage facility and pilot steel plant began in 2018 with the first commercial sales of fossil-free steel from expected in 2026. The technology being used is electric arc furnace (EAF) fed by direct reduced iron (DRI) produced using hydrogen, powered by renewables. HYBRIT estimates that production costs are currently 20–30% higher than conventional steel production. However, the cost gap is expected to shrink as carbon taxation goes up and green electricity prices fall.

In Germany, ArcelorMittal is building a pilot plant at its Hamburg mill to use hydrogen as a reductant in DRI production. The project targets production of 100ktpa of DRI using grey hydrogen sourced from natural gas initially, with subsequent conversion to green hydrogen once renewable energy capacity is available.

Hydrogen used for heat could replace fossil fuel processes in the steel industry, petrochemical industry, pulp and paper industry and in off-gas combinations in the cement industry, or indeed in any industrial process that requires high temperatures. Hydrogen is a highly combustible material and in normal conditions burns at 2000°C. If this hydrogen is combined with carbon, in a fashion similar to the synthetic fuels process being piloted in the aviation and shipping industries, then even higher temperature derivatives such as acetylene can be produced.

Within the industrial heat sector, hydrogen is currently the only plausible solution to decarbonisation, as it is available in abundance, is highly energy dense, is stable and creates very little pollution when burned. There are also high synergies between the existing emissions created by the industrial sector and the ability to produce these hydrogen-based synthetic fuels.

For example, an existing steel smelter could build a wind turbine adjacent to its own facility to produce green hydrogen through the electrolysis of water. This hydrogen can then be combined with the carbon emissions from the smelter off-gasses, thus creating a synthetic hydrocarbon. The smelter can then use this synthetic fuel to supplement or fully replace the fossil fuels being used to heat the smelter. In most cases this would also require minimal plant reconfiguration, as most already run on hydrogen derivatives.

Although this process does not represent a true ‘decarbonised’ scenario, it represents an important bridging step towards lowering global emissions. If this type of technology were to be implemented within the steel industry, or indeed by any industrial carbon emitter, then in effect every carbon atom emitted into the atmosphere is utilised twice, once in its first combustions (i.e. coke used as the reductant of iron) and then a second time in the combustion of synthetic fuel to provide heat to the smelter. This doubling up of carbon use, if implemented globally, would in effect halve global carbon emissions. So, although not carbon neutral, this approach is certainly worth the attention of many industries if they want to curtail carbon emissions and avoid expensive taxes in the future.

The advantage of decarbonisation in the industrial sector is that there is a far less fragmented stakeholder structure to tackle. Since the industrial revolution, 100 producers have accounted for 71% of global emissions. High levels of interdependence in the industrial sector means investment in hydrogen has a better chance of leading to wide-scale adoption.

While hydrogen is not a cost-effective substitute for the industrial heat provided by coal, oil and gas right now, if it is produced at scale, this cost will decrease. When combined with government incentives to adopt green heat sources and tax penalties on carbon emissions, this will create a far more favourable environment for broad adoption.

Industrial feedstock

Currently, the biggest global use of hydrogen, accounting for 55% of all production, is ammonia. Other significant uses include the oil refining process, methanol production, rocket fuels and in the hydrogenation of oils for the food industry. With roughly 95% of hydrogen in the market being produced from either natural gas or coal, and with limited carbon curtailment, this industrial feedstock hydrogen represents a significant source of emissions and the demand for its end products is expected to grow in the coming years. The obvious solution to address these emissions is to source hydrogen from a ‘green’ source, the most likely being the electrolysis of water through renewable electricity. As the unit costs of energy produced from renewables continues to fall and electrolysers continue to become more efficient, the supply of green hydrogen in industrial feedstocks will likely increase.

In July 2020, Air Products and Thyssenkrupp signed an exclusive strategic cooperation agreement (SCA) for world-scale electrolysis plants to generate green hydrogen. The two companies will collaborate exclusively in key regions, using their complementary technology, engineering and project execution strengths to develop projects supplying green hydrogen.

Shortly after the signing of the SCA, Air Products, in conjunction with ACWA Power and Neom, announced the signing of an agreement for a USD5bn world-class green hydrogen-based ammonia production facility powered by renewable energy. The project, which will be equally owned by the three partners, will be sited in Neom, a new model for sustainable living located in the north-west corner Saudi Arabia, and will produce green ammonia for export to global markets.

The project will include the integration of more than 4GW of renewable power from solar, wind and storage to produce 650 tons of hydrogen per day. Thyssenkrupp will be supplying the electrolysis technology, with Air Products supplying nitrogen production via their air separation technology. Once completed, the facility will produce 1.2Mt of green ammonia per year. The project is scheduled to come online in 2025. Air Products will be the exclusive offtaker of the green ammonia and intends to distribute it around the world for the transportation market.

The availability of affordable green hydrogen has other implications for the industrial sector. Many industrial carbon emitters are facing a looming problem in the coming years, either through the need to significantly reconfigure their processes to reduce their emissions or face paying hefty carbon taxes. Cheap green hydrogen could offer a solution to these industry players. As already stated, hydrogen has the ability to capture carbon from industrial (carbon-rich) off-gases and trap it in synthetic fuels.

In Germany, Shell and ITM Power are building the world’s largest onsite electrolysis plant to produce feedstock hydrogen at the Shell Rhineland Refinery. The refinery, Germany’s largest, currently requires approximately 180 000t of hydrogen annually, which is produced by steam reforming from natural gas. The new facility will produce an additional 1 300t of hydrogen per year, which can be fully integrated into the refinery processes, such as for the desulphurisation of conventional fuels. The plant is scheduled to begin operation in 2020 and will be the first industrial-scale test of the polymer electrolyte membrane technology process.

In Iceland, the George Olah carbon dioxide (CO2) to renewable methanol plant is located at the Svartsengi geothermal power station in the town of Grindavik. The plant produces hydrogen from geothermal sources, then captures CO2 from the same geothermal source to create methanol fuel. Renewable methanol is a synthetic liquid fuel used in gasoline blends to meet the renewable energ directives.

Another example of how off-gases can be utilised to create fuel is the Carbon2Chem project in Germany (Exhibit 11). The plant utilises off-gasses from the steel industry and hydrogen produced from excess renewables energy to create synthetic fuels. Hydrogen can be used directly in the industrial process, together with CO2 in synfuels/electro fuels thus acting as a carbon sink.

Exhibit 11

Carbon2Chem facility in Germany

Image courtesy/copyright of thyssenkrupp

Creating fuel from off-gases may prove a far more affordable option for industrial carbon emitters. Not only does it provide a practical solution for their emissions, but it is also one with high potential synergies. If sector coupling is successfully achieved and hydrogen uptake becomes widespread, industrial companies may end up utilising hydrogen to run their vehicle fleets, provide electrical power to their factories and create heat for their processes — and in the process capturing carbon from their off-gases. This ability of hydrogen to address many of the largest issues around decarbonisation is why the argument for the hydrogen economy is so strong.

Opportunities for South Africa

Hydrogen production and export
South Africa has one of the highest renewable energy generation potentials in the world. There have already been billions of rand committed to solar, wind and pumped storage projects across the country. The Government's Integrated Resource Plan (IRP) 2019 makes clear guidance for renewables to account for a bigger proportion of the country's generation capacity. With so much effort being committed to these renewable initiatives, a clear opportunity exists for South Africa to couple renewable generation with hydrogen production through electrolysis. The added benefit of this is that an investment in electrolysis technology would also support the platinum sector and downstream beneficiation, as platinum is the primary component in the electrode assembly.

Given its immense renewable energy potential, South Africa could become an exporter of cost-effective green hydrogen to the world. The infrastructure needed to export hydrogen is similar to existing natural gas networks and is already being piloted in Australia and Japan. South Africa could leverage its existing port infrastructure to support this initiative and, in doing so, protect the jobs and infrastructure that are declining as a result of the drop in global demand for coal exports.

There would also be significant secondary benefits to increasing South Africa's commitment to renewable energy. The need to construct so much renewable capacity would make it increasingly viable to manufacture a number of the components domestically. Especially within the wind turbine sector, this could help support the iron ore, manganese, chrome, ferrochrome, ferromanganese and steel industries.

Blue hydrogen may well be the bridge into the hydrogen economy. Providing a supply of low-carbon hydrogen into the market by utilising existing carbon-intensive production facilities. This would allow the uptake of downstream hydrogen technologies to grow while green hydrogen production is being developed. By utilising its coal and natural gas reserves South Africa has numerous opportunities to develop blue hydrogen production. Existing coal gasification facilities run by Sasol already produce the hydrogen-rich syngas needed to produce pure hydrogen, but these facilities would need carbon-capture technology implemented in order to produce blue hydrogen.

With the newly discovered natural gas claims in the Brulpadda Block and the existing gas-to-liquids (GTL) facility operated by PetroSA, much of the infrastructure already exists to supply pure hydrogen into the domestic and international markets. The natural gas market may also provide another solution in the form of carbon storage. Many of the gas fields off the coast of South Africa are depleted, yet the infrastructure linking these fields to the coast still exists. Similar to the solution being piloted in the UK, hydrogen could be produced on land through either coal gasification or reforming of natural gas and the carbon by-product could be pumped into the depleted gas fields for storage. The transition of the ailing South African coal and natural gas sectors to the production of blue hydrogen could help protect industry jobs and, if exported, generate critical foreign income for the country.

In recent years the concept of nuclear power generation in South Africa has received much press, most of it marred by allegations of corruption and unaffordable costs.

But provision has been made in the IRP 2019 for two small modular reactors to be constructed before 2030. The thinking behind this is that due to uncertainty of supply from the Eskom coal fleet, the country needs additional instantaneous power generation. Nuclear works well in this regard, as it can supply power into the grid almost at the flick of a switch and, unlike renewables, is not weather or timing dependent. However, nuclear reactors (even modular ones) are most efficient and provide maximum returns on investment when they are utilised to the maximum. If these reactors are only being utilised to supplement the grid in times of peak loading or in emergencies, then they will not be being utilised efficiently. The solution may be to combine these reactors with a hydrogen electrolysis plant. This would enable the reactor to run continuously and at maximum efficiency, providing power directly to the grid when needed and producing hydrogen when not. This hydrogen could then be utilised to generate additional peak power, provide buffer generation, long-term energy storage or be utilised in the off-grid or transport fuel-cell industry.

Fuel cell manufacturing

One of the costliest components within a fuel cell is the catalyst. With current levels of technology, the catalyst accounts for a third of the entire cost of a fuel cell. This is because platinum is the most efficient catalytic material. Platinum and the wider group of platinum group metals (PGMs) have historically been used within the automotive sector in the cleaning of exhaust emissions by auto-catalytic converters. On a vehicle-to-vehicle comparison, an FCEV requires between three and ten times the amount of platinum as an ICEV catalytic converter.

Many leading fuel-cell manufacturers are attempting to lower the volumes of platinum utilised in FCEV catalysts in an effort to make the technology more affordable, but even the most optimistic technology targets put the volume of platinum used in an FCEV on par with that of an existing ICEV.

This obviously represents a significant opportunity for the South African platinum sector and explains why the sector has been one of the leading investors in fuel-cell technology on the continent. With the PGM resources located in South Africa and Zimbabwe accounting for 90% of known reserves, these countries stand to benefit from the widespread adoption of fuel cells. With so much of the world's platinum being produced in Southern Africa, it makes sense for South Africa to move along the value chain and begin manufacturing fuel-cell catalysts, creating additional value, before exporting the product.

The technology for producing a fuel-cell catalyst is not dissimilar to that used in auto-catalytic converters, which are already produced in South Africa. If there were large enough economies of scale, manufacture of fuel-cell catalysis in South Africa would reap significant economic benefits. The first fuel-cell factory is already under construction at the Dube TradePort special economic zone outside Durban. However, at this stage the facility is being utilised for fuel-cell fabrication and not the direct manufacture of platinum catalysts.

Manufacturing FCEVs

South Africa already has significant vehicle manufacturing facilities, with major automotive players such as BMW, Mercedes-Benz, Toyota, Volkswagen and Nissan producing vehicles in the Eastern Cape, KwaZulu-Natal and Gauteng. All these companies are working on their own or in collaboration with others in the development of FCEVs. If the demand for FCEVs grows as expected in the coming years, and if South Africa could support the manufacture of fuel cells domestically, then it would be an obvious next step to move along the value chain and utilise these fuel cells in the local manufacture of FCEVs. This would create jobs and boost export earnings.
The secondary upside of increased vehicle manufacturing, both with ICEVs and FCEVs, would be the support of other South

African sectors, especially the chrome, manganese, ferrochrome, ferromanganese, aluminium and steel industries. Although the use of steel has declined in the automotive sector in favour of lighter materials such as aluminium and carbon fibre, use of stainless steel is still high. If stainless steel used in the domestic production of both ICEVs and FCEVs were to be sourced domestically, it could help support other key industry areas.

FCEVs also utilise a significant amount of rare earth elements (REE), lithium, cobalt, nickel and copper. With Africa tipped to be one of the key areas for REE exploration in coming years, the opportunities to beneficiate these minerals domestically and utilise them in the construction of FCEVs may become highly profitable. The US is also very keen to support the development of REE mining and beneficiation outside of China and will provide funding to such projects that can help de-risk their own supply of REEs.

Materials such as copper and nickel are also found in South Africa and they too could be utilised in support of FCEV manufacturing — supporting the domestic mining sector, creating employment opportunities and reducing reliance on imports.

Adoption of FCEVs in commercial fleets

In the coming years the adoption of FCEVs in almost all sectors will make economic sense, especially with their superior performance over ICEVs and BEVs in certain applications. Early adoption of FCEVs in South Africa has the benefit of supporting the wider economy, especially if the FCEVs and the hydrogen powering them are produced domestically. Because of this, government should consider subsidising early adopters of FCEVs, as the benefits for the country as the whole would likely outweigh the cost of the subsidy. Subsidies could either be provided by subsidising the capital cost of the vehicle, or alternatively, the hydrogen fuel could be subsidised.

Certain sectors in South Africa that are already pioneering FCEVs, especially within mining. Impala Platinum has deployed a fleet of FCEV forklift trucks at its refinery in Gauteng, and Anglo-American Platinum is pioneering the first FCEV mining truck at its Mogalakwena Mine in Limpopo.

In the early-adoption stages of FCEVs there will be limited access to refuelling facilities, making those sectors that utilise centralised refuelling the best candidates for the technology. These would include the bus, taxi and trucking sectors as well as ride-sharing fleets and the mining, military and logistics sectors.

Although the initial capital cost of FCEVs may need subsidising by government or the automotive manufacturer, the key to the early adoption of FCEVs will be in the correct pricing of hydrogen. Even if the cost of hydrogen remains on par with fossil-fuels, companies that adopt FCEV fleet solutions should benefit from high utilisation, reliability, cheap maintenance due to less moving parts and the ability to avoid expensive emissions taxes.

Adoption of FCEVs for private use

The adoptions of FCEVs for private use will likely only occur after widespread utilisation in the commercial sector, as it will take time to roll out hydrogen refuelling stations. By this stage, the cost of an FCEV is expected to be lower than or at least on a par with that of an ICEV.

The uptake of FCEVs may also depend on whether or not the FCEVs and catalysts are being produced domestically. If a significant portion of the value chain lies within the domestic economy, then it will make more sense for government to subsidise these vehicles earlier. Should South Africa rely on the importation of FCEVs then adoption by the private sector may take longer.

With the private sector not needing to rely on utilisation, reliability and maintenance in the same way as the commercial sector, the key variables in FCEV uptake will be the vehicle cost and the cost of hydrogen at the pump. If these are priced correctly and the manufacture of FCEVs and catalysts is carried out locally, then the economic multiplier from the private sector's adoption of FCEVs could have a highly positive effect on South Africa's economy.

Fuel cell locomotive manufacture

In Europe there have been great strides in rolling out hydrogen fuelled locomotives on non-electrified rail networks. Fuel-cell trains offer a far cheaper option in the decarbonisation of the rail network compared to the massive capital cost associated with building electrified overhead lines.

South Africa is in a unique position among developing nations in that a large portion of its rail network is already electrified. Therefore, the argument for using fuel-cell locomotive is not as strong. The same cannot be said for the rest of Africa, which relies primarily on diesel-electric locomotives. In the same way that it makes sense to domestically manufacture fuel cells for the power and vehicle markets, South Africa could explore manufacturing fuel cells for locomotives and export these to the rest of Africa.

If sufficient demand could be created for these locomotives, then it may also make sense to incentivise the manufacture of the entire locomotives in South Africa. This could help support the local mining industry through additional demand for base materials. Bringing manufacture of specialised technology such as locomotives would usually require a partnership with a major international player.

If South Africa could foster a hospitable investment environment and leverage its competitive advantage in raw materials (platinum, chrome, manganese), then it could justify the establishment of a global manufacturing hub for fuel-cell locomotives.

Supporting renewable energy adoption

Both through existing commercial and government commitments and the roadmap laid out in the IRP 2019, it is clear that renewables will account for an ever-increasing percentage of South Africa's energy generation capacity. As the usage of renewables grows, the country will face issues around renewable intermittence and providing buffering to the grid. As discussed earlier, the use of hydrogen to address both issues is compelling. The additional benefit of utilising hydrogen at this scale is that it would likely decrease the unit cost of production. Thus, an investment in renewable-energy-to-hydrogen plants will likely support the provisioning of cost-effective hydrogen to other markets.

Across most of Africa, the concept of off-grid power is receiving much attention and the generation of primary power through solar or wind is a well-accepted and proven technology. However, how best to store that power (on an efficient small scale) is still open for debate. In small-scale, short-time-period stationary applications, batteries outperform hydrogen, as very little energy is lost in the storage of renewable energy in batteries as compared to the energy losses associated with producing hydrogen.

Where hydrogen outperforms stationary batteries is in the long-term storage of energy, in volatile climates (especially cold ones) and in the attractiveness of the material to thieves. It is for these reasons that fuel cells have been favoured over batteries and generators for back-up power in the telecommunications sector in South Africa.

When viewing energy holistically, the case for off-grid hydrogen is extremely persuasive. The synergies possible through use of a single fuel to provide energy to the home and provide heat and power to vehicles are substantial. A short-term solution to providing off-grid power, especially to remote communities, may simply be to provide them with FCEVs and cost-effective hydrogen. Not only would communities have transport, but the FCEVs could be utilised as power generators for the home. When paired with the construction of a centralised off-grid renewable-to-hydrogen plant, (i.e. a wind turbine paired with an electrolysis machine) the benefits are clear: Not only would a large centralised facility benefit from greater economies of scale, but it could store the hydrogen for a long period of time and supply it for the fuelling of community vehicles without the need for expensive electrical reticulation to the home.

Development of new industries utilising green hydrogen

By capitalising on its renewable energy wealth and investing in the production of green hydrogen, South Africa would open the door to developing whole new industries. Hydrogen is the feedstock for so many industrial processes and products, including ammonia, methanol, the hydrogenation of oil for the food industry, rocket fuel and hydrochloric acid, to name a few. Approximately 55% of hydrogen produced today goes into the production of ammonia for the fertiliser industry. With the expected rise in the global population and the concerns over food supply, the fertiliser industry is likely to be highly lucrative in the coming years.

Traditionally, the ability to produce these products cost effectively was dependent on access to a hydrocarbon fuel, usually natural gas, and the countries that had easy access to natural gas tended to dominate production. With renewable-to-hydrogen technology, that competitive advantage largely disappears. If South Africa can properly leverage its renewable energy potential, then it could become a major player in the production and export of all hydrogen-based chemicals, creating countless jobs and earning the country significant foreign currency.

multiple special economic zones (SEZs). The geographic location of some of these SEZs gives them access to world-class renewable energy potential, primarily through wind and solar. Furthermore, some SEZs are located in coastal regions within close proximity of port infrastructure, enabling ease of access to the export markets, where a premium for these green-hydrogen-based products can be achieved.

The investor incentives in these economic zones has already resulted in world-leading renewable energy companies, specialist gas solutions companies, steel mills, cement plants, and FCEV component manufacturers investing in these SEZs, which further reinforces the case for South Africa to initiate and develop green-hydrogen-enabled industries.

The utilisation of hydrogen and its blending with carbon to produce synthetic fuels has been discussed in previous sections of this publications, but the argument for South Africa to participate in this industry is perhaps more compelling than for any other country. The process through which hydrogen is combined with carbon and synthesised into liquid fuels, the Fischer-Tropsch process (FTP), is currently utilised by both Sasol in its coal gasification plants and by PetroSA in its GTL refinery. Sasol is a global leader in this technology and already has significant production facilities utilising the FTP. Utilising this deep knowledge of the technology that could drive South Africa's hydrogen-based liquid fuels industry forward.

When combining green hydrogen with any carbon source through the FTP, South Africa can generate synthetic (carbon-natural) fuels for its own domestic demand and for export. Although certain sectors that utilise hydrocarbon-based fuels, such as ICEVs, are set to decline in the coming decades, sectors such as aviation are set to grow. South Africa is in an ideal position to leverage its renewables power and knowledge base to supply carbon-neutral fuels to the world.

Conclusion

There is little doubt that hydrogen will be a major force in achieving the 2°C scenario and that South Africa stands in an unprecedented position to partake in the global hydrogen economy — both through direct use of hydrogen technology and through supplying the raw materials that enable it.

For South Africa to seize this opportunity, it needs to develop a clear hydrogen strategy and roadmap. This roadmap should speak not only to South Africa's own strategy, but the strategy of global players and how the country can support and integrate its investments to expedite the development of the global hydrogen economy. The roadmap needs to contain clear implementation timelines for decarbonisation targets and hydrogen investments, with genuine accountability for these targets. Without such a timeline, the private sector will not have the surety needed to invest.

The government needs to promote clear coordination across sectors, both public and private. Maximum economic impact will be achieved through the coordination of efforts and through sector-coupling hydrogen technologies.

Clarity is needed on both the taxation of carbon emissions and on the taxation of hydrogen. Carbon emissions need to be properly disincentivised and penalties need to be enforced, while uptake of hydrogen technology needs to be incentivised through tax relief. Decisions will need to be made on how to tax grey hydrogen in the short term, and if some tax relief it should be provided to support adoption of downstream technologies.

The government will need to set out clear and realistic safety guidelines for the generation, transport and storage of hydrogen and, within reason, attempt to remove barriers to entrepreneurial involvement and innovation.

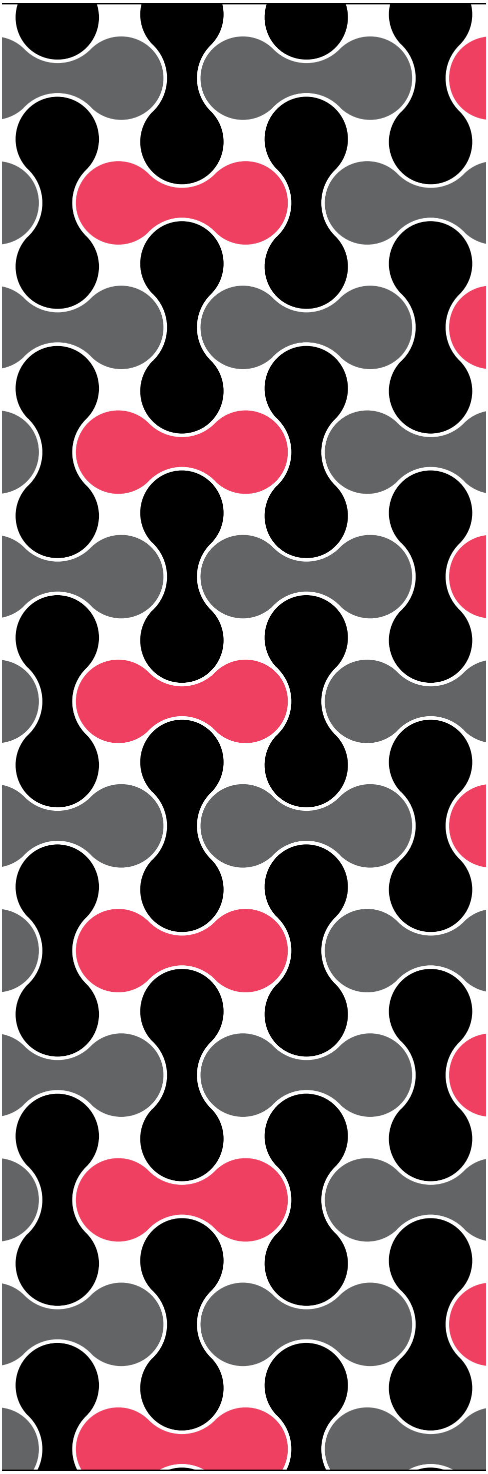
Government and the banking sector will need to promote funding initiatives to support early adopters of hydrogen technology. In order to speed up the adoption of hydrogen and to lower unit prices, investments will need to be made at scale. Government needs to support de-risking strategies through long-term offtake agreements and by providing guarantees.

The subsidisation of technology and potentially hydrogen fuel, may be needed to support the timeous adoption of hydrogen. Although some subsidies are available from government within the fuel cell industry, these need to be expanded to cover the wider hydrogen economy. Initiatives similar to those proposed in Europe for creating an additional fuel levy on fossil fuels, to be utilised to subsidise and fund hydrogen, have merit in supporting the right behaviours.

There must be clear protection of innovation and companies that have invested heavily in research and development must be able to retain competitive advantage in the South African marketplace. Twinned with this, government must create clear guidelines and definitions for instances of market abuse and the repercussions of such acts.

Investment in blue hydrogen may well be the stepping stone to developing a fully decarbonised hydrogen economy. Clarity is needed from government on the classification, regulation, production methods and taxation of this method of hydrogen production, with preferential incentives being granted to green hydrogen production.

The detrimental effect of continued use of fossil fuels may only be fully realised in generations to come. Already, increasing global temperatures, worsening air quality and issues of water scarcity are directly impacting South Africa. Prioritising investment in the global hydrogen economy will help ensure the economic and environmental sustainability of the country for years to come.



Biography

“Air Products and Thyssenkrupp Sign Exclusive Strategic Cooperation Agreement for World-scale Electrolysis Plants to Generate Green Hydrogen.” Air Products South Africa. Last modified 8 July 2020. https://airproductsafrica.co.za/air-products-to-acquire-ges-gasification-business-and-technology-copy/

“Air Products, ACWA Power and NEOM Sign Agreement for $5 Bill.” Air Products, ACWA Power and NEOM Sign Agreement for $5 Bill. Last modified 9 July 2020. https://www.acwapower.com/news/air-products-acwa-power-and-neom-sign-agreement-for-5-billion--production-facility-in-neom-powered-by-renewable-energy-for-production-and-export-of-green-hydrogen-to-global-markets/

“Anglo American Partners ENGIE to Develop World’s Largest Hydrogen Powered Mine Truck.” Re-imagining Mining to Improve People’s Lives | Anglo American. Accessed 12 October 2020. https://www.angloamerican.com/media/press-releases/2019/10-10-2019

“ArcelorMittal Commissions Midrex to Design Demonstration Plant for Hydrogen Steel Production in Hamburg.” ArcelorMittal - Home. Accessed 12 October 2020.

https://germany.arcelormittal.com/icc/arceloren/broker.jsp?uMen=90f30763-4a1d-2861-0392-8d05b8e0b2b6&uCon=e7560d3f-5001-3d61-ca98-3d0632940ec7&uTem=aaaaaaaa-aaaa-aaaa-aaaa-000000000011

“Carbon2Chem.” Thyssenkrupp. Accessed 12 October 2020. https://www.thyssenkrupp.com/en/newsroom/content-page-162.html

“China: World Record Flight Time for Hydrogen Fuel Cell Drone.” FuelCellsWorks. Last modified 24 March 2020. https://fuelcellsworks.com/news/china-world-record-flight-time-for-hydrogen-fuel-cell-drone/

“E4tech Fuel Cell Industry Review 2019.” E4tech. Accessed 12 October 2020. https://www.fuelcellindustryreview.com/#:~:text=The%20Fuel%20Cell%

“Energy Content of Some Combustibles (in MJ/kg).” The Geography of Transport Systems. Last modified 17 August 2019. https://transportgeography.org/?page_id=5837

Fuel Cell & Hydrogen Energy Association. Hydrogen Fuel and Infrastructure Research & Development Workshop Report. 2019. https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5d5c24ea694fb700019ca5b1/1566319851623/

“George Olah CO2 to Renewable Methanol Plant, Reykjanes.” Chemical Technology - The Leading Site for News and Procurement in the Chemicals Industry. Last modified 24 July 2012. https://www.chemicals-technology.com/projects/george-olah-renewable-methanol-plant-iceland/

“Germany Launches World’s First Hydrogen-powered Train.

” The Guardian. Last modified 17 September 2018. https://www.theguardian.com/environment/2018/sep/17/germany-launches-worlds-first-hydrogen-powered-train

H21. Accessed 12 October 2020. https://www.h21.green/

Hawkins, Andrew J. “GM Acquires Stake in Electric Truck Maker Nikola, Will Help Make the Company’s First Vehicle.” The Verge. Last modified 8 September 2020.

https://www.theverge.com/2020/9/8/21427009/gm-nikola-acquisition-electric-hydrogen-truck0908-gen2fcs.html

“Heavy-Duty Hydrogen: Fuel Cell Trains And Trucks Power Up For The 2020s.” Business Quick Magazine. Last modified 29 December 2019. https://bq-magazine.com/heavy-duty-hydrogen-fuel-cell-trains-and-trucks-power-up-for-the-2020s/

“HYBRIT - Vattenfall Partnership with LKAB and SSAB.” Vattenfall. Last modified 5 October 2020. https://group.vattenfall.com/what-we-do/roadmap-to-fossil-freedom/industry-decarbonisation/hybrit

“HydroFLEX Hydrogen-powered Train, United Kingdom.” Railway Technology | Rail & Train News & Views Updated Daily. Last modified 28 June 2019. https://www.railway-technology.com/projects/hydroflex-hydrogen-train/

Hydrogen Council. How hydrogen empowers the energy transition. 2017. https://hydrogencouncil.com/wp-content/uploads/2017/06/Hydrogen-Council-Vision-Document.pdf

Hydrogen Council. Hydrogen scaling up - A sustainable pathway for the global energy transition. 2017. https://hydrogencouncil.com/wp-content/uploads/2017/11/

Hydrogen-scaling-up-Hydrogen-Council.pdf
Hydrogen Council. New opportunities for the energy and mobility system. 2018.

https://hydrogencouncil.com/wp-content/uploads/2018/10/Hydrogen-Council-Hydrogen-Meets-Digital-2018.pdf

Hydrogen Europe. Hydrogen Enabling A Zero Emission Europe. 2018. https://www.hydrogeneurope.eu/sites/default/files/2019-01/2018.11_Position%20Paper%20on%20CO2ES_Final.pdf

Hydrogen Europe. Hydrogen Europe Vision on the Role of Hydrogen and Gas Infrastructure on the Road Toward a Climate Neutral Economy. 2019.

https://hydrogeneurope.eu/sites/default/files/2019_Hydrogen%20Europe%20Vision%20on%20the%20role%20of%20Hydrogen%20and%20Gas%20Infrastructure.pdf

“Hydrogen Roadmap Europe: A Sustainable Pathway for the European Energy Transition.” Www.fch.europa.eu. Accessed 12 October 2020. https://www.fch.europa.eu/publications/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition

“Hydrogen.” IEA. Accessed 12 October 2020. https://www.iea.org/fuels-and-technologies/hydrogen

“HYUNDAI: 1.600 H2 Xcient Trucks in Switzerland.” H2-Share. Accessed 12 October 2020. https://fuelcelltrucks.eu/project/hyundai-1-600-h2-xcient-trucks-in-switzerland/

“Innovation Insights Brief - New Hydrogen Economy - Hype or Hope?” World Energy Council. Accessed 12 October 2020. https://www.worldenergy.org/publications/entry/

innovation-insights-brief-new-hydrogen-economy-hype-or-hope

“Japan: A Success Story in Deploying Fuel Cell Micro-Cogeneration.” PACE. Last modified 20 February 2019. https://www.pace-energy.eu/japan-a-success-story-in-deploying-fuel-cell-micro-cogeneration/

“JCB LEADS THE WAY WITH FIRST HYDROGEN FUELLED EXCAVATOR.” JCB Request a Quote | JCB.com. Accessed 12 October 2020. https://www.jcb.com/en-gb/news/2020/07/jcb-leads-the-way-with-first-hydrogen-fuelled-excavator

O’Kane, Sean. “Anheuser-Busch Orders Hundreds of Hydrogen Trucks from Zero-emission Startup Nikola.” The Verge. Last modified 3 May 2018. https://www.theverge.com/2018/5/3/17314606/anheuser-busch-budweiser-hydrogen-trucks-zero-emission-startup-nikola

REFHYNE. Last modified 25 June 2019. https://refhyne.eu/

“Snam and RINA Team Up to Accelerate the Development of Hydrogen Sector.” Green Car Congress. Last modified 20 April 2020. https://www.greencarcongress.com/2020/04/20200409-snam.html

“The Case for Investing in Direct Air Capture Just Got Clearer | Greenbiz.” GreenBiz. Accessed 12 October 2020. https://www.greenbiz.com/article/case-investing-direct-air-capture-just-got-clearer

“The Hydrogen Economy | Barclays Investment Bank.” Investment Bank | Barclays. Accessed 12 October 2020. https://investmentbank.barclays.com/our-insights/the-hydrogen-economy-fuelling-the-fight-against-climate-change.html

“The World’s First Carbon-free Ammonia-fuelled Supply Vessel on the Drawing Board.” We Energize the Lives of 170 Million People. Every Day. - Equinor.com. Last modified 23 January 2020. https://www.equinor.com/en/news/2020-01-23-viking-energy.html

“Toyota to Unveil Next-Generation “Mirai Concept” at 2019 Tokyo Motor Show’s “Future Expo”.

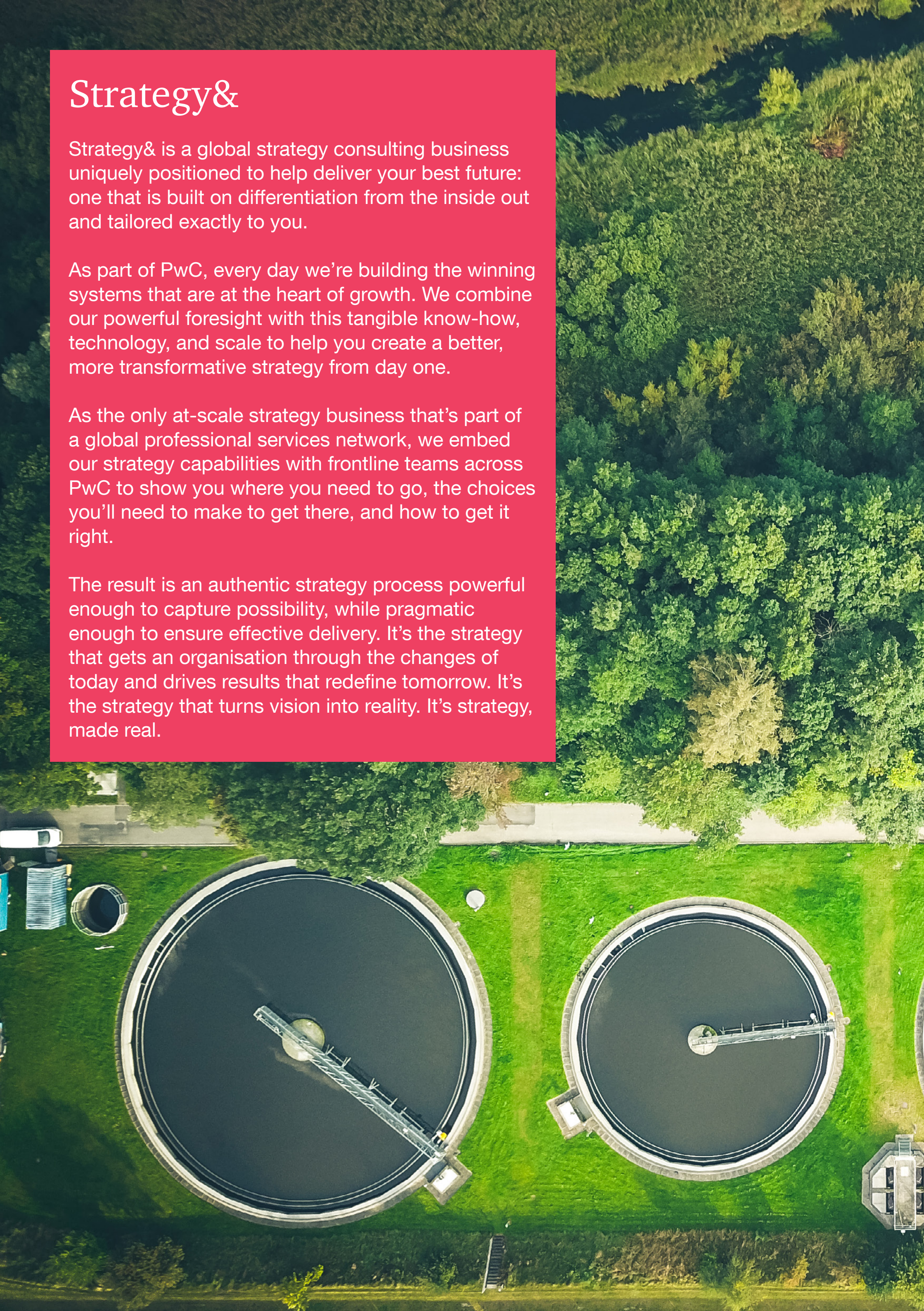
Toyota Motor Corporation Official Global Website. Accessed 12 October 2020. https://global.toyota/en/newsroom/toyota/29933463.html

World Energy Council. Hydrogen - Industry As Catalyst - Accelerating the decarbonisation of our economy to 2030. 2019. http://www.wereldenergieraad.nl/wp-content/uploads/2019/02/190207-WEC-brochure-2019-A4.pdf

“World’s First Liquefied Hydrogen Carrier SUISO FRONTIER Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-free Society.

Kawasaki Heavy Industries, Ltd. Accessed 12 October 2020. https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487

“World’s Largest Hydrogen Electrolysis in Shell’s Rhineland Refinery.” ITM Power. Last modified 18 January 2019. https://www.itm-power.com/item/38-world-s-largest-hydrogen-electrolysis-in-shell-s-rhineland-refinery



Strategy&

Strategy& is a global strategy consulting business uniquely positioned to help deliver your best future: one that is built on differentiation from the inside out and tailored exactly to you.

As part of PwC, every day we're building the winning systems that are at the heart of growth. We combine our powerful foresight with this tangible know-how, technology, and scale to help you create a better, more transformative strategy from day one.

As the only at-scale strategy business that's part of a global professional services network, we embed our strategy capabilities with frontline teams across PwC to show you where you need to go, the choices you'll need to make to get there, and how to get it right.

The result is an authentic strategy process powerful enough to capture possibility, while pragmatic enough to ensure effective delivery. It's the strategy that gets an organisation through the changes of today and drives results that redefine tomorrow. It's the strategy that turns vision into reality. It's strategy, made real.

strategy&

Part of the PwC network

strategyand.pwc.com