WORLD ENERGY COUNCIL

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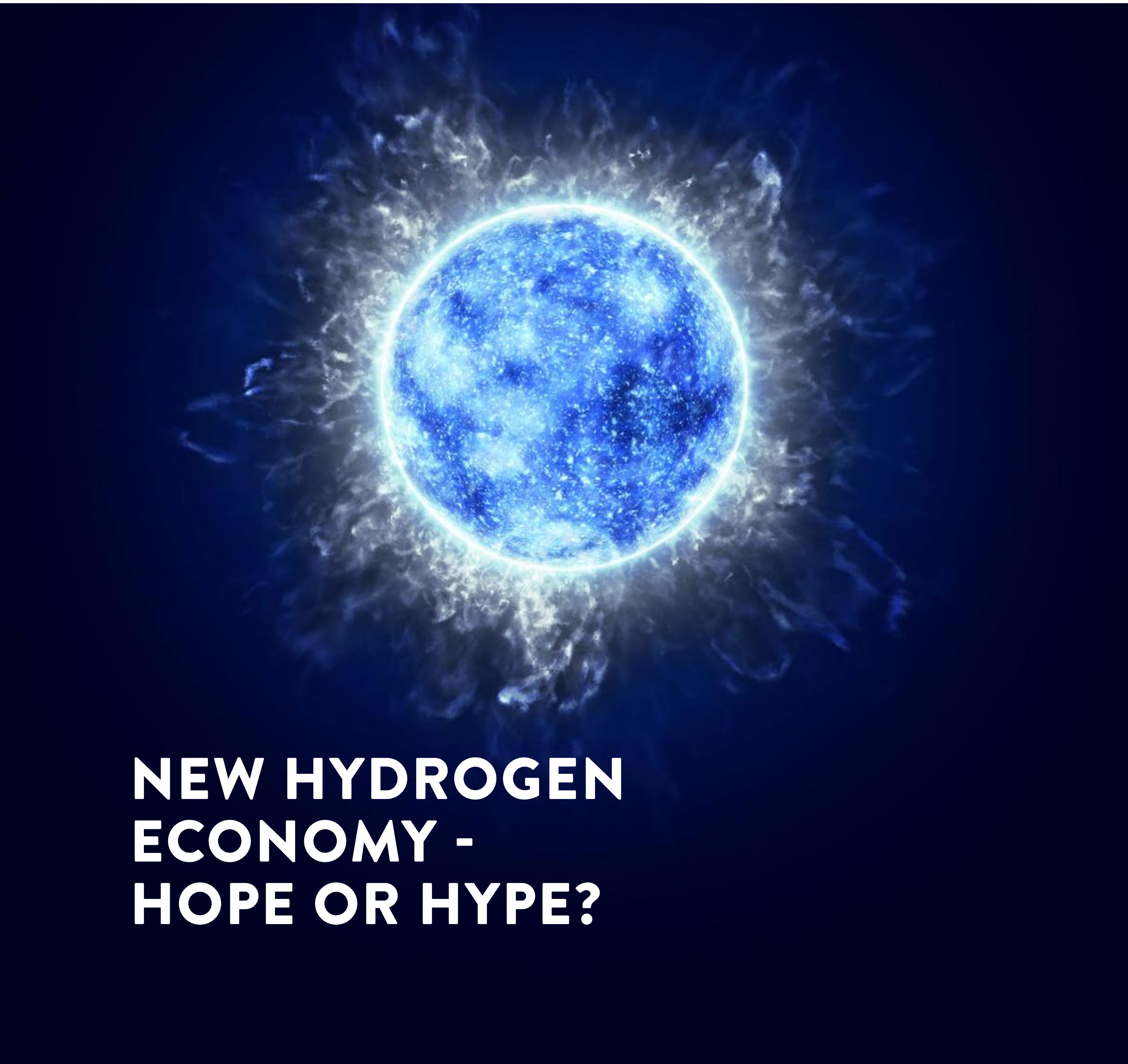

NEW HYDROGEN ECONOMY - HOPE OR HYPE?

ABOUT THE WORLD ENERGY COUNCIL

The World Energy Council is the principal impartial network of energy leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all.

Formed in 1923, the Council is the UN-accredited global energy body, representing the entire energy spectrum, with over 3,000 member organisations in over 90 countries, drawn from governments, private and state corporations, academia, NGOs and energy stakeholders. We inform global, regional and national energy strategies by hosting high-level events including the World Energy Congress and publishing authoritative studies, and work through our extensive member network to facilitate the world's energy policy dialogue.

Further details at www.worldenergy.org and @WECouncil

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ABOUT THIS INNOVATION INSIGHTS BRIEF

This Innovation Insights brief on hydrogen is part of a series of publications by the World Energy Council focused on Innovation. In a fast-paced era of disruptive changes, this brief aims at facilitating strategic sharing of knowledge between the Council's members and the other energy stakeholders and policy shapers.

TABLE OF CONTENTS

ENTITIES INTERVIEWED BY THE WORLD ENERGY COUNCIL

The insights conveyed in this Innovation Insights brief are underpinned by the valuable learnings from a series of 36 interviews conducted with key leaders across the energy sector hailing from around the globe. The interviewees include well-established energy incumbent utilities, oil and gas industries as well as technology providers, investors, governments and think-tanks, all actively engaged within the hydrogen space. The broad participation from different sectors was purposely pursued to ensure this publication could provide a reliable and relevant snapshot of the current state of progress of hydrogen.

Air Liquide

Airbus

Alstom

Business NZ

Caisse des Depots

California Fuel Cell Partnership

Emerald Ventures

Enagas

Energy Institute, University of Texas at Austin

Engie

Equinor

French Alternative Energies and Atomic Energy Commission

Government of Japan, Ministry of Economy, Trade and Industry

Government of South Australia, Department for Energy and Mining

Government of the Netherlands, Ministry of Economic Affairs Climate Policy

H21 North of England

Horizon Fuel Cells

Hydrogen Council

Hydrogenics

Hype

Hyundai

Imperial College London

ITM Power

Kawasaki Heavy Industries

Korea Gas Safety Corporation

Leonardo DiCaprio Foundation

NOW GmbH

Salzgitter AG

Saudi Aramco

SIP Energy Carriers

Siemens

Tokyo Institute of Technology, Institute of Innovative Research

Toyota

A detailed list of the interviewees can be found at the end of this brief.

EXECUTIVE SUMMARY

NEW HYDROGEN ECONOMY, HOPE OR HYPE?

Hydrogen and fuel cell technologies have experienced cycles of high expectations followed by impractical realities. This time around, however, falling renewable energy and fuel cell prices, stringent climate change requirements and the discrete involvement of China are step changes. The combination of these factors is leading to realistic potential for hydrogen's role in the Grand Transition.

Having conducted exploratory interviews with leaders from all around the globe, the World Energy Council is featuring eight use cases which illustrate hydrogen's potential. These range from decarbonising hard-to-abate sectors such as heat, industry and transport to supporting the integration of renewables and providing an energy storage solution. Still, their success is not only based on the step changes described above, but also depends on the following factors:

1 RECOGNISING HYDROGEN AS A WHOLE SYSTEM TRANSITION SOLUTION
Whether hydrogen's full potential is deployed or remains limited to niche applications depends on the adoption of long-term energy strategies and cross sector cooperation.

2 UNLOCKING SUSTAINABLE PRODUCTION PATHWAYS
Economically viable and less carbon-intensive processes alternatives to steam methane reforming and coal gasification are emerging. They still face considerable cost challenges.

3 BUILDING AN INTERNATIONAL HYDROGEN MARKET
There are growing opportunities for international hydrogen production and trade on a global scale, for which several countries are well positioned to participate. Long distance transportation challenges remain to be answered.

4 ACHIEVING COST EFFECTIVENESS
Considerable improvements are still required for hydrogen to become truly cost competitive. Recent government commitments for large-scale production and consumption of hydrogen are rapidly establishing deep foundations for a hydrogen economy.

5 DEVELOPING INFRASTRUCTURE
The successful adoption and commercialisation of hydrogen and its role in succesful energy transitions relies on strategically integrated infrastructure and storage solutions. The most important elements of the hydrogen infrastructure are points of production, transmission and distribution systems and refuelling station networks.

This brief digs deeper into each use case, followed by a detailed analysis for each success factor. The brief will also provide a future outlook based on different current uncertainties and end with next steps for the Council.

INTRODUCTION

The Council's focus on hydrogen for this brief is largely due to the recent Issues Monitor results, a global survey of energy leaders, which has been conducted annually since 2009. In the past few years, the survey displayed a heightened sense of urgency to mainstream the production and consumption of hydrogen for some of our Asian Member Committees, specifically Korea, China and Japan. While these countries are focused on promoting the use and consumption of hydrogen, other countries such as Australia are focusing on becoming leading exporters of low-carbon hydrogen.

WHY HYDROGEN?

Failure to decarbonise our economies is not an option and a complete reliance on the electrification of heat, industry, transport and wider power demand is increasingly being contested as unrealistic. As a versatile energy carrier, hydrogen has the long-term potential to be the ideal complement to renewable generated power and provide a solution to decarbonise hard-to-abate sectors and store energy. Many challenges to this vision exist, which we discussed in our interviews, together with possible solutions.

WHAT IS NEW?

The key differences since the last hydrogen "hype cycle" in the late 2000s"[1] are a series of coexisting technological advances together with environmental and political drivers. Fuel cell and electrolysis are technologies that are maturing. Additionally, increased manufacturing and wide-spread availability is driving cost reductions[2]. Finally, the world-wide deployment and reduction in prices for renewable technologies are leading to opportunities to decarbonise the production of hydrogen.

Climate change targets and air pollution concerns are also leading governments and companies to seek decarbonising solutions which differ in terms of applications, scale and time-frames. Beyond the government to be at the forefront of this new hydrogen wave - Japan, Korea, Germany, UK, California - China's discrete efforts may very well catapult the production and consumption of hydrogen for energy sector applications into the mainstream.

[1] "The car industry and the blow-out of the hydrogen hype," Bakker, Sjoerd, 2010

[2] Fuel cell costs decreased by 60% from 2006 to 2018 according to the US Department of Energy

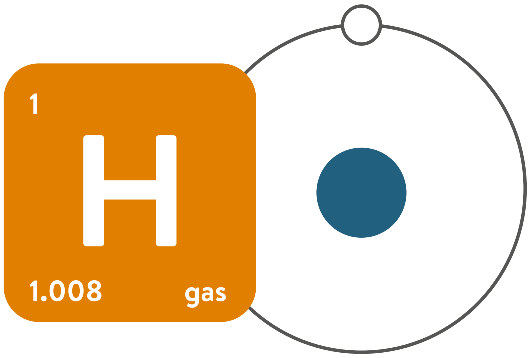
“THE MOMENT HAS COME TO DEVELOP AND DEPLOY RENEWABLE HYDROGEN AT INDUSTRIAL SCALE. WITHIN ENGIE, WE EXPECT TO DEVELOP A VALUABLE AND SUSTAINABLE BUSINESS FOR THE WHOLE HYDROGEN ECOSYSTEM. WE THINK THAT IN ORDER TO FULLY UNLOCK THE POTENTIAL OF RENEWABLE ENERGY WE NEED TO STORE LARGE QUANTITIES OF IT.”

**MICHELE AZALBERT,
ENGIE**

“THERE USED TO BE A CONCEPTION THAT A LOW CARBON ENERGY SYSTEM WOULD BE BUILT AROUND ONE PARTICULAR ENERGY VECTOR. TODAY, WE RECOGNISE THAT THE ROLE OF HYDROGEN IS A MORE NUANCED AND SOPHISTICATED ONE.”

**NIGEL BRANDON,
IMPERIAL COLLEGE LONDON**

WHAT IS HYDROGEN?



LIGHTEST AND MOST ABUNDANT

Hydrogen is the first element in the periodic table. It is the lightest, most abundant and one of the oldest chemical elements in the universe.

NEVER ALONE

On Earth, hydrogen is found in more complex molecules, such as water or hydrocarbons. To be used in its pure form, it has to be extracted.

FUEL OF STARS

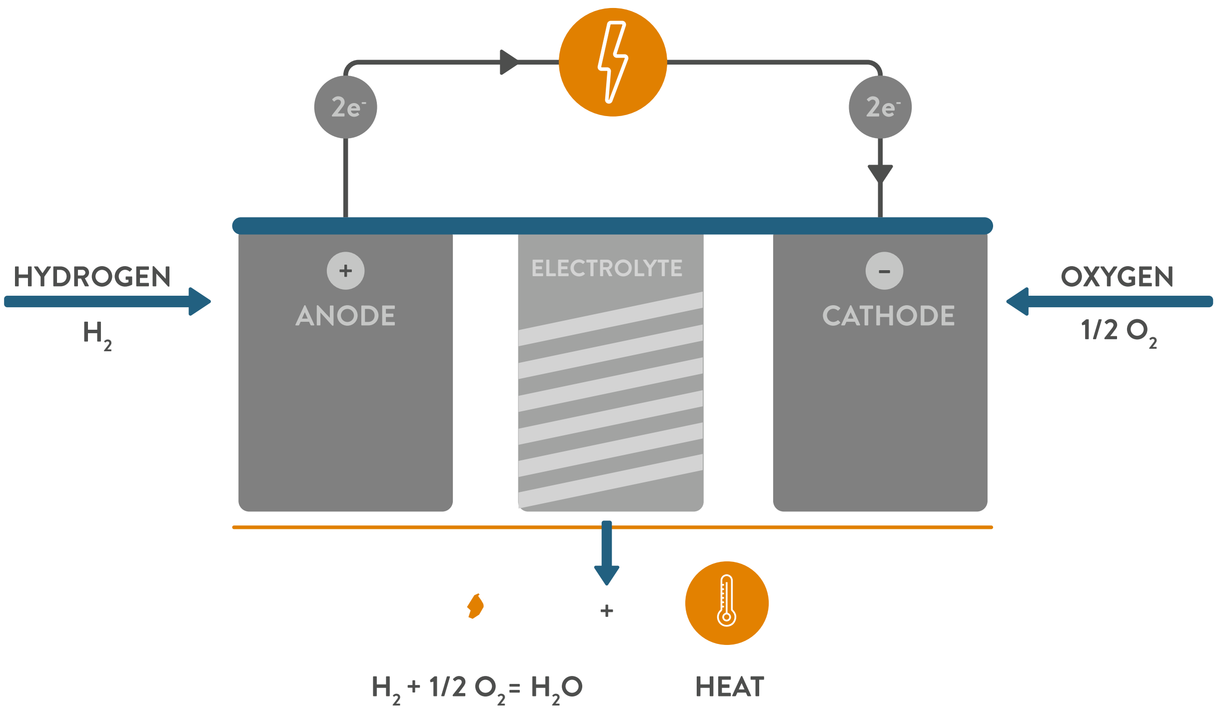
Hydrogen fuels stars through nuclear fusion reaction. This creates energy and all the other chemicals elements which are found on Earth.

HOW IS IT USED?

Hydrogen is not a source of energy but an energy carrier. It must be produced and stored before use. This molecule of gas that stores energy can restore it in several ways:

1. COMBUSTING IT: combusting one kilo of hydrogen releases three times more energy than a kilo of gasoline and produces only water.

2. FUEL CELL: a fuel cell is an electrochemical cell that converts the chemical energy of hydrogen and oxygen into electricity through a pair of redox reactions. The waste product of the reaction is water. Fuel cells can produce electricity continuously for as long as hydrogen and oxygen are supplied.



HOW IS IT PRODUCED?

Hydrogen can be produced using a number of different processes. The source of energy used and the method define whether it is informally considered grey, blue or green.

GREY HYDROGEN

Currently, 96% of hydrogen is produced from fossil fuels via carbon intensive processes.

Main production routes

Steam Methane Reforming (SMR)

Coal Gasification

Characteristics

Intensive CO_2

Low cost

Social acceptance

BLUE HYDROGEN

Grey hydrogen whose CO_2 emitted during production is sequestered via carbon capture and storage (CCS).

Main production routes

+ SMR + CCS

+ Coal gasification + CCS

Characteristics

Low CO_2

Expensive

Social acceptance

GREEN HYDROGEN

Low or zero-emission hydrogen produced using clean energy sources.

Main production routes

Electrolysis using renewables

Characteristics

Zero emissions of CO_2

Expensive

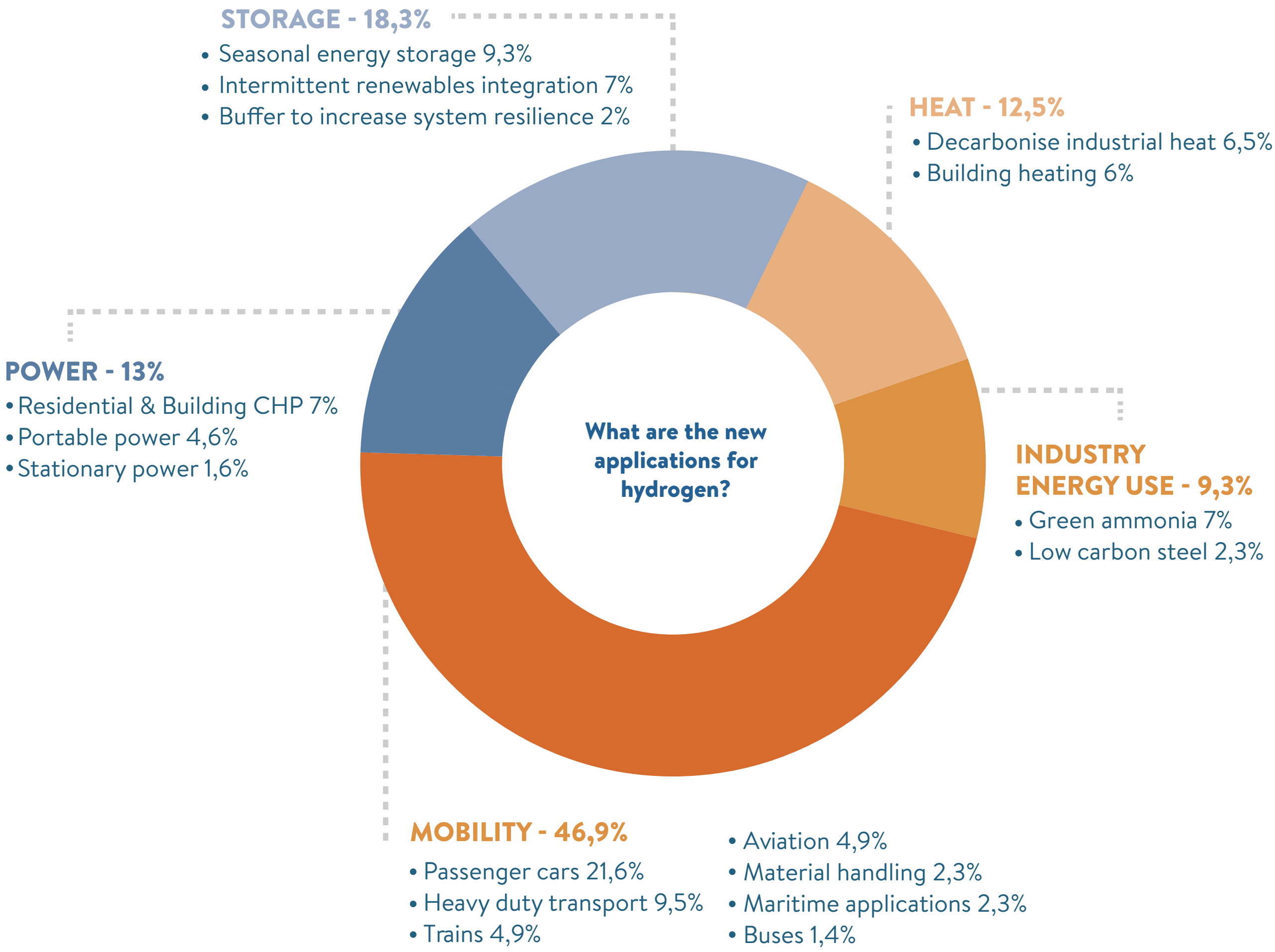
Social acceptance

CURRENT STATE OF PLAY

Hydrogen is a highly versatile basic chemical which can be used both as a feedstock and as an energy vector. Today, it is mainly used as a feedstock for industrial processes, including ammonia production for fertiliser (50%), in refining (35%) as well as for the food, electronics, glass and metal industries[3]. However, as energy leaders seek solutions to decarbonise or strengthen energy security, hydrogen as an energy vector is gaining momentum.

As noted in Figure 1, when asked "What is hydrogen used for in 2040?", interviewees largely focused on mobility, long-term energy storage, integrating power from renewables and producing green ammonia. For the rest of the applications, focus varied depending on the region and sector of the interviewee.

Figure 1: Interviewees' answers to the question: What are the new applications for hydrogen?



From technology development (e.g. hydrogen fuelled planes) and demonstration (e.g. hydrogen fuelled power plants) to commercial scale-up (e.g. passenger vehicles), maturity of applications differs greatly. This section aims at providing the reader with an overview of the current state of play for hydrogen as an actor of energy transitions and showcase emerging opportunities in four sectors: mobility, power, heat and industry.

The applications discussed in this brief vary greatly in terms of scale and readiness to switch to hydrogen. For applications such as material handling, passenger vehicles or drones, commercial viability is expected to be achieved by 2025, according to interviewees. For aircraft, steel production or heat, the timeframe is

[3] Chemical Economics Handbook, IHS Markit, 2018

in decades. Decarbonising these latter applications by 2050 implies investing in research and development and conducting feasibility studies starting now. Overall, for all applications, sector cooperation will be crucial. As you will notice by reading the upcoming use cases, deploying hydrogen as a decarbonisation solution requires the involvement of the whole supply chain as well as local and national governments.

One of the key findings of this section is the fact that overall, the development of the hydrogen applications relies more on continuous innovations and deploying projects at scale rather than technological breakthroughs. Interviewees often compared the current state of hydrogen to wind and solar fifteen years ago, before the implementation of supporting policies.

> **"Hydrogen could mean a paradigm shift, provided that the whole value chain works on it and moves at the same time. It cannot be an effort which one sector runs alone."**
>
> **JEAN-BRICE DUMONT, AIRBUS**

MOBILITY

Mobility was identified by interviewees as the most promising sector for hydrogen and fuel cell development. The most important advantages of this technology are zero-pollutant operation and functionality comparable to established internal combustion engine (ICEs) vehicles. Mostly used in the form of fuel cells, hydrogen is suitable for virtually all means of transport.

MAIN ADVANTAGES

- Fast refuelling, similar to ICEs
- Longer range than batteries
- Long lifespan of fuel cells

MAIN CHALLENGES

- Initial high cost and low volume
- Technology risk and safety perception
- Dedicated infrastructure unavailable
- Costs of vehicles

PASSENGER CARS AND HEAVY DUTY

As the transport industry seeks solutions to decarbonise, fuel cell electric vehicles (FCEVs) are emerging as a complementary technology to battery electric vehicles (BEVs). In the case of passenger cars, they may be more suitable for consumers who travel longer distances (i.e. 400-600km without refuelling) and expect shorter refuelling times. Despite current high prices and limited refuelling stations, several car manufacturers are betting on this promising technology. Some are shyly testing the market, like Mercedes and its GLC hydrogen or Audi and its future model "h-tron", promised for 2020. Others are much more advanced, as Toyota, Hyundai or Honda with approximately 10,000 vehicles in circulation around the world.

As noted by several interviewees, especially investors, the higher hydrogen demand of heavy-duty vehicles and typical 'back to base' transport routes can make them a more favourable target market than passenger vehicles during the scale up of refuelling stations. For instance, a bus can accept 30-40kg of hydrogen when refuelling as compared with passenger vehicles that take between 3-6kg. Several OEMs are currently developing fuel cell heavy-duty trucks, including Nikola, Esoro, Kenworth and Toyota (see use case).

Broader technological changes & safety

FCEVs may be a favourable option for ride sharing and taxis as they reduce the need for a high volume of refuelling stations but still allow for optimised refuelling time and greater distances travelled. For example, in Paris, the project Hype launched the first hydrogen taxi fleet in the world (see use case). This also contributes to normalising hydrogen fuelled vehicles and the risks commonly associated with it. As noted by the California Fuel Cell Partnership, safety training is critical for refuelling stations operators and emergency responders

"In 2040, I picture autonomous BEVs being used in cities while passenger FCEVs are used for weekend trips. Trains, buses, ships and long-range vehicles will also use fuel cells. 2040 May be too early for airplanes, but things may accelerate due to stringent regulation on emissions from air transport."

KATSUHIKO HIROSE, TOYOTA MOTOR CORPORATION

USE CASE -

1ST FUEL CELL ELECTRIC VEHICLE TAXI FLEET

Hype, Société du Taxi Electrique Parisien, France

OVERVIEW

What?

Hype is the world's first hydrogen-powered taxi fleet

Commercial stage

Commercial trial, small scale

Scale

600 vehicles by 2020, or around 1000t/year of hydrogen consumed

Stakeholders

Société du taxi électrique parisien, Toyota, Air Liquide, Idex, City of Paris, Region of Ile de France, Caisse des Dépôts, Fuel Cells and Hydrogen Joint Undertaking

Financing

100+ million €

A CLEAR PROBLEM TO SOLVE

Hype aims at reducing local air pollution by providing on-demand transportation operators a solution to switch to zero emission vehicles in congested cities such as Paris.

A POTENTIAL SOLUTION

Provide on demand transportation operators a zero-emission package by 2021 at the same rate as hybrid and diesel vehicles, including:

- Lease of FCEVs + maintenance
- Access to hydrogen refuelling stations
- Customer base

WHY ON-DEMAND TRANSPORTATION?

Opportunity for industrial partners to showcase hydrogen fuelled mobility. The risks are limited due to the market's stringent air pollution rules and high renewal rate. The local pollution focus provides Hype a platform with policy-makers.

HOW DOES IT WORK?

For the customer, the cost of the ride is the same as in any taxi, there is no overcharge for not polluting. For the driver, this means no changes to the way they operate or live.

SOURCING OF HYDROGEN

Hype currently uses grey hydrogen and they plan on using green hydrogen produced via electrolysis, partially on-site.

WHAT'S NEXT?

- Deploy 600 vehicles in Paris by 2020
- Offer this solution internationally and to other French cities

USE CASE -

CLASS 8 SEMI-TRUCKS POWERED BY HYDROGEN

Project PORTAL, Toyota North America, USA

OVERVIEW

What?

Toyota's Project PORTAL demonstrates the scalability of hydrogen fuel cell electric technology by developing a zero emissions solution for Class 8 semi-trucks.

Commercial stage

Feasibility study

Scale

12 trucks

Stakeholders

Toyota North America, Kenworth, Port of Los Angeles, UPS, TTSI, Shell, Air Liquide, State of California

Financing

Total investment:
$82 million
$41 million dollars paid by the State of California and the rest from project participants such as Toyota and Shell.

A CLEAR PROBLEM TO SOLVE

The ports of Los Angeles and Long Beach are the largest single source of emissions in California. These ports account for the bulk of the diesel-powered semi-trucks (18-wheelers) which lumber along freeways, spreading unhealthy particulates through populous parts of Los Angeles, as they carry containers to distribution centres about 100 km inland.

A POTENTIAL SOLUTION

Toyota is testing the scalability of their fuel cell technology by developing class 8 fuel cell semi-trucks for use in the port.

STATUS

Toyota currently has 2 prototype 18-wheelers that are operating under standard drayage routes in the San Pedro area Ports capable of 600+ horse power, 1300+ ft-lbs of torque and 480+ km of range.

Toyota and Kenworth will jointly develop the next 10 trucks under a California State grant which will also include the development of 2 heavy duty fuelling stations by Shell.

SOURCING OF HYDROGEN

Toyota is developing its own renewable hydrogen production using fuel cell tri-generation technology. The Tri-Gen facility will use bio-waste sourced from California to generate water, electricity and hydrogen.

WHAT'S NEXT?

This is a feasibility study to determine whether the trucks meet the duty cycle demands in an affordable and compelling way.

MATERIALS HANDLING

One of the most suitable applications for hydrogen is materials handling (e.g. forklifts, narrow aisle lifts trucks, stock pickers and pallet jacks). Interviewees noted that fuel cells are becoming a favourable technology option over battery and diesel equivalents. This is due to the fact that warehouse materials handling has stricter requirements on air quality due to poor ventilation in indoor operations. The speed of hydrogen refuelling, and absence of odours therefore make FCEVs more attractive in these types of operations. In 2017, Walmart and Amazon signed deals of up to $600-million for fuel cell powered material handling machinery.[4]

RAIL TRANSPORT

Interest in hydrogen fuelled trains is growing, particularly in Europe, Japan, Korea and North America. The interview with Alstom highlighted that the decision of the company was driven by fuel cell technology improvements and the need to develop a zero-emission train, which could replace diesel trains. These account for almost half of the share of rail transport. A recent study[5] by Metrolinx in Canada found that fuel

[4] Amazon and Wal-Mart Finally Found a Use for Hydrogen Power, Bloomberg Businessweek, 31 July 2017

[5] Regional Express Rail Program Hydrail Feasibility Study Report, Metrolinx, 2018

cell trains are comparable in terms of cost with electrification given the capital requirements for overhead rail as compared with being able to use existing infrastructure. Nevertheless, Alstom does not expect their hydrogen fuelled trains to be cost competitive with diesel in the next decade. Overall, early adoption of hydrogen fuelled trains depends on government hydrogen strategies and the willingness of train operators to work with hydrogen suppliers and local governments to develop the required infrastructure.

> **"In the coming 5 to 10 years, these trains will still have a disadvantage from a purely economic point of view. In a decade, we consider that fuel costs will go down and that the cost of fuel cell stacks will decrease because the technology will spill over different sectors. We can then find a commercial balance. in general, the more hydrogen is consumed, the more the price will decrease."**
>
> **BENOIT CARNIEL, ALSTOM**

USE CASE -

HYDROGEN FUELLED TRAIN

Coradia iLint, Alstom, Germany

OVERVIEW

What?

Alstom's Coradia iLint is a solution to the need to provide environmentally sustainable, cost effective alternatives to diesel trains.

Commercial stage

Commercial trial, small scale

Scale

14 trains in Germany by 2021

Stakeholders

Alstom, German Ministry of Economy and Transport, Lower Saxony Transport Authority, Linde Group

Financing

German federal government's National Innovation Programme for Hydrogen and Fuel Cell Technology: €8m: development of Coradia iLint €8.4m: refuelling facility

A CLEAR PROBLEM TO SOLVE

Provide a cost effective and sustainable alternative to electrification to decarbonise rail transport. Hydrogen trains offer a solution where the network is not electrified, nor is it ever likely to be.

A POTENTIAL SOLUTION

In the Coradia iLint, the diesel traction is replaced with an electric traction system. The primary energy supply comes from hydrogen fuel cells. The train is also equipped with intermediate energy storage in the form of Li-Ion batteries to help boost power during acceleration and to recover kinetic energy during braking. These are low-noise, zero-emission trains that reach up to 140 km/h and have an autonomy of 1000 km

STATUS

Alstom will deliver the trains, maintain and service them for 30 years and work with partners to build and operate the necessary hydrogen infrastructure. An additional 14 hydrogen trains will be delivered by the end of 2021.

SOURCING OF HYDROGEN

In a later phase of the project, hydrogen will be produced on-site at Bremervörde using electrolysis with a wind turbine providing power for the process. For now, the trains rely on grey hydrogen.

WHAT'S NEXT?

Due to long cycles in the rail sector, Alstom aims that by 2030, 10% of diesel trains will be replaced by hydrogen trains and by 2050, it will be 30%.

AVIATION

In aviation, fuel cells have already been adopted for Unmanned Aerial Vehicles (i.e. UAV/drones) to power propulsion mechanisms. They are currently available commercially and are sought by both military and civilian UAV operators[6] .

For aircraft, our interview with Airbus highlighted that the sector is paying close attention to the developments in the hydrogen space[7] . Airbus is currently considering and researching two options. First, using hydrogen to produce synthetic fuels. This would require only little adjustments to aircraft. Yet, while this option would be the easiest for the industry, it poses challenges for synthetic fuel producers. Second, combusting hydrogen directly. Engines combusting kerosene today could combust hydrogen, given some modifications. The main challenge for the sector would be to store hydrogen on aircraft, as the industry is concerned with weight and size. More generally, the decision to choose hydrogen as a decarbonisation pathway depends on two main factors: hydrogen's safety case and the ability of the hydrogen ecosystem to produce hydrogen at the right cost, at scale and in a carbon neutral manner. Due to the aviation industry's long cycles, if hydrogen became a viable solution, it would take at least a couple of decades to renew the entire fleet.

MARINE

As noted by interviewees, fuel cells are currently being tested as energy providers for the on-board power supply. The use of hydrogen-powered fuel cells for ship propulsion, by contrast, is still at an early design or trial phase–with applications in smaller passenger ships, ferries or recreational craft. Indeed, ferries which have a 'back to base' operating route could be a suitable early mover market. For larger ships such as those used for freight, use of synthetic fuels derived from hydrogen such as ammonia rather than fuel cells may be more suitable because of their greater power density requirements. International technical standards still need to be developed in order to use gaseous fuels such as hydrogen[8].

> **"The advantage of ammonia is that it is one of the agents that can be used to transport hydrogen over long distances. Through marine transportation. Ammonia can be combusted directly and utilised as a fuel for those markets."**
>
> **SHIGERU MURAKI, SIP ENERGY CARRIERS**

CONCLUSIONS ✓

In sum, short refuelling times, long ranges and the possibility to use hydrogen without emitting greenhouse gases make mobility a promising field for hydrogen and fuel cells. However, these technologies face some difficult challenges in terms of cost, required investments and infrastructure. Work on mainstreaming hydrogen as a possible decarbonisation pathway is required and demonstration projects are crucial. This also includes working on the safety case of hydrogen and engaging customers.

[6] Four ways fuel cells power up the U.S. military, Office of Energy Efficiency; Renewable Energy, USA, 2017
[7] Airbus also recently joined the Hydrogen Council
[8] "Strategic impact of efficient supply systems and alternative fuels. Safety, standards and guidelines", Würsig/Marquardt, 2016

POWER SYSTEM

While power generation using hydrogen is still nascent, we found that countries such as Japan and Korea are investing in technology development and demonstration projects. In addition, hydrogen is being considered as a solution to assist with both the integration and expansion of low-carbon electricity generation.

MAIN ADVANTAGES

- Fuel cells are flexible and scalable
- Seasonal storage of energy
- Longer term: replacing natural gas with hydrogen for power generation

MAIN CHALLENGES

- Technology unpreparedness and scale of required investments
- Lack of hydrogen delivery network
- Current price of hydrogen

OFF-GRID AND BACK-UP ELECTRICITY GENERATION

Along with materials handling, hydrogen fuel cells for off-grid and back-up electricity generation are emerging as clear hydrogen applications. As noted by several interviewees, in remote villages, islands, mountain shelters or telecom sites, deploying a traditional centralised electricity grid can be extremely expensive. In these locations, coupled with renewables, hydrogen could provide an alternative solution to diesel generators while reducing greenhouse gas emissions and logistical constraints. Moreover, off-grid sites provide an ideal ground for experimentation and pilot projects due to the smaller size of their electrical systems (see use case).

Fuel cells are increasingly being used as an alternative to generators and rechargeable batteries as a backup power supply, in the form of either emergency generator sets or uninterruptible power supplies (UPS). Areas of use include in particular telecommunications and IT systems, such as radio towers, construction flood lights or data processing centres.

LARGE SCALE HYDROGEN ELECTRICITY PRODUCTION

In addition to mobility, our interviews with Korean and Japanese actors all focused on large scale power generation using hydrogen. Interviewees mentioned several feasibility studies to explore converting existing gas turbines to combust hydrogen rather than natural gas. According to GE, its Dry Low NOx 2.6 Combustion Solution already has the ability to combust fuel that contains up to 50 percent (by volume) hydrogen in certain applications[9].

> **"Gas turbine power generation will play an important role to enhance the stability of the electricity grid, by compensating intermittent power from renewable energies. To decarbonise this process, which currently relies on natural gas, we are currently developing hydrogen powered gas turbines"**
>
> **MOTOHIKO NISHIMURA, KAWASAKI HEAVY INDUSTRIES**

[9] The Hydrogen Generation: These Gas Turbines Can Run on The Most Abundant Element in the Universe, GE Reports, 2019

Another approach is to produce electricity by stacking fuel cells, as currently explored in Korea and China. For example, in Hwasung City in Korea, FuelCell Energy recently built the world's largest fuel-cell plant, with 21 2.8-MW stacks, producing a total of 59 MWs. Hyundai is also working to develop the first hydrogen city in Ulsan, where it is headquartered.

Beyond the required technical improvements to use hydrogen in gas turbines, the main challenge for both power production methods discussed previously remains the price of hydrogen in comparison to natural gas. In Japan, the target is to produce 1 GW of power from hydrogen by 2030 and 15 to 30 GW by 2050. To be competitive in the power market, the price of hydrogen[10] needs to decline to approximately US $2 to US $3 per kg. According to Japan's recently published Strategic Roadmap for Hydrogen and Fuel Cells, the country's target is US $2 to 3/kg for 2030.

INTEGRATION OF RENEWABLE ENERGIES

As an energy carrier, hydrogen is gaining momentum as a solution for the integration of renewable energies into the electricity or gas grid. According to the majority of interviewees, the production of hydrogen by electrolysis is the leading technology to store energy from one day to a whole season.

> **When working on the design of production units, you clearly see that hydrogen and batteries are complementary. Batteries ensure fast-balance response and hydrogen complement on a longer period of time. To store large excess of power, hydrogen is fit for purpose. And it can either be transformed again into power thanks to fuel cells or injected into the gas grid**
>
> **MICHELE AZALBERT, ENGIE**

Electrolysers, which can start in a few minutes and stop in a matter of seconds, can absorb surplus electricity produced from renewable energies when the demand is not sufficient, in order to transform it into green hydrogen. This green hydrogen can in turn either be used for applications such as mobility or industrial processes, stored or injected into the gas grid as either hydrogen or synthetic methane. Nevertheless, as discussed later on, beyond the challenges related to storage, transmission and distribution, interviewees disagreed on the economic viability of relying solely on excess renewables.

> **"In several countries, there is a strong momentum to make use of the increasing amounts of excess renewable power from wind and solar. Electrolysers are a critical solution to enable this transistion. However, what is lacking at the moment are clear business cases. Electrolyser utilisation rates would need to be almost 24/7 for it to be economically viable. What if you only have 2000 or 5000 hours per year of excess renewable power?"**
>
> **PHILIPP HASLER, EMERALD VENTURES**

[10] In this case, we are discussing low-carbon hydrogen. According to METI's hydrogen strategy, the current price of low-carbon hydrogen is about US $10.

USE CASE -

H2FUTURE

A European Flagship Power-to-X Project

OVERVIEW

What?

This project brings together energy suppliers, the steel industry, technology providers and research partners, to generate green hydrogen from electricity from renewable energy sources.

Commercial stage

Demonstration project

Scale

A capacity of 6 mw with a production of 1,200m^3 of green hydrogen per hour.

Stakeholders

VERBUND Solutions GmbH, Voestalpine Stahl GmbH, Siemens AG, K1-MET GmbH, Austrian Power Grid AG, TNO

Financing

Project budget: 18 million EUR Grant: 12 million EUR by FCH JU

A CLEAR PROBLEM TO SOLVE

H2FUTURE aims at demonstrating that an industrially integrated a proton exchange membrane (PEM) electrolyser is able to produce green hydrogen and supply grid services at the same time.

A POTENTIAL SOLUTION

Under the coordination of the utility VERBUND, the steel manufacturer voestalpine and Siemens, a PEM electrolyser manufacturer, a large-scale 6 MW PEM electrolysis system will be installed and operated at the voestalpine Linz steel plant in Austria. The Austrian transmission system operator (TSO) Austrian Power Grid (APG) will support the prequalification of the electrolyser system for the provision of ancillary services. The Netherland's research centre TNO and K1-MET (Austria) will study the replicability of the experimental results on larger scales in EU28 for the steel industry.

STATUS

In installation phase, the plant is scheduled to be fully operational in 2019.

WHAT'S NEXT?

Study the replicability of this study and address regulatory challenges which could enable a European hydrogen ecosystem.

USE CASE -

SHOWCASING A REPLICABLE HYDROGEN TERRITORY

Big Hit, Scotland

OVERVIEW

What?

The BIG HIT study in the Orkney Islands is a demonstration project aimed at encouraging new deployments of renewable energy with fuel cell technologies and hydrogen in isolated or constrained territories.

Commercial stage

Demonstration project

Scale

50 tonnes of hydrogen per year

Stakeholders

12 participants based across six EU countries, including: Foundation for the Developmet of New Hydrogen Technologies in Aragón, ITM Power, Orkney Islands Council, Ministry for Transport and Infrastructure of Malta, Symbio Fcell, EMEC Orkney

Financing

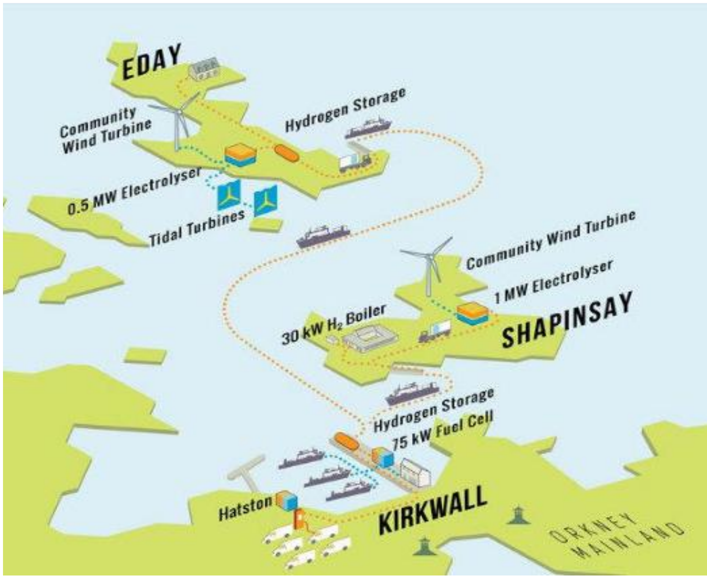
Project budget: 10.9 million EUR - Grant: 5 million EUR from FCH JU

A CLEAR PROBLEM TO SOLVE

The Orkney Islands of Scotland comprise 20 inhabited islands, with a total population of about 21,000. With over 50MW of installed wind and tidal energy capacity, Orkney has been a net exporter of electricity since 2013. However, local grid capacity restrictions lead to significant curtailment, losing on average more than 30% of their annual output.

A POTENTIAL SOLUTION

BIG HIT aims at demonstrating the Orkney Islands as a replicable Hydrogen Territory, using curtailed renewable energy generated locally to produce hydrogen which can then be used as a clean energy vector to store and use valuable energy for local applications, including auxiliary power and heat for ferries, fuelling for light vehicles and heating for buildings.



CONCLUSIONS ✓

In the short term, hydrogen technologies are being explored to assist with both the integration and expansion of low-carbon electricity generation as well as alternatives to generators and rechargeable batteries as a backup power supply. In the longer term, base load power generation from hydrogen is being explored in Japan and Korea. The main challenge remains the price of low carbon hydrogen.

HEAT

The heat sector is proving hard to decarbonise. The scale of the challenge, along with the diversity of heating requirements (i.e. from low temperature space heating to high-temperature industrial loads) and the flexibility and affordability of fossil fuels are some of the main reasons. The gradual conversion of natural gas to hydrogen has the potential to decarbonise the sector of industrial, commercial and domestic heat.

MAIN ADVANTAGES

- Decarbonisation of heat
- Possibility of flexible scale-up in output and infrastructure
- Enable other hydrogen applications by contributing to reduction in the cost of hydrogen

MAIN CHALLENGES

- Possible retrofitting of appliances
- Essential backing from governments
- Necessity of cost-effective green hydrogen and CCS at scale for blue hydrogen

TRANSITIONING NATURAL GAS TO HYDROGEN

Interviews indicated that to decarbonise heat, hydrogen could either be mixed with natural gas or substitute it altogether. Today, mixing small quantities of hydrogen with natural gas and injecting it into the existing gas network is already feasible. The UK and US have amongst the lowest legal limits of hydrogen blending with natural gas of any country at 0.1%, compared to 10–12% (by volume) in Germany and the Netherlands[11] . When discussing blending with our interviewees, a 20% objective was often mentioned. This would be equivalent to 6 to 7% on an energy basis [12] and, although it could be used with existing domestic gas appliances, this would have a modest contribution to decarbonisation[13].

Switching the existing gas system to 100% hydrogen is unprecedented. It would dramatically decrease emissions associated with heat, but it would present critical challenges, which are laid out in the H21 North of England report[14] . One of the most common remarks to this approach is the unsuitability of the existing distribution gas grid for hydrogen. However, in the case of steel pipes, the distribution pressures are very low, therefore limiting the risk to factors which are comparable tothose of natural gas. In the case of high-density polyethylene pipes, which are currently substituting part of the existing gas grids around the world, the problem would not exist. Yet, given the scale of the sector, the transition to low-carbon heat through the conversion of natural gas to hydrogen, requires long term strategies, which should be adopted in the few years to come.

"What we proved is that converting the gas network to 100% hydrogen is technically possible. We have also proved that you can source hydrogen at the right scale with a low carbon footprint with technology available today."

DAN SADLER, H21 NORTH OF ENGLAND

In summary, the hydrogen blending approach, which would be technically easier and cheaper appears to be the most widely supported. It is nevertheless unlikely that hydrogen injection alone could achieve deep decarbonisation. Both scenarios – i.e. hydrogen blending or complete replacement of national gas by hydrogen - require thorough safety assessment and subsequent regulatory adjustments.

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[11] ITM Power, National Grid, Shell, SSE, Scotia Gas Networks and Kiwa, Power-To-Gas: A UK Feasibility Study, ITM Power, Sheffield, 2013.

[12] Hydrogen is a lighter molecule than natural gas with lower volume density (3 to 3.7 times lower) at the same pressure.

[13] "The role of hydrogen and fuel cells in the global energy system", Staffel et al., 2019

[14] H21 NoE Report, Northen Gas Networks, Equinor, 2018

USE CASE -

DECARBONISING HEAT

H21 North of England

OVERVIEW

What?

Conversion of natural gas grid to a 100% hydrogen to decarbonise industrial, commercial and domestic heat in the UK by means of ATR hydrogen production coupled with CCS, utilising the existing gas distribution networks.

Commercial stage

Feasibility Study

Scale

Conversion of 3.7 million-meter points equivalent to 85TWh of annual demand (14% of all UK heat). A 12.15GW natural gas-based hydrogen production. 8TWh of inter-seasonal hydrogen storage. 125 GW capacity hydrogen transmission system. 20Mtpa of CO_2 sequestered by 2035.

Stakeholders

Northern Gas Networks, Equinor, Cadent

Financing

Investment required: £23 billion CAPEX + £1 billion OPEX

A CLEAR PROBLEM TO SOLVE

The UK has committed to reducing its carbon emissions to at least 80% of 1990 levels by 2050. Currently, over 30% of emissions are generated by domestic heating and cooking.

A POTENTIAL SOLUTION

The H21 North of England is a detailed engineering solution for converting 3.7 million UK homes and businesses from natural gas to 100% hydrogen, starting in 2028. The forecasted increase in customer bill would be of ~7%. A further six-phase UK rollout could convert additional 12 million homes across the UK by 2050. The project offers several benefits: re-using of existing assets already paid by UK customers; ensuring continuation of customer choice (gas or electric)

STATUS

The project design, engineering, operation and costs have been thoroughly assessed. Screening for production facility, inter-seasonal storage and CO_2 transport and storage are on-going and their feasibility studies should be ready by 2021. HSE, EIA, permitting, procurement and design basis are on-going and should be completed by 2023.

SOURCING OF HYDROGEN

Production of blue hydrogen by means of natural gas + CCS, by means of nine ATR units operating in parallel, each with a capacity of 1.35 GW for a total of 12.15 GW. The multi-unit setup insures high operational flexibility and security of supply, which are critical in the domestic heat sector. The predicted CO_2 storage capacity is of 516 Mt by 2035.

WHAT'S NEXT?

Developing the critical evidence of the safety case for conversion and the strategic evidence to underpin the basis for a policy of conversion of heat necessary for the project to develop. Securing the needed investments.

CONCLUSIONS ✓

Direct combustion of hydrogen to generate heat is unlikely to compete with natural gas on a commercial basis before 2030. This form of utilisation would therefore need a clear policy signal from government focussed on decarbonisation of the gas networks for this conversion to occur.

INDUSTRIAL APPLICATIONS

As noted by a recent study [15] by our Dutch Member Committee, low carbon energy carriers to decarbonise industry are needed. Several interviewees noted that further focus on green molecules both as feedstock and as an energy source are crucial. With the exception of iron ore processing, hydrogen and its derivatives are already a key input in many industries, especially in chemicals and refining. This means that a great deal of expertise and infrastructure linked to hydrogen is already available in various industries.

MAIN ADVANTAGES

- Existing hydrogen expertise and infrastructure
- Large scale green hydrogen production could boost other sectors

MAIN CHALLENGES

- Absence of market for green products
- Significant CAPEX commitments
- Large amounts of new dedicated renewables required to produce green hydrogen via electrolysis

As noted previously, green hydrogen can be produced using clean processes. This allows products such as syngas, bio-methanol, ammonia, and more, to be derived from carbon-neutral hydrogen and therefore be clean. Interviewees focused extensively on ammonia, steel making and refineries, which is what this section will emphasise on.

AMMONIA

Green ammonia (i.e. ammonia derived from clean hydrogen) is gaining momentum as a candidate to carry and store hydrogen. The synthesis of ammonia is carried out from hydrogen and nitrogen, through the Haber-Bosch process. Ammonia is liquid at minus 33°C and is easier and cheaper to store and transport than pure hydrogen. It is comparable to propane and butane both in terms of conditioning and combustion characteristics. As a feedstock, it could contribute to decarbonise fertiliser and chemicals markets. As an energy carrier, as discussed with SIP Energy Carriers[16], green ammonia could be also used for power, industrial and marine markets as it can directly be combusted without CO_2 emissions.

The key to green hydrogen adoption may be the notion of procurement. A potential solution would be to have car manufacturers require low carbon steel. An example is the Buy Clean California Act, signed into law in 2017. It means that suppliers' emissions performance will be considered when an agency is contracting to buy steel, flat glass, and mineral wool (insulation) for infrastructure projects. This type of initiative requires the support of a significant part of consumers and economic agents.

> **"SIP Energy Carriers Programme in Japan has developed technologies to use ammonia directly in power generation, industrial and marine applications. Those results and feasibility studies prove that ammonia can be a viable option for carbon-free energy sources.**
>
> **SHIGERU MURAKI, SIP ENERGY CARRIERS**

[15] Hydrogen – Industry as catalyst, World Energy Council Netherlands, 2019
[16] The Japanese Cross-Ministerial Strategic Innovation Promotion Program's Energy Carriers initiative

USE CASE -

GREEN AMMONIA TECHNOLOGY

Yuri Project, ENGIE And Yara, Australia

OVERVIEW

What?

Yara and ENGIE have joined forces to test green hydrogen technology in fertilizer production. The project consists in feeding the existing Yara Pilbara ammonia plant in Western Australia with renewable-based hydrogen.

Commercial stage

Feasibility study

Scale

66MW electrolysis system (for the 1 st phase)

Stakeholders

YARA, Engie

Financing

YARA, Engie (for this project phase)

A CLEAR PROBLEM TO SOLVE

Approximately 50% of the GHG emissions associated with nitrogen fertilisers are attributable to the production process. Companies such as Yara are seeking solutions to produce carbon-free fertiliser.

A POTENTIAL SOLUTION

Clean hydrogen is the major enabler for making CO_2-free or “green” ammonia, which is the key ingredient for “green” fertiliser. The Yuri project aims at reaching a high-renewable share (approximately 80%) on the Yara Pilbara asset. With Yara, Engie will be focusing on the upstream production of renewable hydrogen (designing, building, investing in and operating).

VISION

Engie’s ambition is to become a major player in renewable hydrogen scaling a hydrogen economy. Integrated projects like the green hydrogen plant at Yara Pilbara allow for a real-world, real-time analysis of costs and processes.

STATUS

Engie and Yara are currently focusing on the feasibility of adding a PV-based green hydrogen production facility to an existing ammonia production plant. This is the first stage of a four-stage project.

SOURCING OF HYDROGEN

With an anticipated capacity of 100 MW solar field and around 66MW electrolysis system, this plant will be the largest green hydrogen-to-ammonia plant on the planet.

WHAT’S NEXT?

Validate the feasibility & enter into the construction phase

METALS PROCESSING

According to interviewees, steel production could become a significant application for hydrogen. The transition from iron ore to steel relies heavily on its reaction with coking coal inside a blast furnace. This allows for the reduction (removal of oxygen) of the ore. A similar reduction reaction can occur using hydrogen (a reducing agent) with the resulting ‘directly reduced iron’ then placed in an electric arc blast furnace to produce steel. Use of hydrogen in iron processing is being considered further in Europe, East Asia and other regions.

USE CASE -

DECARBONISING STEEL PRODUCTION

Salzgitter Low CO_2 Steelmaking (SALCOS), Germany

OVERVIEW

What?

Salzgitter AG is proposing decarbonising primary steelmaking by replacing carbon by hydrogen in iron ore reduction processes, leading to the final formation of water rather than CO_2

Commercial stage

Industrial scale implementation technically possible

Scale

Gradual cutting of CO_2 emissions, potentially cutting them by 7.5 million tonnes per annum at final stage (-95% of CO_2 compared to current emissions)

Stakeholders

Salzgitter, Fraunhofer-Gesellschaft (FhG), Tenova

Financing

Pending

A CLEAR PROBLEM TO SOLVE

According to the World Steel Association, on average for 2017, 1.83 tonnes of CO_2 were emitted for every tonne of steel produced. To drastically reduce emissions, recycling, increasing efficiencies and the development of cleaner production methods are crucial.

A POTENTIAL SOLUTION

The SALCOS project aims at gradually moving away from carbon-intensive steel production based on blast furnaces, to a direct reduction and electric arc furnace route, with an increasing use of hydrogen. The project is based on a modular concept, offering the possibility to be realized in subsequent steps, tailor-made to address the challenging further development of CO_2 reduction targets in Europe after 2030.

STATUS

Salzgitter is currently in the process of working with all relevant political stakeholders to create suitable economic framework for industrial implementation as well as to raise public funding. The main challenge today is the absence of a market for green steel products.

SOURCING OF HYDROGEN

Currently, Salzgitter uses hydrogen from external steam reforming and on-site electrolysers only for annealing lines, but not yet in metallurgy. For SALCOS, hydrogen will be produced via electrolysis with renewable power at a scale of 60,000 tonnes per year for the first realization step and up to 300,000 tonnes per year for the final realisation step.

CONCLUSIONS ✓

The shift to sustainable hydrogen production methods for industrial processes largely depends on the growing recognition of green fuels as well as a suitable pricing for green industrial products, which could materialise through an adequate carbon price and regulatory framework. The use of green hydrogen in industrial processes also presents the advantage of contributing to large-scale hydrogen demand and consequently lower cost of production, which in turn would positively impact other sectors such as mobility.

For more details, please see the World Energy Council Netherlands report.

SUCCESS FACTORS

Based on our exploratory interviews five key factors were identified as a roadmap for whether hydrogen will play a significant role in the Grand Transition. In this section we will take a closer at each factor along with its opportunities and challenges.

1 RECOGNISING HYDROGEN AS A WHOLE SYSTEM TRANSITION SOLUTION

2 UNLOCKING SUSTAINABLE PRODUCTION PATHWAYS

3 BUILDING AN INTERNATIONAL HYDROGEN MARKET

4 ACHIEVING COST EFFECTIVENESS

5 DEVELOPING INFRASTRUCTURE

1 RECOGNISING HYDROGEN AS A WHOLE SYSTEM TRANSITION SOLUTION

From decarbonising hard-to-abate sectors such as heat, industry and transport to supporting the integration of renewables and providing an energy storage solution, hydrogen's potential role in the energy system is substantial. Whether hydrogen's full potential is deployed or remains limited to niche applications depends on the adoption of long-term energy strategies and cross sector cooperation.

CONVERGING ENERGY, ECONOMIC AND POLITICAL FACTORS

Beyond new applications for hydrogen, interviewees focused on the economic and political factors which are driving renewed interest for hydrogen, mainly climate targets and air pollution concerns. The need to ensure long-term energy security and the potential to generate long-lasting employment and economic opportunities within a decarbonised economy were also frequently mentioned. These converging factors are creating the right environment for hydrogen development as a complement to the electrification route.

Due to dramatic cost reductions and uptake of renewables, much emphasis has been given to the latter as an all-encompassing decarbonisation solution in the past few years. However, while electrification has a central role to play, it is not a one-size-fits-all option. Sectors such as industry, transportation and heat, remain very difficult to decarbonise and their electrification would present significant technical and economic challenges. Hydrogen could be a suitable and effective way to shift these hard-to-abate sectors towards zero emissions[16].

COMPLEMENTING ELECTRIFICATION

Hydrogen produced via electrolysis is emerging as a solution to interconnect different energy consuming sectors (i.e. buildings, transport, and industry, etc.) with the power-producing sector, an approach which is referred to as sector coupling. This would contribute to improved efficiencies, and cheaper decarbonisation

[16] A. Fargère, B. Kolodziejczyk, J. Carton, L. Lapeña Martinez, A. Pica Téllez, C. Karaca, Y. Chae, L. Fuselli, 2018, Hydrogen an enabler of the Grand Transition, Future Energy Leaders, World Energy Council

of the entire energy system. A recurring theme of the interviews was that clean molecules will play a complementary role to electrons in future energy systems, advocating for the end of the "cold war" between the two. In addition, this longer-term vision could utilise hydrogen to balance global renewable energy requirements. Countries with excess renewable energy supplies could trade green energy, in the form of hydrogen or another subsequent synthetic fuel, with countries with shortages and in distant markets.

> **Sector coupling, by converting electricity from renewables into hydrogen, is an opportunity to bring in renewables into other consumption sectors. Hydrogen does not need to be the end product. It could be further refined or transformed into methanol or be used to make ammonia.**
>
> **VOLKMAR PFLUG, SIEMENS**

The challenge to attain this vision is twofold: first, the need to develop demand markets for low-carbon hydrogen and products derived from it; second, the need to decarbonise hydrogen production. The two elements are conditioned by proactive decarbonisation policies and financing schemes. These are emerging today mainly in developed countries with high environmental and carbon reduction concerns. They combine mandatory targets (e.g. zero emission vehicles mandate in California) and financial support (e.g. subsidies for hydrogen vehicles and related infrastructure in China). The key to the success of this paradigm shift is coordination and commitment. The role of policy makers and international cooperation is essential and cannot be under-emphasised.

As a counterbalance to the global hydrogen vision that we have presented, a more nuanced story also emerged from the interviews. Depending on energy policies of individual countries, hydrogen development may focus on specific applications only (e.g. material handling or heavy duty transport), rather than becoming the energy carrier choice for a whole system.

2 UNLOCKING SUSTAINABLE PRODUCTION PATHWAYS

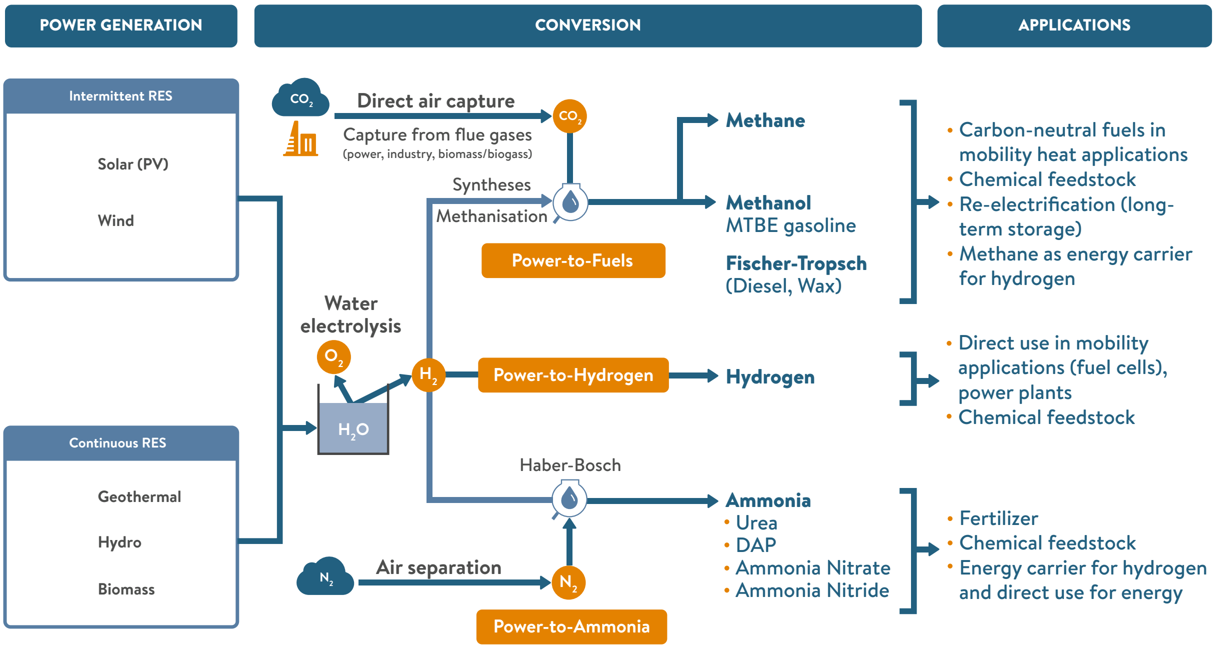
> While hydrogen is the most abundant element in the universe, it is always combined with other elements (e.g. water or hydrocarbons) and extracting it is very energy demanding. The main difference this time around is the emergence of economically viable alternatives to steam methane reforming (SMR) or coal gasification, carbon intensive processes which remain the main methods to produce hydrogen today.

Low-carbon hydrogen can be produced via several processes, including electrolysis using renewable power or via steam methane reforming (SMR) and coal gasification coupled carbon capture technologies (CCS). Production pathways are not mutually exclusive and will be determined by several factors, including scale, investment volumes, government support and available feedstock. For example, for oil and gas incumbents, SMR coupled with CCS offers an opportunity to continue on the basis of business as (almost) usual, while contributing to global decarbonisation efforts. On the other hand, those focused on the high penetration of renewables are likely to focus on producing green hydrogen using electrolysis.

A PROMISING CANDIDATE: POWER-TO-X

The increasing role of intermittent renewables in the power sector is raising storage and grid balancing concerns, opening opportunities for hydrogen production via electrolysis. This approach is referred to as power-to-x (P2X), by which synthetic fuels are produced with renewables power capacities based on gas and liquid reconversion pathways. P2X allows the decoupling of the direct use of power from the electricity sector, for use in other sectors (such as transport or chemicals) and provides at the same time the opportunity to replace conventional fossil fuels with low emission synthetic fuels, such as hydrogen, ammonia or methanol (see Figure 2).

Figure 2: P2X: Conversion of renewable power into various forms of chemical energy carriers



Source: International aspects of a power-to-x roadmap, Weltenergierat Deutschland, 2018

The main drawbacks of this route are low renewables penetration and the high cost and limited output of current electrolysers. Several interviewees raised concerns over the idea of solely relying on clean power, as illustrated by the quote below. Nevertheless, hydrogen producers using electrolysis all mentioned technology maturity and falling costs as recent key developments. Combined with imports, which we discuss in the next section, the economic fundamentals of P2X may be about to change.

> **"Surplus renewable power will be fought for by various sectors such as battery mobility and flexible demand. We should not base business cases only on surplus power but, instead, connect hydrogen production with low carbon power production in general."**
>
> **JEAN GUY DEVEZEAUX LAVERGNE, FRENCH ALTERNATIVE ENERGIES AND ATOMIC ENERGY COMMISSION (CEA)**

As noted by the quote above, nuclear power was mentioned several times by interviewees as a promising option for hydrogen production, although it is not a frequently mentioned one. As a matter of fact, the Japan Atomic Energy Agency has been developing a hydrogen production technology using high temperature gas-cooled reactors, which is called the IS-process.

A BLUE ALTERNATIVE: STEAM METHANE REFORMING AND COAL GASIFICATION COUPLED WITH CCS

Another hydrogen production pathway is combining steam reformed natural gas or coal gasification with carbon capture and storage (CCS). This is referred to as "blue hydrogen". Such a technological combination would allow for industrial scale volumes of carbon neutral hydrogen, as detailed in the H21 North of England report. This would in turn, through economies of scale, help the subsequent integration of smaller-scale green hydrogen and contribute to accelerate the development of the necessary infrastructure for all hydrogen end applications. As noted by interviewees involved in CCS projects, the main challenges of this route are the cost-effectiveness of CCS technology at scale and the need for considerable investment and appropriate government backing through regulatory and financial schemes.

" The capacity to generate blue hydrogen is going to acceleratein next decade, because of the need of big oil And gas companies to find their cause for carbon capture."

PIERRE ETIENNE FRANC, AIR LIQUIDE

Several interviewees noted that the major barrier to CCS is no longer technological but political and commercial. We discussed with Kawasaki Heavy Industries their project to turn lignite coal into liquid hydrogen in Australia. The co-produced CO_2 will be captured and sequestrated in Australia. This is anticipated to be operational by 2020 and will only run for one year. A decision to proceed to a much larger commercial stage will occur after that and would not be operational until the 2030s. Major issues remain associated with this project, namely the social license to operate and the bankability of the CCS project.

EMERGING TECHNOLOGIES

Tri-generation, a process which produces electricity, hydrogen and excess hot water, using agricultural waste is gaining traction. A commercial plant is currently being built in California by Toyota and FuelCell Energy. The plant will produce 2.35 MWs of electricity and 1.2 tons of hydrogen per day.

" We decided to develop this plant because electrolyser technology remains too expensive, it still requires significant capex cost reduction and very low wholesale electricity rates. We also saw tri-gen as an opportunity to demonstrate that there are multiple pathways for produce renewable hydrogen."

CRAIG SCOTT, TOYOTA NORTH AMERICA

Other possible ways of producing hydrogen, such as thermochemical water splitting and artificial photosynthesis, are at earlier stages of development.

The different hydrogen production, distribution and consumption pathways present important trade-offs between cost, emissions and scalability. Local circumstances (e.g. renewable energy or suitable sites for CO_2 sequestration) is likely to largely influence the choice of pathway. These different approaches can also be suitable for different stages of the energy transition. Gaining all the benefits of the hydrogen energy ecosystem requires a fine-tuned balancing of the hydrogen production mix during the energy transition and a competition among different technologies. The commitment to transition to a fully carbon-free hydrogen production over time and the setting of clear medium- and long-term milestones can facilitate the achievement of an optimum and accelerate the technological development. For example, SMR coupled with CCS could be deployed in the short term to provide very large volumes of blue hydrogen in a centralised way, while mid- and large-scale electrolysis from renewables accommodates decentralised power production. The timing and contribution of different hydrogen production technologies are points of disagreement between interviewees, as illustrated by the quotes below.

"We should first focus on developing the demand for hydrogen vehicles by reducing costs. The way in which hydrogen is produced should besecondary. We don't ask BEVs to only run on green power."

CAR MANUFACTURER SECTOR INTERVIEWEE

VERSUS

"There is no point in doing hydrogen unless it is green hydrogen. Production mode is fundamentally important as we need to start bringing down costs of green hydrogen by scaling up."

UTILITY SECTOR INTERVIEWEE

3 BUILDING AN INTERNATIONAL HYDROGEN MARKET

When asked about regions and countries leading the deployment of low-carbon hydrogen in the energy sector, most interviewees insisted on the difference between consuming countries and producing countries. Those generating demand do not necessarily have an economic or technical advantage in supplying it. This is opening opportunities for international hydrogen production and trade on a global scale, for which several countries are well positioned to participate.

EMERGENCE OF A GLOBAL HYDROGEN MARKET

For countries such as Japan or Korea, delivering their hydrogen strategies will require importing low- carbon hydrogen and therefore developing an international market for it. According to a recent study[17] by our German Member Committee, exporting countries would benefit from investments and growth and importing countries would benefit from lower energy costs. More concretely, the advantages of developing such imports include: (i) cost advantages, (ii) availability of sites for RES-E, (iii) transport and integration of renewable energy and (iv) global trade of fuels such as hydrogen would support economic grown and welfare. As illustrated in table 1, several countries are already positing themselvesto participate in this market.

[17] International Aspects of a Power-to-X Roadmap, Weltenergierat Deutschland, 2018.

JAPAN'S IMPORT STRATEGY

Japan is developing an international CO_2-free hydrogen market to meet its 2050 consumption target as set up in its Hydrogen Society strategy. The strategy mixes production methods and primary energy sources and includes projects such as AHEAD in Brunei and HySTRA in Australia (see METI hydrogen strategy), focused on steam methane reforming and coal gassification coupled with CCS. For the latter project, Kawasaki Heavy Industries is currently developing the world first liquefied hydrogen cargo ship, which remains under the close scrutiny of the International Maritime Organisation. Other companies such as Chiyoda Corp are working on storing and transporting hydrogen utilising the organic chemical hydride (OCH) method. Through initiatives such as SIP Energy Carriers, Japan is also promoting R&D related to hydrogen carriers such as ammonia.

Table 1: Interest of actors involved in the hydrogen space based on findings from interviews

COUNTRY	INTEREST FOR HYDROGEN	FUTURE SUPPLY	DOMESTIC DEMAND
Australia	• Opportunity to position itself as major exporter • Focus on avoiding job losses and making the most of lignite coal resources and renewables potential • Currently developing a hydrogen strategy	For export, focused on coal gasification and electrolysis	To be developed
California	• Driven by stringent decarbonisation regulation • Focus on opportunities related to transport • Nascent interest in long term storage and decarbonising heat via injections into the gas grid	Locally produced, focused on electrolysis and tri-generation	Leader – passenger vehicles
Chile	• Foreign interest to develop RES potential to develop green fuel export market • Domestic interest in hydrogen to integrate renewables and as a storage solution • Requires international facilitation and investments	Mostly for export, focused on electrolysis from renewable power	Limited – focus on decarbonising mining processes
China	• Driven by air quality and decarbonisation concerns • Fuel cell & hydrogen export motivation • Clear targets and heavy subsidies in place	National, focused on coal gasification and electrolysis	Leader - focused on heavy duty and long-distance transport & stationary fuel cells
France	• Focus on reducing fine particles pollution in major cities, decarbonising the industrial sector, energy independence and jobs • Desire to remain a global leader in the sector • Interest in democratising hydrogen production via electrolysis using nuclear power	National, seeking opportunities to remain at the forefront	Limited – passenger vehicles and trains
Germany	• Driven by deep decarbonisation and integration of renewable energies agenda • Leading efforts to democratise power-to-x and develop an international market for green fuels • Large scale demonstration and feasibility studies	National and imports, focus on green hydrogen	Leader – focused on storage, heat and industry
Japan	• Driven by commitment to decarbonise, to mitigate dependence of specific countries and affordability • Leading the deployment of production transportation and use technologies • World's first national hydrogen strategy	Reliance on imports, developing international market	Leader, developing transportation, power generation and industrial applications
Korea	• Focused on economic growth opportunities as it shifts to a low-carbon economy • Leading R&D in the mobility and power sectors • Strategy, subsidies and incentives in place	Reliance on imports, developing international market	Leader, focused on mobility and power

Morocco	• Geographical location and potential in wind and solar energy, open opportunity for 'Power-to-X' • Roadmap currently under development	Mostly for exports, green hydrogen from wind and solar	To be developed
New Zealand	• Very well placed to produce green hydrogen and export it to the region • Interest driven by energy storage concerns due to high renewables penetration • Hydrogen strategy currently under development	National, focused on green hydrogen, exploring export opportunities	Limited – focused on mobility and storage

As highlighted in our interviews, significant investments in hydrogen production technologies and transportation in producing countries will be essential to develop an international hydrogen market. These investments require an adequate political framework and therefore not all countries may be suitable candidates. In the short term, potential producers and consumers can develop partnerships and feasibility studies such as those developed by Japan in Australia and Brunei. More generally, for a hydrogen export market to develop, it is essential that it is part of the political agenda of multilateral negotiations on climate and energy.

4 ACHIEVING COST EFFECTIVENESS

Challenges around cost persist and considerable improvements are still required for hydrogen to become truly competitive. Yet, competitiveness in the medium-term future no longer seems an unrealistic prospect. Recent government commitments for large-scale production and consumption of hydrogen are enabling the emergence of a nurturing hydrogen ecosystem, encouraging the engagement of the wider energy system.

As of today, the emerging hydrogen applications mentioned in this brief are not yet cost effective. For example, FCEVs have higher capital cost than BEVs: $60–75k for the Toyota Mirai or Hyundai ix, versus $25–30k for the Renault Zoe or Nissan Leaf. Enabling cost effectiveness entails bringing down cost of production of low carbon hydrogen and cost decreases for fuel cells, hydrogen transportation, storage and fuelling infrastructure. However, the interviews conducted as part of this brief suggest that there are strong grounds for believing that hydrogen and fuel cells can experience a cost and performance trajectory similar to those of solar PV and batteries. This sub-section provides a deep-dive into what is happening for FCEVs, the most advanced emerging hydrogen application.

GOVERNMENT ENGAGEMENT

Interviewees' unanimously agreed that we are witnessing the emergence of a hydrogen market for energy sector applications. This is mainly due to decarbonisation and air pollution targets, which are driving governments from all around the world to find innovative solutions. In addition to market-based policies (e.g. California), which are key to drive large-scale private investments, interviewees focused on the need for government support in the form of incentives and subsidies during initial deployment period (e.g. China, Japan, Korea). Several countries have already developed national targets for hydrogen mobility and associated supporting mechanisms (see Table 2).

Table 2: Summary of the support offered in various countries for hydrogen mobility in 2018

FUEL CELL VEHICLES			REFUELLING STATIONS
COUNTRY	TARGET FOR 2030	SUPPORT IN 2018	SUPPORT IN 2018
California	1,000,000	up to $13,000 per vehicle	$100m up to 2023
China	1,000,000	up to $74,300 for larger vehicles	$1.1m per unit
Germany	100% ZEV by 2040	$4,000 per vehicle	$466m
Japan	800,000	$147m	$61m
UK	100% ZEV by 2040	$33m (60% of cost for refuelling)	-
South Korea	630,000	up to $35, 000 per vehicle	$1.8 to $2.9m per unit

Source: adapted from Energy Environ. Sci., 2019, 12, 463 and complemented with learnings from interviews

In California, the Low Carbon Fuel Standard (LCFS) sends strong a price signal to incentivize the market. Every car manufacturer operating in California is to sell a certain portion of zero emission vehicles according to an increasing quantity schedule known in advance. Quantifiable emissions are converted, sending a strong price signal to clean technology providers who can make more aggressive investments, based on the ability to earn credits. For example, a hydrogen fuelled transit bus may generate an average of US $7,000 per year (operating 40,000 miles/year). Clean fuels replaced more than 2 billion gallons of petroleum and natural gas through the LCFS in 2017[18] .

Whilst these demonstrate ambition towards FCEV uptake, incentives are today smaller than for other technologies. For example, the UK budget for hydrogen transport projects is £23m, while the funding for BEV recharging and manufacturing infrastructure is £646m[19] . However, a potential game changer is China's focus on the topic. As it looks to reduce its reliance on fossil fuels and tackle its greenhouse gas emissions and air pollution issues, China is working on replacing its heavy vehicles (e.g. buses, delivery trucks, etc.) fuelled by diesel or gasoline with FCEVs. In 2018, the subsidy for fuel cell passenger vehicle was US $29,700[20] for each car, and US $44,500/$74,300 for each small sized truck and bus/mid-large sized truck. Additionally, the Chinese government is heavily subsidizing both refuelling stations[21] and the price of hydrogen.

> Late in the first decade of the 2000s, China's aspirations to become a battery-electric superpower faced difficulties. At the time, electric vehicles were all but non-existent in the country, there was no charging infrastructure, and almost no technology or companies. In 2009, the government launched "Ten Cities, Thousand Vehicles", a programme to stimulate electric-vehicle sales through large-scale pilots. A decade later, after tens of billions of dollars in subsidies and extensive policy support, China is the world's battery-electric major player. Can it repeat it with fuel cells? Recent government announcements suggest that it is going to try.

A challenge often mentioned by investors is the business case for hydrogen applications. On the one hand, there is no global pricing for carbon externalities, and on the other hand, carbon-based incumbent

[18] California Air Resource Board, Press Release, May 9 2018
[19] HM Government and Automotive council UK, Industrial Strategy: Automotive Sector Deal, 2018
[20] US Dollars converted as 1 CNY = 0.15 USD
[21] "Chinese authorities announce 2019 subsidy scheme for NEVs", IHS Markit, 2019

technologies benefit from optimised cost structures and on amortised infrastructure. In this context, assurance that governments will comply with their decarbonisation targets and that hydrogen is here to stay are crucial. Several interviews mentioned that regulation around the injection of hydrogen into the gas grid and seasonal storage would accelerate the adoption of green hydrogen through power-to-x mechanisms.

The investors interviewed emphasised the importance of showcasing success stories, which tend to be bottom-up and are able to showcase economic viability. These may not be the large scale projects the industry is thinking of, but they have the advantage of acting as lighthouse projects and enable actors to compete with ideas or models. Once deployed locally, projects can be replicated globally to drive the associated cost curve further down and improve global competitiveness of hydrogen technologies.

As noted by interviewees, hydrogen as a decarbonisation solution is currently a costly pathway. Nevertheless, our interviews identified several factors signalling that there is realistic hope:

- Fuel cell and electrolyser technology costs are rapidly decreasing as a matter of scale up
- Lighthouse projects are showing the long-term economic viability of hydrogen commercially
- Long term energy visions and hydrogen specific regulation are being developed

For low-carbon hydrogen markets to continue to develop, clear government visions, enabling regulations and appropriate incentives need to be in place. Challenges in terms production, transport and other infrastructure remain to be solved, but as noted by several interviewees, the challenge is not a technical one but one of long-term strategy and commitment to curb climate change.

5 DEVELOPING INFRASTRUCTURE

The successful adoption and commercialisation of hydrogen as a decarbonisation tool relies on strategically integrated infrastructure. For many applications, especially mobility, infrastructure is considered as the main challenge. The most important elements of the hydrogen infrastructure are points of production, transmission and distribution systems and refuelling station networks.

Infrastructure dedicated to hydrogen production and transportation already exists. However, the vast majority of it is not intended for hydrogen as energy carrier, but, rather as feedstock. As emphasised by interviewees, hydrogen's deployment in the energy sector will require some new infrastructure to be built or repurposed. This infrastructure includes:

- **Production Points:** Their type and scale dependant on the production route and the supply targets.
- **Transportation:** Hydrogen vessels and tank trucks for long distance delivery of compressed or liquid hydrogen.
- **Transmission:** A pipeline system to store and transport hydrogen to distribution points and industry.
- **Fuelling Stations:** Mostly for mobility.
- **Distribution:** A pipeline system to supply hydrogen to end uses (e.g. domestic heat).

LARGE SCALE PRODUCTION INFRASTRUCTURE

Hydrogen production methods have been discussed previously in this report. Depending on the production pathway, the infrastructure requirements will vary. At present, large electrolysers can be connected to the electric grid to produce energy in the 5-15MW range. As a matter of fact, a 10MW facility is being built in Germany while a 30MW AE electrolyser facility will be built in Australia at a production cost of $117m[22]. In regards the latter project, H2U and Baker Hughes have also announced a partnership with the intention to deploy a 100% hydrogen gas turbine (16MW) at the site[22].

On the other hand, blue hydrogen production via SMR or ATR coupled with CCS, as envisioned in the H21 North of England project, would imply the construction of facilities whose production output could be gradually increased over time in a cost-effective way aligned to demand.

TRANSMISSION AND DISTRIBUTION GRIDS

To deliver hydrogen to its end use points, a practical way would be by means of transmission and distribution pipelines able to transport large quantities of hydrogen from production points. The pipelines would also be used for line packing, a storage technique whereby the gas in the pipeline network can be stored for days and used to meet peak demand when required. Several interviewees noted the possibility of repurposing the existing gas distribution infrastructure, once the safety regulations are put in place. This approach would provide logistic and economic benefits, mitigating the environmental and economic risks of asset decommission and stranding, at least in the short term, as discussed in the upcoming Innovation Insights brief on Infrastructure. On the other hand, new transmission pipelines could be strategically built, also serving refuelling stations. The easiest and most economic pathway regarding transmission was an area of disagreement between interviewees and requires further focus.

> **"People often forget that the oil industry is currently the main producer and consumer of hydrogen. We see hydrogen becoming an important primary source of energy by 2050. Hydrogen production is not the issue, transport and delivery are. To this end, we can leverage our existing infrastructure."**
>
> **AHMAD AL KHOWAITER, SAUDI ARAMCO**

LONG DISTANCE TRANSPORTATION

As noted by most interviewees, for very long distances and especially for export purposes, a more suitable solution is the transportation of hydrogen under the form of ammonia. Yet, as mentioned earlier, Japan is currently developing technology related to liquid hydrogen, which would be shipped via a specialised vessel with a capacity of 1250m^3 . The first shipments should take place by the end of 2020.

REFUELLING STATIONS

One of the most promising hydrogen applications is the utilisation of fuel cells in the mobility sector. As all the interviewees highlighted, the main challenge regarding mobility remains the availability of hydrogen refuelling stations (HRSs). The challenge represents a classic “chicken-and-egg” situation where the adoption of FCEVs requires the availability of a refuelling station network, while investments require demand. As noted by the California Fuel Cell Partnership, collaboration with oil and gas companies is crucial in this area. They possess the real estate, the resources, the logistics and networks to manage this transition in a participatory fashion which could benefit all parties involved in the value chain.

[22] http://www.renewablessa.sa.gov.au/topic/hydrogen/hydrogen-projects/hydrogen-green-ammonia-production-facility; https://www.gasworld.com/baker-hughes-generators-to-power-h2u-plant/2016575.article

DECENTRALISED INFRASTRUCTURE

Although often overlooked, several interviewees mentioned hydrogen applications within a decentralised energy system. For example, in developing countries, distributed hydrogen production based on solar could represent a way to store energy and to produce ammonia, which could then be used as fertiliser to support local agriculture. The main hurdle to the development of such decentralised infrastructure remains the cost of electrolysis.

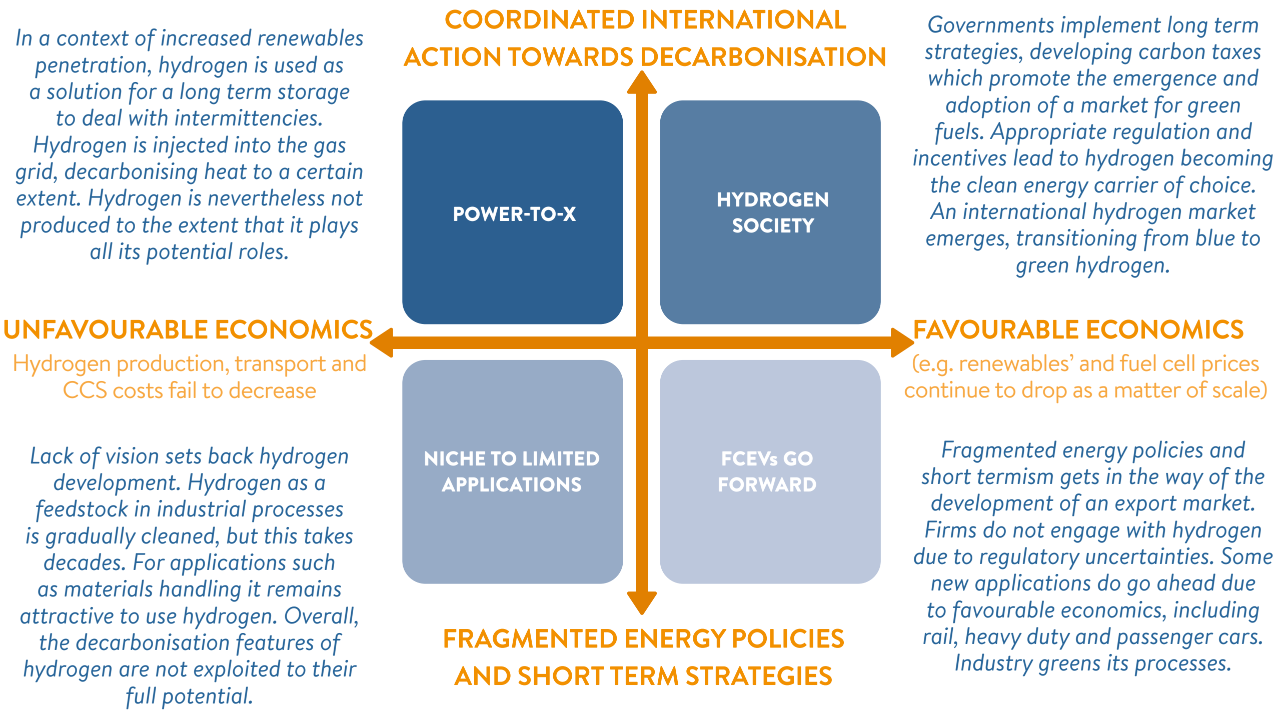
Large investments across the value chain will be required for hydrogen production, transmission and distribution infrastructure. In the mobility sector the majority of investment would be devoted to the development of refuelling station networks, which are essential to accelerate FCEVs commercial availability. In the heat sector, production plants linked to renewable generation, transmission and distribution networks will require large investments. The grid investments could be mitigated, at least in the short term, by utilising the existing gas grid for natural gas mixed with hydrogen. The use of hydrogen, due to the large infrastructure investment required, becomes an energy choice within a long-term energy strategy which has to be supported by governments in coordination with energy firms.

FUTURE OUTLOOK FOR HYDROGEN

Hydrogen is a potential paradigm shifter. Hydrogen can play a major role alongside electricity in future low-carbon economies, with the versatility to provide mobility, power system, heat and industrial services. Whether hydrogen becomes the energy carrier of choice in several decades or delivers specific energy services, it has a role to play in future energy systems.

The intelligence gathered as a result of this work provides a means of setting the scene for the outlook of hydrogen. Given the diversity of production, transport and consumption pathways, a clear government strategy will reduce the costs of introducing hydrogen and fuel cell technologies. The single greatest challenge in realising the hydrogen and fuel cell potential is predictable and consistent energy policy. In addition, cost and performance trajectories rely on what we identified as favourable economics, mostly continued falling renewable prices, performance and cost drop of fuel cells. The combination of sustained government support, technological progress and large-scale investments may well mean that hydrogen is here to stay.

Figure 3: Future outlook for hydrogen



NEXT STEPS

This Innovation Insights brief has touched upon several areas which require further cross-sector and cross-region alignment and cooperation. These include:

- Modernising and harmonising **regulation** to enable hydrogen and fuel cells
- Unlocking large scale **investments** in product development and infrastructure
- Rules of the game for the development of a low-carbon **hydrogen export market**

To progress the discussion on these topics, the World Energy Council will be hosting a series of Innovation Forums (IF) in the upcoming months. To host or join us for this rare opportunity to exchange ideas and challenge assumptions with a diverse group of leaders from around the world, please contact blanc@worldenergy.org.

ANNEX 1: TABLE OF ABBREVIATIONS

ATR	Autothermal Reforming
BEV	Battery Electric Vehicles
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
FCEV	Fuel Cell Electric Vehicles
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Green House Gas
GW	Gigawatt
HRS	Hydrogen Refuelling Station
ICE	Internal Combustion Engine
IF	Innovation Forum
LCFS	Low Carbon Fuel Standard
METI	Ministry of Economy, Trade and Industry
MW	Megawatt
OPEX	Operating expense
PEM	Proton Exchange Membrane
PTX	Power to x
RES-E	Renewable Energy Sources for Electricity
SMR	Steam Methane Reforming
TSO	Transmission System Operator
UAV	Unmanned Aerial Vehicles
UK	United Kingdom
UPS	Uninterruptible Power Supplies
US	United States of America

ANNEX 2: LIST OF USE CASES

Sector	Use Case	Brief Description	Source of hydrogen	Stage of development
Mobility	1st Fuel Cell Electric Vehicle Taxi Fleet	Provide on demand transportation operators an FCEV package by 2021 at the same rate as hybrid and diesel vehicles.	Grey – transition to green planned	Commercial, small scale
	Class 8 Semi-Trucks Powered by Hydrogen	Toyota is testing the scalability of their fuel cell technology by developing class 8 fuel cell semi-trucks for use in the port.	Green	Feasibility Study
	Hydrogen Fuelled Train	Provide a cost effective and sustainable alternative to electrification to decarbonise rail transport.	Grey – transition to green planned	Commercial, small scale
Power	A European Flagship Power-to-X Project	Aims at demonstrating that an industrially integrated electrolyser is able to produce green hydrogen and supply grid services at the same time.	Green	Demonstration Project
	A Replicable Hydrogen Territory	Uses curtailed renewable energy generated locally to produce hydrogen to be stored and used for local applications	Green	Demonstration Project
Heat	Decarbonising Heat	Detailed engineering solution for converting UK homes and businesses from natural gas to 100% hydrogen, starting in 2028.	Blue and green	Feasibility Study
Industrial Applications	Decarbonising Ammonia	Clean hydrogen is the major enabler for making CO2-free or “green” ammonia, which is the key ingredient for “green” fertiliser.	Green	Feasibility Study
	Decarbonising Steel Production	The SALCOS project aims at gradually moving away from carbon-intensive steel production based on blast furnaces, to a direct reduction and electric arc furnace route, with an increasing use of hydrogen.	Green	Demonstration Project

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