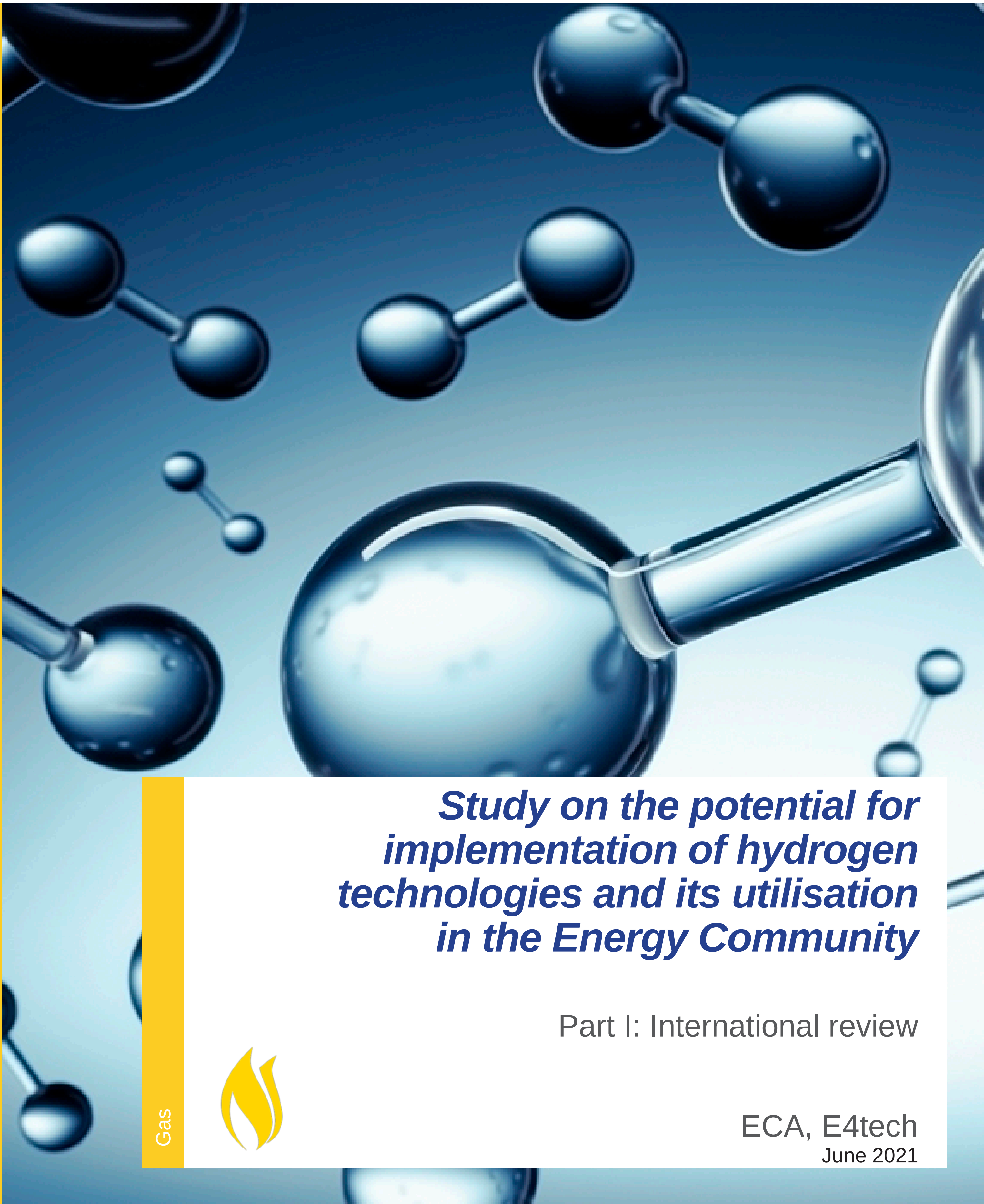
Energy Community



Study on the potential for implementation of hydrogen technologies and its utilisation in the Energy Community

Part I: International review

Gas

ECA, E4tech

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Abbreviations and acronyms

AEL	Alkaline water electrolysis
APG	Austrian Power Grid
ATR	Auto thermal reforming
BEVs	Battery electric vehicles
BF	Blast furnace
BOF	Basic oxygen furnace
CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CEF	Connecting Europe Facility
CERTH	Centre for Research and Technology Hellas
CHF	Swiss franc
CHP	Combined heat and power
CP(s)	Contracting Party(ies)
CSR	Corporate social responsibility
DAC	Direct air capture
DRI	Direct reduced iron
EPC	Engineering, procurement and construction
EU	European Union
FCEV	Fuel cell electric vehicle
FCH-JU	Fuel Cells and Hydrogen Joint Undertaking
FCVs	Fuel cell vehicles
GHG	Greenhouse gas(es)
HHM	Hyundai Hydrogen Mobility
HSE	Health and Safety Executive (UK)
HRS	Hydrogen refuelling stations
ICE	Internal combustion engine
IEA	International Energy Agency
IPCEI	Important Project of Common European Interest
LCFS	Low Carbon Fuel Standard
LCPD	Large Combustion Plant Directive
LHV	Lower heating value
LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carriers

LPG	Liquefied petroleum gas
MFF	Multiannual Financial Framework
MHPS	Mitsubishi Hitachi Power Systems
MoU	Memorandum of understanding
MW	Megawatt
NECP	National energy and climate plans
NEV	New energy vehicle
PEM	Polymer electrolyte membrane
PEMFC	Proton exchange membrane fuel cells
ppm	Parts per million
PtG	Power-to-das
PtH	Power-to-hydrogen
PtL	Power-to-liquids
PtX	Power-to-X (any of several electricity conversion, energy storage, and reconversion pathways that use surplus electric power, typically during periods where fluctuating renewable energy generation exceeds load)
PV	Photovoltaic
RD&D	Research, development and demonstration
RED II	Renewable Energy Directive II
RFNBO	Renewable fuels of non-biological origin
RFO	Renewable Fuel Obligation
SAF	Sustainable aviation fuel
SEND	Smart energy network demonstrator
SMR	Steam methane reforming
SNG	Synthetic natural gas
SOEL	Solid oxide electrolysis
SOFC	Solid oxide fuel cell
TAP	Trans-Adriatic Pipeline
Toe	Tonnes of oil equivalent
UK	United Kingdom
US	United States
WHO	World Health Organisation
ZEV	Zero Emissions Vehicle

1 Introduction

The Paris Agreement on Climate Change[1] is centred on 'holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels'. This has led to both the European Union (EU) and many governments worldwide (such as China, Japan, South Korea, New Zealand) to commit to net zero carbon targets. The Contracting Parties (CPs) of the Energy Community (Albania, Bosnia and Herzegovina, Georgia, Kosovo*, Moldova, Montenegro, North Macedonia, Serbia and Ukraine) are all signatories to the Paris Agreement, except Kosovo*, which commits them to developing strategies and actions for achieving a climate neutral world by mid-century.

Globally, the stated commitments from different countries vary in terms of their ambition and timeframe, but they all recognise that **decarbonisation is essential throughout all sectors of the economy, including those that had hitherto been considered difficult to transition away from fossil fuels**. Hydrogen as an energy vector is now attracting increased interest as one of the potential solutions for these hard-to-decarbonise sectors and has become an integral part of many countries' energy transition plans.

At a supra-national level, the European Green Deal is a set of policy initiatives designed to make the EU's economy sustainable through an action plan to boost the efficient use of resources by moving to a clean circular economy, restoring biodiversity and cutting pollution. With the ultimate goal for the EU to be climate neutral by 2050, the EU reasons that a just and inclusive transition will require collective action through all sectors of the economy. The CPs have also acknowledged the Green Deal, while the Western Balkan members have endorsed and committed to the fundamental pillars of the Deal through the Green Agenda for the Western Balkans adopted by the Sofia Declaration in November 2020[2] and recognised by the 18th Ministerial Council[3].

The Green Deal stipulates a number of objectives including:

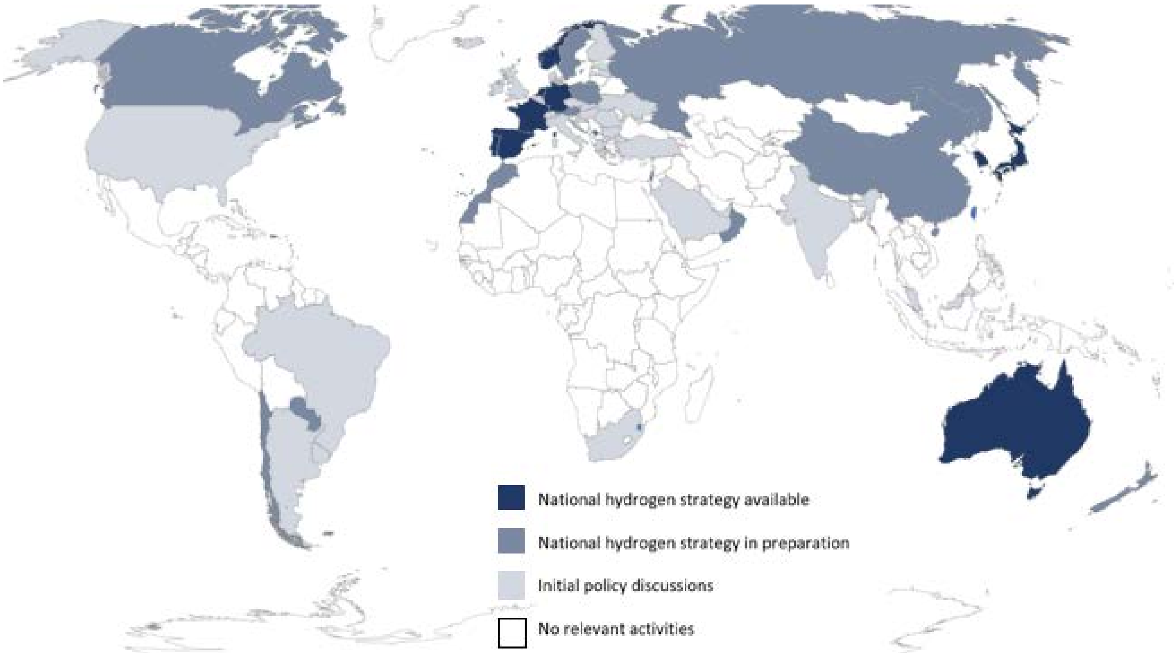
- Investing in environmentally friendly technologies;
- Supporting industrial innovation;
- Deploying clean and low cost forms of transport;
- Decarbonising the energy sector; and
- Improving the efficiency of buildings.

1 https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.
2 https://www.rcc.int/download/docs/Leaders%20Declaration%20on%20the%20Green%20Agenda%20for%20the%20WB.pdf/196c92cf0534f629d43c460079809b20.pdf.
3 https://energy-community.org/events/2020/11/MC.html.

The plan also outlines the investment tools needed to realise these objectives as well as the financing instruments available. Through the Just Transition Mechanism[4], the EU aims to mobilise at least €150 billion between 2021 and 2027 in those EU regions most heavily dependent on fossil fuels and therefore most affected by the transition to a renewables based economy.

The focus of this study is on the production of zero and low carbon hydrogen in the Energy Community. Figure 1 indicates those countries which have significant current or planned hydrogen activities. Within these, hydrogen generally plays a role in decarbonising sectors where electrification is challenging including heat, heavy duty transport and industry. However, hydrogen is also envisaged as playing a part in energy storage and sector coupling, ensuring that the whole energy system can manage the challenges of decarbonisation.

Figure 1 Overview of hydrogen strategies and activities (Status: August 2020)[5]



The use of hydrogen is already well established in industries where it is a pre-requisite feedstock (e.g. the synthesis of chemical products and in processes such as refining or food manufacture), where drivers for its production are independent of decarbonisation. A large proportion of this hydrogen is currently produced from fossil fuels through the reforming of natural gas, while the rest is predominantly derived from the gasification of coal. The first step to decarbonising hydrogen production is applying carbon capture and storage (CCS) to these processes, which should have sufficient benefits in the short term to help the hydrogen economy develop but is not viewed as a long term sustainable solution. Hydrogen produced from the electrolysis of water using renewable electricity presents a viable alternative to fossil fuels for hard-to-decarbonise sectors.

[4] This comprises grant, loan, and guarantee facilities to support the transition to a climate-neutral economy. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu/just-transition-mechanism_en.
[5] https://www.weltenergierat.de/wp-content/uploads/2020/11/20201027_Energy-Day_Dr.-Uwe-Albrecht_Hydrogen-Study_pub.pdf.

Developments towards transitioning to large scale use of sustainable hydrogen are not new, although they had been stalled for about a decade. However, the focus on hydrogen and its ability to store and transport energy has recently accelerated, paving the way for it to play a growing and prominent role as a sustainable energy carrier of the future. This recent interest is driven by the understanding that to realise net zero ambitions and arrest global climate change, a future energy scenario must be underpinned by renewable electricity, and hydrogen can act as a store of renewables thereby helping to compensate for their fluctuating nature. Also, in some sectors, the substitution of fossil fuels for direct electrification is straightforward, but in others it is not a viable solution (e.g. heavy duty vehicles, marine, aviation fuels) and so hydrogen potentially provides an alternative means to accessing renewable energy.

Within Europe, renewable energy resources are limited, so a grid of sufficient capacity will likely have to be supplemented with electricity originating internationally but transported into the EU either via renewable hydrogen or long distance cables depending on the distance and quantities involved. Inherent geographic constraints mean locations where renewable electricity can be produced cost effectively from abundant, low cost resources are often remote from demand centres and lack a grid connection (offshore wind or desert solar). Additionally, a high proportion of renewable sources are intermittent suppliers of energy, but consumer demand is equally irregular, so it is increasingly accepted that the storage of energy for its transportation in space or time, for load balancing electric grids and for backup power, has also become an important element of decarbonisation plans and the transition to clean energy.

It is generally argued that there will need to be a shift from a society of “energy gatherers” to one of “energy farmers” making use of vectors that allow energy to be stored, transported and converted to electricity. Once produced, hydrogen can be transported and stored in multiple ways, allowing it to be utilised in different end use applications, such as transport, heat, industry or electricity generation. This flexibility as an energy vector has therefore underpinned the argument for its use alongside the other major energy vector, electricity.

The key benefits of hydrogen are:

- **Abundance and flexibility**: hydrogen is the most abundant element and is found in many compounds from which it can be extracted and used;
- **High gravimetric energy content**: 120 MJ/kg is released during the oxidation of hydrogen, which is almost three times the energy density of traditional fossil fuels by weight (methane 55.6 MJ/kg, gasoline 46.4 MJ/kg, diesel 45.6 MG/kg, crude oil 42 MJ/kg and coal 26-33 MJ/kg – see the middle column of Table 1);
- **Clean emissions profile**: hydrogen is free from CO_2 at the point of use;
- **Storage potential compared with electricity**: hydrogen can be fairly readily stored in large volumes and over relatively long periods of time in decentralised locations;
- **Applicability to multiple end use sectors**: hydrogen can be used for many different applications and is more practical than alternatives in many of these, e.g. heavy duty transportation;
- **Efficient end use applications** (fuel cells).

Table 1 Comparison of fossil-based fuels with hydrogen

Fuel	Gravimetric energy density MJ / kg	Volumetric energy density MJ / dm3
LNG (−160°C)	53.6	22.2
Gasoline	46.4	34.2
Diesel	45.6	38.6
Crude oil	41.9	37.0
Coal	26-33	34-43
Liquid H_2 (–240°C)		8.5
H_2 gas: 700 bar, room temperature	120 (LHV)	4.5
H_2 gas: 350 bar, room temperature		2.8
H_2 gas: 1 bar, room temperature		0.01

However, the use of hydrogen also suffers from several drawbacks:

- **Low volumetric energy density** creates challenges for storing hydrogen, particularly in places where space is at a premium such as for onboard applications within a road vehicle fuel tank. The volumetric energy density of hydrogen is compared with that of fossil-based fuels in the right-hand column of Table 1.

- **Need for better and more efficient infrastructure for distributing and transporting hydrogen to the end user**. There are technical and economic drawbacks to the use of both gaseous (high pressure) and liquid (cryogenic temperatures) hydrogen, meaning identifying and developing suitable reversible hydrogen storage materials is of growing and significant importance.

- **Overall efficiency and cost**: although hydrogen can be produced from multiple feedstocks, the hydrogen-based energy cycle must first start with the production of hydrogen which requires the input of large amounts of energy to separate hydrogen from these molecules through processes like electrolysis or steam methane reforming. This has an impact on efficiency and cost of production.

- **Industrialisation of component manufacture**: the component parts of electrolysers and fuel cells, for example, are relatively complex to manufacture and quite hard to industrialise. They also frequently use expensive catalyst materials (e.g. platinum) which together make capital costs relatively high and raise potential concerns about the sustainability of mineral extraction. Electrolyser scale-up and hydrogen production via electrolysers will need to increase dramatically to meet projected demand volumes.

- **Increased need for centralised approach**: significant use of hydrogen, for example in the heating network, is expected to require a rather centralised approach, e.g. mandated blending or wholesale network conversion if it is to be delivered successfully. The preference in recent years has been to take a market-based approach to the deployment of new energy technologies which may be inconsistent with this more centralised approach.

Several initiatives are being put in place at national and supra-national level which will support engagement in hydrogen energy solutions and build on the momentum and interest already present. These include:

- Support for **research and development** into hydrogen-related technologies;
- **Funding of projects or infrastructure investments** that would facilitate the proof of concept;
- **Incentives to bridge the cost gap** that exists currently between hydrogen solutions and their fossil counterparts; and
- Establishment of the **necessary market and regulatory structures** to allow the flourishing of the hydrogen sector.

Given the increasing interest in hydrogen, supply and demand are expected to grow, with the prospect of hydrogen becoming a traded commodity able to replace fossil fuels in many applications. Hydrogen could, in principle, underpin the low carbon energy system, increase energy security, and support the ‘green recovery’.

This report presents a high-level overview of the international picture with regards to hydrogen as an energy vector, by examining:

- What the drivers for hydrogen are;
- How hydrogen can be used in the energy system;
- What policy mechanisms are being used to overcome technical and commercial barriers to the introduction of hydrogen; and
- What strategies are being employed by countries to realise their decarbonisation objectives using hydrogen.

We also examine three country case studies and four project case studies, with relevance to the CPs in detail, to highlight key success factors, major obstacles and best practices. This collective evidence base will help to inform the later analysis of the economics of hydrogen under different use cases, and how hydrogen might ultimately form part of the energy system in the CPs.

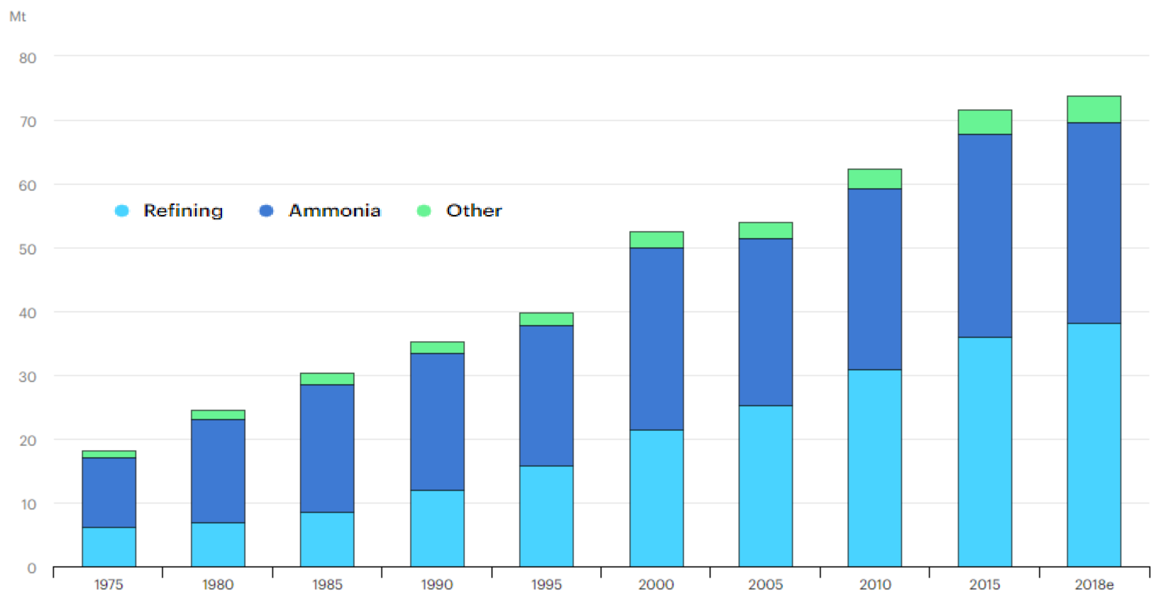
2 Drivers for hydrogen use

This section outlines the drivers and reasoning for the use of hydrogen within the energy system to achieve policy goals including decarbonisation, energy security and industrial strategy. Like electricity, hydrogen is an energy vector which can be produced from multiple sources and used in a wide range of applications. It is also transportable and storable in a variety of forms making it highly versatile. We describe how hydrogen is being considered as part of the energy transition across a wide spectrum of end-uses and what roles it might best fulfil. But first, for background purposes, we briefly review the current demand and supply of hydrogen.

2.1 Hydrogen energy today

The International Energy Agency (IEA) estimates that in excess of 70 million tonnes (Mt) of hydrogen are produced globally per year, primarily for industrial purposes, namely refining and for the synthesis of ammonia and methanol, with the overwhelming majority (>90%) from fossil sources (see Figure 2).

Figure 2 Global demand for pure hydrogen by sector, 1975-2018 (mT)



Source: IEA - The Future of Hydrogen Technology report

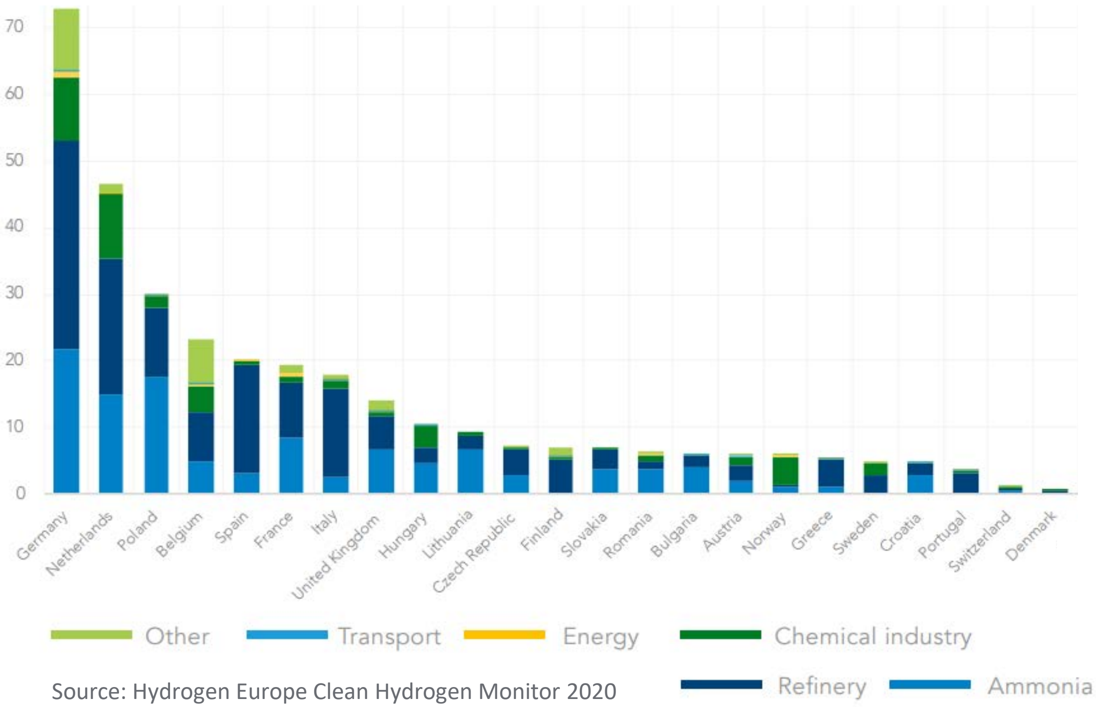
The current total hydrogen production capacity in Europe[6] is 11.5 Mt, of which 80% (9.2Mt/year) is dedicated production capacity and 20% (2.3Mt/year) is by-product hydrogen, produced as part of various chemical processes[7]. Of the 80% dedicated capacity, 65%

[6] European Economic Area (the EU-27 plus the UK, Norway, Switzerland and Iceland).
[7] Hydrogen Europe – Clean Hydrogen Monitor 2020 Report.

(7.5Mt/year) is produced on-site at captive plants (e.g. refineries and chemical plants) and 15% (1.7Mt/year) by merchant producers with the EU market dominated by four companies, namely Air Liquide[8], Air Products[9], Linde Gas[10], and Messer[11].

The majority of EU hydrogen production currently uses fossil fuels, with clean hydrogen representing less than 1% of overall hydrogen production. At the country level, Germany is the main EU producer, with 21% of EU hydrogen production capacity followed by the Netherlands with 14% of EU production (1.5 Mt of hydrogen per year). Total demand for hydrogen in the EU in 2018 was 8.3 Mt (277 TWh), with the biggest consumers being refineries (3.7 Mt, 45% of total), ammonia industry (2.8 Mt, 34%), and chemicals industry (1.0 Mt, 12%) (Figure 3).

Figure 3 European Economic Area hydrogen demand (TWh) by country and end use in 2018



Source: Hydrogen Europe, Clean Hydrogen Monitor, 2020

2.2 Net zero and a hydrogen pathway

A critical driver for growing interest in hydrogen has been the shift in emphasis among policymakers towards a net zero carbon future. Global temperature rises are dependent on the parts per million (ppm) of CO_2 in the atmosphere and the Paris Agreement acknowledges that not only is a complete halt on net carbon emissions needed, but there is an additional requirement for negative emissions technology to reduce the concentration of CO_2 already

[8] https://www.airliquide.com/.
[9] https://www.airproducts.co.uk/.
[10] https://www.linde-gas.com/en/index.html.
[11] https://www.messergroup.com/.

present to ensure the global temperature rise relative to pre-industrial levels remains below 2°C or if possible 1.5°C.

The EU aims to be an economy with net zero greenhouse gas emissions by 2050. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement. Progressively stricter decarbonisation targets as the urgency to transition to a climate neutral society is better understood means solutions must now be found for even those sectors considered extremely difficult and/or costly to decarbonise. As noted in Section 1, most of the CPs are signatories of the Paris Agreement, which commits them to similar targets and strategies. Moreover, all are (or will be) covered by EU regulations which transpose much of the Paris Agreement's intent into law.

To date, the focus of decarbonisation efforts has been on electricity production, where fossil fuel plants are displaced by renewable generation, and on biofuels which can be used to substitute fossil fuels in applications like transport. However, electricity suffers limitations in terms of its suitability for certain end use applications, e.g. long distance road transport, and there are concerns around direct and indirect land use change for the production of some biofuels (although biofuels from waste are actively promoted under the EU Methane Emissions Strategy[12]). Furthermore, unlike electricity which emits no CO_2 at the point of use, biofuels can at best be carbon neutral and do not necessarily address other environmental concerns, such as air quality in urban zones.

This has led to the promotion of hydrogen as a complement to electricity and biofuels. It emits no carbon dioxide at the point of use and can support sectors where it is difficult to reach net zero emissions with electricity or biofuels alone. Hydrogen, like electricity, is an energy vector meaning it is produced to enable the storage, transfer and end use of energy, rather than being a primary source like fossil fuels. This allows it to be used flexibly in the energy system, being produced from a wide range of sources and applied to a wide range of end use applications. These features have made it a focus of attention for governments setting decarbonisation goals.

At the same time as the understanding and need for hydrogen has been growing, the benefits of investments in hydrogen technologies have started to bear fruit. The costs of hydrogen-based technologies have been decreasing and technological hurdles in many sectors have been overcome. Further significant cost reductions over the coming decades have been highlighted in a recent report into hydrogen competitiveness from the Hydrogen Council[13], which drew on data submitted by a wide range of companies active in the sector. Most of these reductions are expected to be achieved not through major technological breakthroughs, but through the industrialisation of manufacturing processes. It concludes that '90 per cent of cost reduction for non-transport applications are from scaling up the supply chain' while 'up to 70 per cent of cost reductions for transport applications are from manufacturing scale-up'. The report also highlighted that by 2030 hydrogen would become competitive with low carbon alternatives in 22 of the 35 applications investigated, which collectively comprise roughly 15 % of global energy consumption. Examples include commercial vehicles, trains, and long-range transport applications, hydrogen boilers, especially for existing buildings currently served by natural gas networks, industrial heating, and in balancing the power system. Low carbon and

[12] https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1833.
[13] Hydrogen Council: Path to hydrogen competitiveness, A cost perspective, January 2020 https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.

renewable hydrogen is also expected to become competitive with high carbon hydrogen used for industry feedstock today as costs fall and carbon prices rise[14].

Increasingly, governments in developed countries are viewing hydrogen as a possible engine of economic growth. In the EU, the Green Deal is targeting investments in low carbon energy, including hydrogen, with specific calls being issued to support hydrogen deployment. More specifically for the CPs, the Economic and Investment Plan for the Western Balkans[15] suggests a number of renewable energy power plants, gas pipelines and interconnectors to be invested in to aid the transition to renewable sources of energy production, particularly away from coal. Many countries are emphasising the need to ensure that recovery from the effects of the Covid-19 pandemic is premised on a cleaner, renewables based future. The UK, for example, is focusing on a 'Build Back Better' approach[16], which incorporates themes including protection of the environment, social justice and rebalancing the economy throughout all geographic regions.

2.3 Hydrogen in the energy system

Hydrogen production and use within the energy system is not a new concept, with examples of large scale production via electrolysis from the early 20th century onwards for its use in the production of ammonia. Hydrogen made from coal was also a key element of 'towns gas', which powered a significant amount of heating and street lighting systems in many countries in the first half of the 20th century, until the use of natural gas became more widespread.

However, hydrogen does not commonly exist in its elemental form on Earth and is typically found in combined chemical forms such as water (H_2O) or in hydrocarbons such as methane (CH_4). Consequently, a hydrogen-based energy cycle must first start with the production of hydrogen which requires the input of large amounts of energy to separate hydrogen from these molecules through processes like electrolysis or steam methane reforming (SMR).

Hydrogen can be stored and transported in many ways. Although by mass the oxidation of hydrogen releases more energy than any other hydrocarbon fuel, it is volumetric energy density that is the most practical measure for the comparison of energy storage methods. Despite significant compression or liquefaction, the volumetric energy density of elemental hydrogen remains low (see Table 1 above). Hydrogen can be transported as a gas in pipelines or in high pressure tanks (on trucks/ships/trains) or liquefied at cryogenic temperatures and transported in ships or trucks in much the same way as liquefied natural gas (LNG). Alternatively, hydrogen can be reversibly, chemically converted to liquid or solid "carrier

[14] Throughout this report we refer to three broad types of hydrogen production: 'renewable hydrogen' is that which is produced by zero-emitting renewable energy; 'low carbon hydrogen' includes hydrogen produced from natural gas with carbon capture, use and storage, or from nuclear energy, or from grid electricity where the carbon intensity of the grid is less than 100kg CO_2/MWh; 'high carbon hydrogen' refers to unabated hydrogen production. See also the discussion in Section 3.2.

[15] https://ec.europa.eu/neighbourhood-enlargement/sites/near/files/communication_on_wb_economic_and_investment_plan_october_2020_en.pdf.

[16] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/968403/PfG_Final_Web_Accessible_Version.pdf.

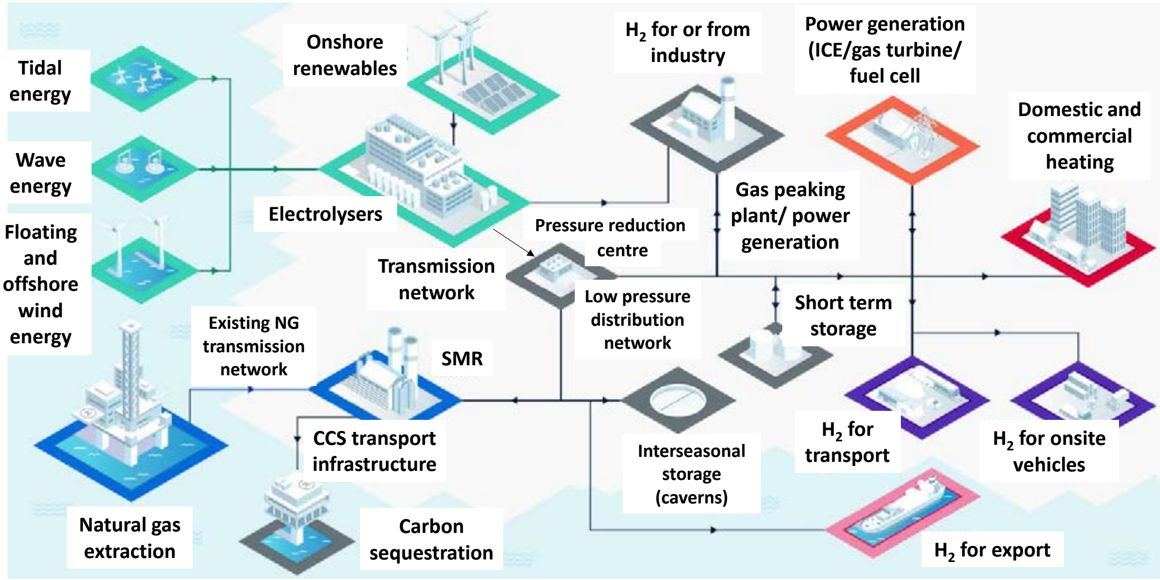
molecules" such as ammonia and liquid organic hydrogen carriers (see further discussion in Section 3.3.1).

There are two significant limitations which are currently hindering the widespread implementation of the potential "hydrogen economy". **The biggest hurdle is the need for better and more efficient infrastructure for distributing and transporting hydrogen to the end user.** The second drawback is the insufficiencies of current methods for safely and effectively storing large quantities of high density hydrogen. Although hydrogen presents an attractive solution to the storage of energy, the storage of hydrogen itself remains a challenge. Additionally, technical challenges such as infrastructure material choice and leakage (Section 3.3.1), as well as the abundance of cheap fossil fuels, have prevented hydrogen gaining a foothold in the energy system until recently.

Hydrogen is a flexible fuel that can be burned as a fuel in appliances such as boilers or internal combustion engines (ICE) or used in fuel cells that convert the hydrogen into electrical energy (with higher overall efficiency than combustion engines) which can in turn be used to power motors or other devices.

Figure 4 provides an illustration of how hydrogen could potentially be used widely throughout the energy system.

Figure 4 Example hydrogen energy system

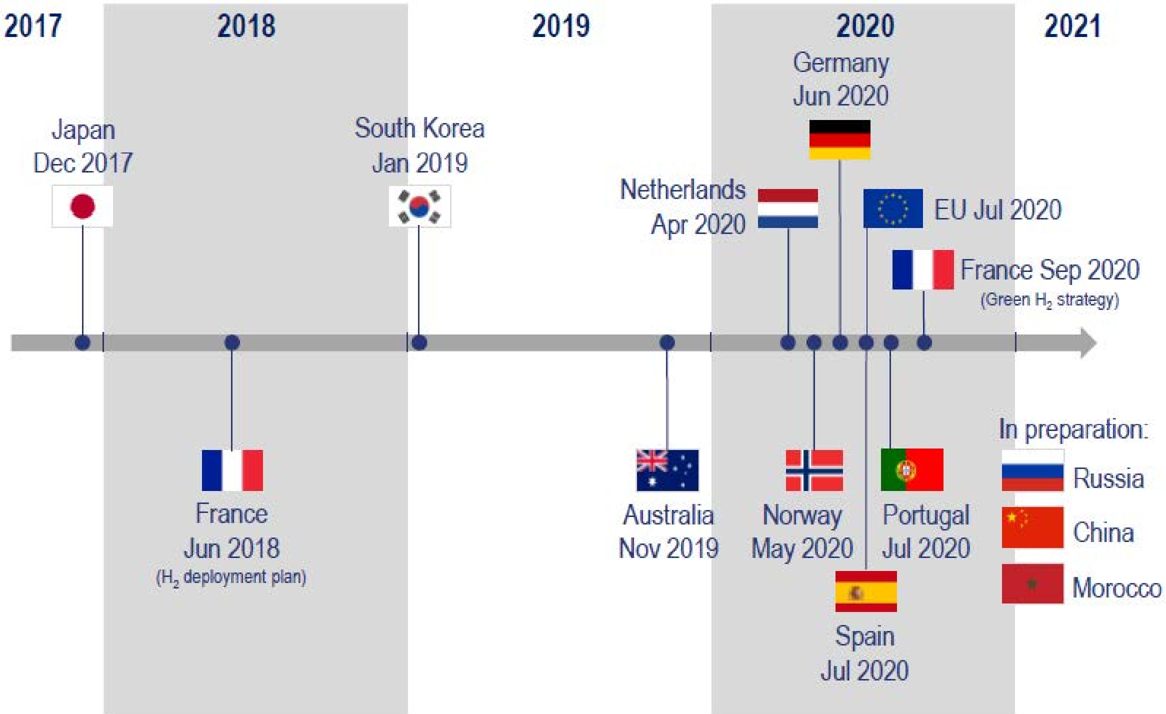


Source: Arup

2.4 Global policy action

There is a growing acceptance of the role that hydrogen can play and increasing support at both national and supra-national level. As illustrated in Figure 5, an increasing number of countries are developing hydrogen strategies and policy frameworks, to set out their national ambitions. Japan, a consistent supporter of developments in hydrogen, led the way with its hydrogen strategy in late 2017 followed quickly by France and later South Korea. A second wave of more recent announcements saw several other European countries entering the fray in 2020, while Russia, China and Morocco are expected to follow soon. A UK National Hydrogen Strategy is to be published around Q3 2021. The EU encourages Member States to include planned hydrogen policies and measures in their National Energy and Climate Plans (NECPs). Furthermore, the Territorial Just Transition Plans and the Recovery and Resilience Plans of EU Member States for phasing out coal, reducing the footprint of carbon-intensive industries and addressing the social and economic effects of the transition towards a climate-neutral economy are now also incorporating the development of a hydrogen economy as one of the potential solutions.

Figure 5 Timeline of some major hydrogen strategy announcements



Source: LBST for the World Energy Council

The strategies, described in more detail in Section 4.2, reflect both the inherent capabilities that these countries display but also their priorities and policy objectives. For example:

- Germany emphasises the contribution that investments in hydrogen could have towards its industrial base and aims to leverage its high calibre science and technology R&D sectors to position itself as a lead provider of renewable hydrogen technology on the global market. However, at the same time recognising that in the long term it is likely to have to import renewable hydrogen produced outside its borders to satisfy demand.

- Australia, meanwhile, is positioning itself as an exporter of hydrogen given its potential to exploit both its natural gas and massive renewable resources to produce and ship hydrogen, much as it does today with fossil fuels.

Each of these nations is trying to maintain its position in the fast-paced environment by setting clear and ambitious targets and policy frameworks. More detail on the policies that have been put forward is provided in Section 4 but fall broadly into two categories:

- **Support for demonstration projects** to provide the evidence base to de-risk commercial deployments; and
- **Wider market support to enable commercial deployment at scale**.

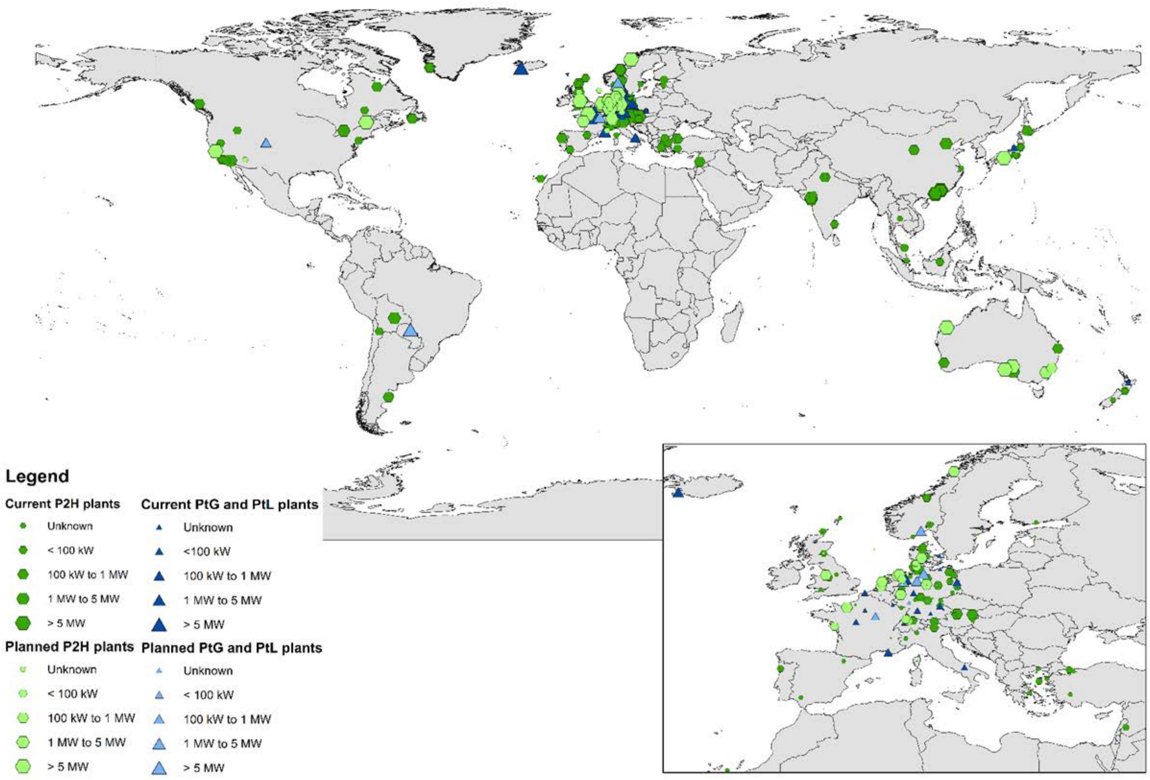
This has led to the realisation of a multitude of projects worldwide, a selection of which is illustrated in Figure 6, which shows power-to-hydrogen (PtH) and power-to-liquids (PtL) projects globally[17]. Figure 7 shows a broader range of hydrogen projects specifically in Europe[18].

Power-to-X (PtX) refers to the conversion of electricity into other forms of energy, where the 'X' can stand for a variety of products (raw materials/energy carriers), processes, technologies and applications. Examples include power-to-gas, power-to-liquid, power-to-fuel, power-to-chemicals and power-to-heat. PtH involves the electrolysis of water and PtL includes the synthesis of liquid ammonia (via Haber Bosch) or e-fuels (synthetic hydrocarbons) via Fisher-Tropsch synthesis.

Each conversion step reduces the roundtrip efficiency of the underlying energy, but advantages of PtX include the storage of energy to decouple power generation (especially intermittent renewables) from its subsequent use. Other benefits, particularly if the power is converted to liquid fuels, are more efficient and less costly distribution of this renewable energy (as liquids) than as the original electricity in high voltage direct current cables. Some sectors cannot be easily electrified, such as aviation which may rely on e-kerosene (a synthetic hydrocarbon power-to-liquid product) to reach decarbonisation.

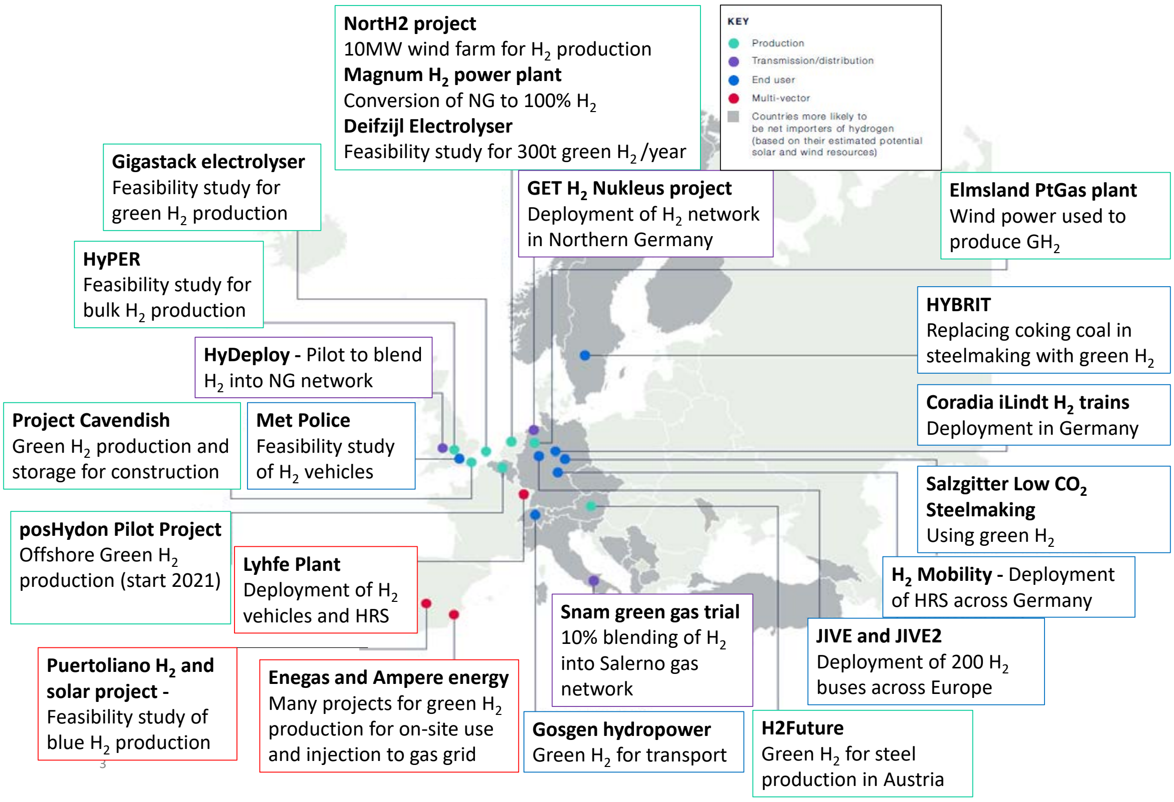
[17] This figure, which is not intended to be exhaustive, was compiled and published in August 2020 and so announcements since then are not included on the map.
[18] Map compiled for Scottish Hydrogen Assessment, December 2020, Arup and E4Tech, https://www.gov.scot/publications/scottish-hydrogen-assessment-report/.

Figure 6 Global PtH and PtL projects



Source: E4tech

Figure 7 Map of hydrogen use projects

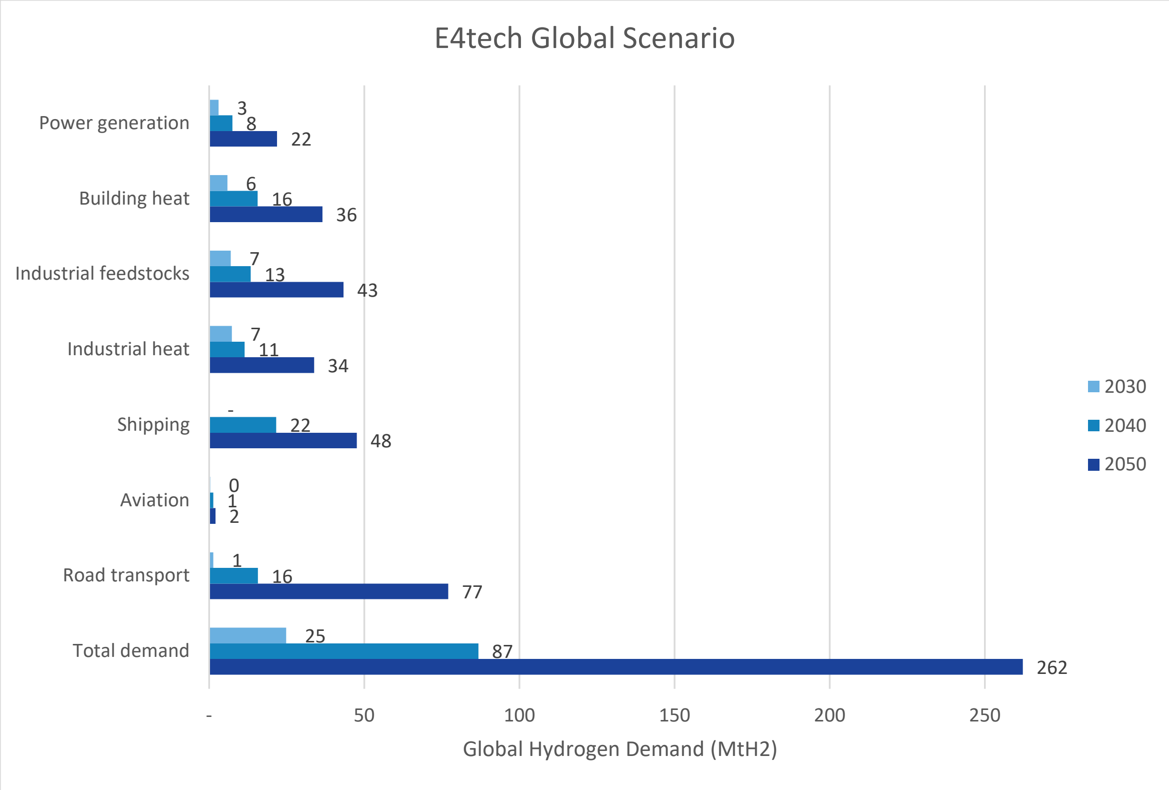


Source: E4tech

2.5 Future market demand and trade

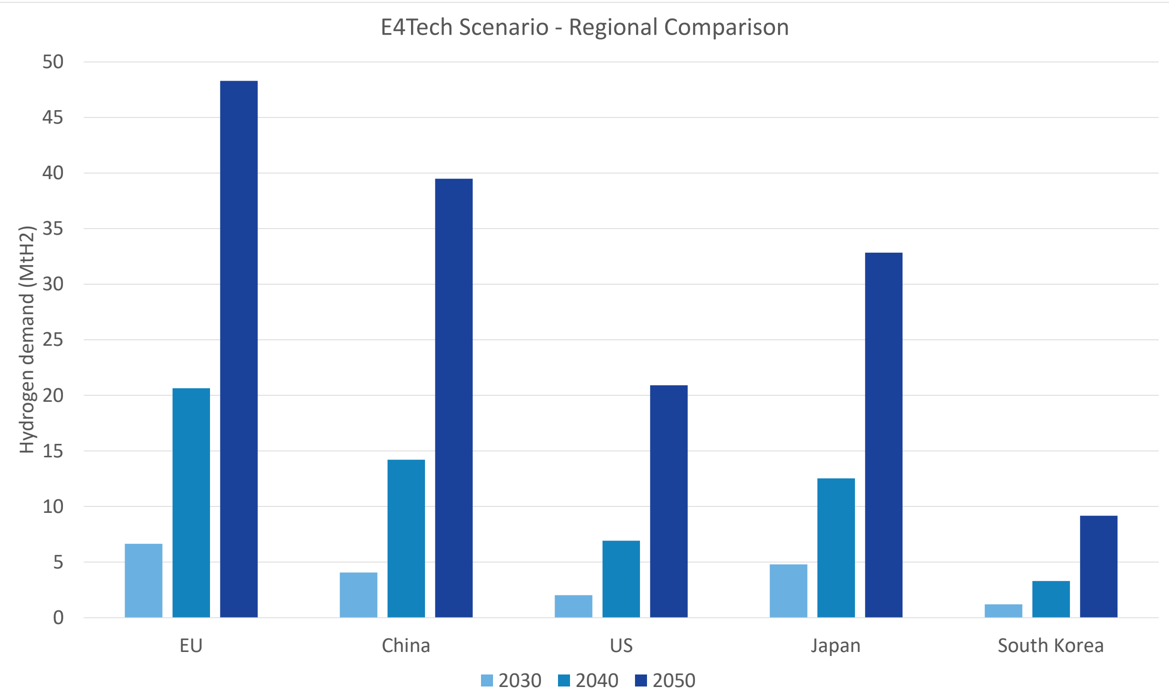
Estimates of future demand for hydrogen vary widely as there is a huge amount of uncertainty as to how a hydrogen economy will develop. In work recently undertaken for a major corporate client, E4tech developed forecasts for future global hydrogen demand based around energy demand forecasts and an assessment of where hydrogen can be used in the energy system (Figure 8). These estimates point to additional and replacement renewable or low carbon hydrogen demand globally of 25Mt/year (835TWh) in 2030 rising to 262Mt/year (8,751TWh) in 2050. Figure 9 shows this global demand broken down into five main regions/countries and shows the predicted hydrogen demand of the EU under the E4tech scenario relative to that for China, the US, Japan and South Korea.

Figure 8 Global hydrogen demand scenario



Source: E4tech

Figure 9 Hydrogen demand split by region/country



Source: E4tech

One of the benefits of renewable energy systems is that they can be built and operated effectively at a distributed level. This contrasts with fossil fuel based systems which out of necessity focus production where fossil fuels are present. However, areas of energy surplus and deficits are starting to emerge and while hydrogen systems can be built in a distributed way, hydrogen can also be used to satisfy a future need for global trade in energy. A future international hydrogen commodity market is in its infancy but could develop rapidly, especially if technologies to cost effectively and efficiently distribute hydrogen are developed (Section 2.3).

Countries like Germany and Japan anticipate a deficit of domestic renewable energy while Australia or Morocco will have a surplus, with hydrogen providing the conduit to trading this energy. For example, energy scarce Japan has secured hydrogen supplies from Australia for the Tokyo 2021 Olympics which is likely to be transported as liquid hydrogen aboard ships. Whether or not a country can be a successful exporter of hydrogen will depend on the delivered cost of hydrogen, considering both the cost of production and the cost of transport. Whether hydrogen is domestically produced or imported will ultimately be driven by economics, but policy could be introduced to ensure the overall supply chains with the smallest GHG emissions are indeed the cheapest. Factors (or combinations of factors) which will affect relative competitiveness of different supply chains include:

- **Access to low cost renewable and other low carbon (e.g. nuclear) energy sources** which will lower the production costs of hydrogen produced via the electrolysis of water;

- **Availability of low cost natural gas combined with the necessary presence of carbon storage infrastructure** (to make the overall process approaching carbon neutrality) which will lower production costs of hydrogen produced via steam reformation of methane;

- **Existence of transport infrastructure** such as pipelines for hydrogen distribution and / or cost-effective means of deep sea hydrogen transport such as cryogenic liquid hydrogen, which would lower transportation costs of imported hydrogen; and

- **Distance of travel between production and demand** – longer distance generally translates into higher transportation costs although different transport media have different cost characteristics over distance (e.g. liquid trucking of hydrogen is cheaper than gaseous over long distances and *vice versa* over short distances).

At present, global hydrogen trade remains in its infancy but several important steps are being taken to promote this, notably the cooperation between Japan and Australia on the delivery via liquid hydrogen carrier of low carbon hydrogen. Assuming that the technological barriers can be overcome, the extent of global trade will largely hinge on the relative competitiveness of different pathways. However, there is a general expectation that with regions, like Central Europe, having significant hydrogen deficits and others, such as the Middle East, with the potential to produce hydrogen cheaply, trade will emerge. The scale of future global trade in hydrogen is, however, difficult to predict. Germany is the only EU country which has set explicit targets in its national hydrogen strategy and has stated it intends to import up to 85% of its hydrogen demand by 2030 and €2 billion is earmarked for import partnerships. Germany has some bilateral relationships with nearby sources to import hydrogen, a Memorandum of Understanding (MoU) with Morocco, a package of measures with Nigeria and initial talks and an MoU with Ukraine.

2.6 Concluding comments

The combination of demand pull resulting from net zero targets and supply push relating to increasing commerciality of hydrogen, combine to form a more compelling story for using hydrogen, beyond the industrial applications where it is used today. Interest in hydrogen as an energy vector is gathering momentum and it now seems more likely to form part of the energy mix both within Europe and globally in countries like Japan and South Korea. While it will not be used in all energy applications, evidence points to hydrogen providing a complementary energy vector alongside electricity and biofuels in certain energy applications.

At the same time, pressure is mounting to decarbonise the industrial sectors where hydrogen is already used as a feedstock such as refining and ammonia production. It has also been shown that hydrogen could play a role in other high carbon industries where it is not currently used, such as steelmaking, leading to carbon reductions.

As a result, the EU, in common with other nations has developed a hydrogen strategy[19] together with a set of policies that support the vision for using hydrogen in the energy and industrial system. This presents both opportunities and risks for the CPs. While the shift to using hydrogen may not be an immediate preoccupation for the CPs, as major European countries announce ambitious strategies for hydrogen, it behoves the CPs, as a minimum, to keep abreast of developments. This will allow them to seize potential early opportunities that may arise and to guard against the impacts of legislative changes which may prove detrimental to their industries. For example,

- **Increasing demand for hydrogen in Europe could present opportunities** for CPs with favourable conditions for renewable or low carbon hydrogen production. Many of the CPs have excellent solar and wind resources while others have access to significant reserves of natural gas and locations suitable for CO_2 storage. Germany has already held initial talks and signed an MoU with Ukraine for a 'Hydrogen Bridge Initiative' which could see the export of hydrogen from Ukraine to Germany via existing pipelines.

- **Global or regional trade in hydrogen** could present opportunities for CPs, notably Ukraine and Georgia with existing natural gas transmission infrastructure as well as access to extensive storage capacity much of which has the potential to be repurposed for use in conjunction with hydrogen.

- **Increasingly tight decarbonisation requirements for industries using hydrogen, such as refining, and ammonia production may put plants in the CPs at risk of being uncompetitive** if they are not able to meet EU targets for the use of renewable or low carbon hydrogen. Conversely, premiums may be paid for these renewable and low carbon products and leveraging local renewable capacity to quickly upgrade plant could put the CPs at an advantage relative to EU counterparts.

- If hydrogen becomes the de facto fuel in certain end use applications, then the CPs will almost certainly have to **adapt their energy systems to incorporate**

[19] https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf. Also relevant is the EU's strategy for energy system integration (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0299&from=EN).

these technologies. For example, if hydrogen becomes the de facto standard for long distance trucking then the CPs may be forced to shift to hydrogen given the interconnected nature of the road network. Trucks which fail to meet the standards set by the EU may not be able to operate and fuelling logistics may become difficult for diesel engine vehicles. Indeed, over the longer term, hydrogen trucks may be the only option available necessitating a shift by all hauliers in the CPs.

Exactly how each CP will be affected by the shift towards using renewable and low carbon hydrogen in the energy system and existing industrial activities will depend on the particular circumstances of that CP. This includes aspects such as the access the CP has to renewable energy generation, the extent of existing natural gas infrastructure and the nature of its industrial and commercial base. These aspects are explored and discussed, together with the implications for hydrogen strategy development in the region, in the accompanying report on the CPs.

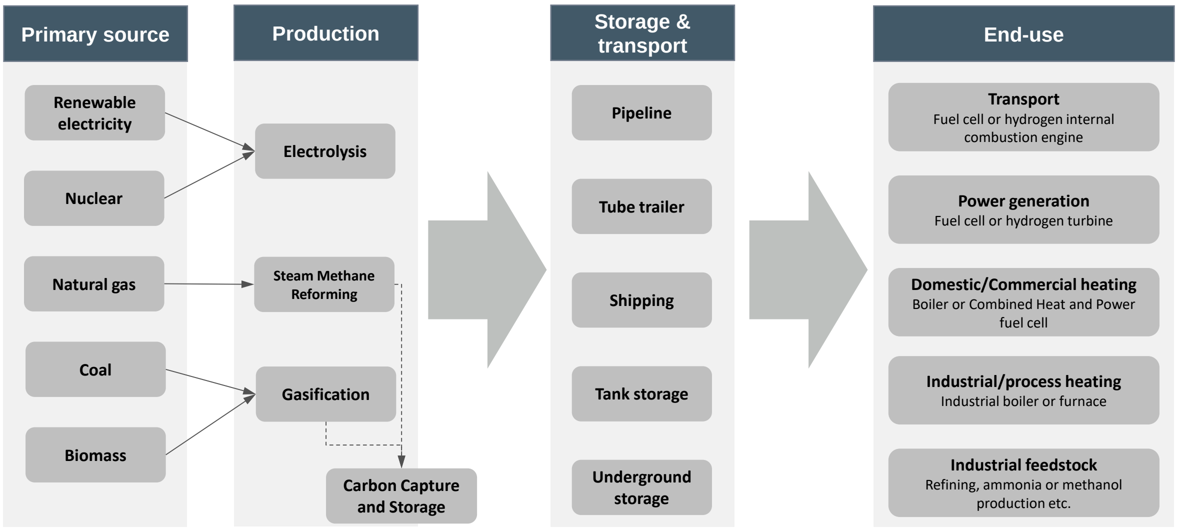
3 The hydrogen value chain

This section provides an overview of hydrogen technologies detailing their technical characteristics, as well as their commercial status and readiness levels, highlighting any particular challenges for full commercialisation. This overview includes technologies associated with the entire hydrogen value chain, encompassing production, storage, transport and end use of hydrogen. We provide indications of the range of production costs from different sources and in different regions while the costs of hydrogen transport and distribution as well as in the relevant end use sector costs are covered in the Economic Analysis Report.

3.1 Introduction

In common with practically all energy systems, the hydrogen value chain can be broken down into three main parts: production, storage and transport, and end use. This is illustrated in Figure 10 and in the following sections each stage of the value chain is described in more detail.

Figure 10 Hydrogen value chain



Source: E4tech

3.2 Production of hydrogen

Hydrogen is currently produced predominantly from fossil fuel sources such as natural gas or coal; we refer to this as high carbon hydrogen as it results in CO_2 emissions. The main production process is steam methane reforming of natural gas (SMR) or gasification of coal. The focus of this study though is on the production of zero and low carbon hydrogen which encompasses three main synthesis routes which are at different levels of technical and commercial maturity:

1. The electrolysis of water using renewable electricity produces ‘renewable hydrogen’ which is sometimes referred to as ‘green hydrogen’. Low carbon electricity, such as nuclear, can also be used in water electrolysis and we include this within the definition of ‘low carbon hydrogen’.

2. Biomass gasification is a process to produce hydrogen from biogenic material; generally speaking we would refer to this as renewable hydrogen as well.

3. CCS can be added to traditional SMR resulting in capture of 90% of the CO_2. We also refer to this as low carbon hydrogen, although it is frequently referred to as ‘blue hydrogen’.

Other less mature technologies for hydrogen production exist. Autothermal reforming (ATR) and partial oxidation are alternative thermochemical processes for hydrogen production and can be used to produce syngas[20] from the same range of feedstocks (fossil fuels or wet biomass). These approaches use oxygen to generate the heat required through partial combustion of the feedstock. These processes can operate at smaller scales and both approaches have similar efficiencies as SMR. Gas-Heated Reforming (also known as Heat Exchange Reforming) is a process enhancement of SMR/ATR in which part of the heat required for the reforming process is supplied by the hot syngas stream exiting the primary reformer.

It is possible to decompose hydrocarbons such as methane through pyrolysis, which produces solid carbon and hydrogen gas. The process involves heating the hydrocarbon to around 1,065 °C in the absence of oxygen (it is a high-volume and low cost refinement of the Kvaerner process). Solid, non-polluting carbon black is produced as a by-product, which once isolated could be collected and sequestered safely over long time periods, used in rubber products or as a colour pigment. The technology to do this is at a very early research stage[21].

Underground, ‘downhole’ coal gasification was originally developed as a method of producing hydrogen and syngas from un-mined coal resources through the underground combustion of coal in the presence of water. The resulting gas mixture has a low energy content compared to natural gas and there are also environmental concerns. However, shale gas reservoirs offer the potential for hydrogen production if coupled with CCS, but detailed analysis of the economic and environmental considerations would be required.

New microwave techniques using renewable electricity and cheap, abundant catalysts such as iron or nickel have been shown to release large amounts of over 98% purity hydrogen from hydrocarbons such as diesel and wax with only solid carbon produced as a by-product. Again, this is at a low technology readiness level.

Hydrogen can also be thermochemically produced using high-temperature heat from nuclear power through the sulphur-iodine cycle which is a three-step reaction, overall splitting water into hydrogen and oxygen.

[20] Syngas is an abbreviation for synthetic gas, which is a mixture of hydrogen, carbon monoxide and sometimes carbon dioxide. Syngas can be produced from many hydrocarbon feedstocks, including natural gas, coal, biomass or some waste sources such as municipal solid waste. Production methods include steam reforming, dry reforming, partial oxidation or gasification.
[21] Weger L, Abánades A, Butler T 2016 Methane cracking as a bridge technology to the hydrogen economy International Journal of Hydrogen Energy Volume 42, Issue 1, 5 January 2017.

Meanwhile, solar to fuels technology harnesses sunlight to split water into hydrogen and oxygen and has been referred to as ‘artificial photosynthesis’. Solar to fuels is an active area of scientific innovation, with potential to lead to a disruptive future process but is currently only a subject of basic research with elements undergoing technological development. There are no current estimates for potential output and questions over ultimate cost and efficiency.

Biological methods have the potential to make a small contribution to the hydrogen economy. Technologies for the microbial conversion of by-products of fermentation to hydrogen are emerging, including the conversion of organic acids to hydrogen using photo-fermentation or microbial electrolysis with the aid of a small amount of electricity (bio-electrochemical systems).

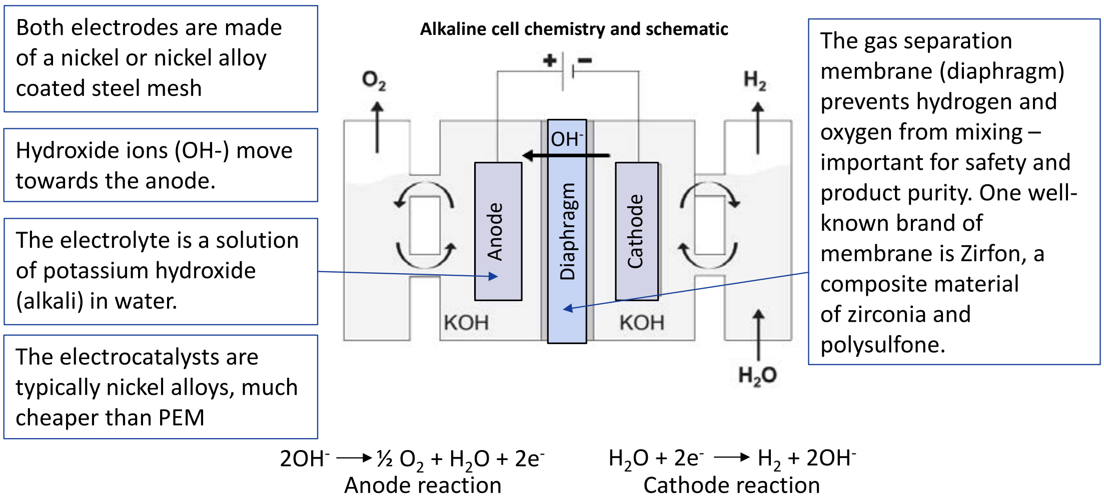
By-product hydrogen is available from chlor-alkali plants or ethylene plants. For example, hydrogen produced as a waste product from the Dow ethylene cracker in the Netherlands is used in Yara Sluiskils ammonia plant. However, the environmental credentials require careful examination.

All of these production methods are at a low technology readiness level and are not discussed in detail in this report. The three main renewable and low carbon hydrogen production methods are outlined in more detail below.

3.2.1 Electrolysis from renewables

In the electrolysis process, water is split into its component elements using electricity and the hydrogen is subsequently separated from the oxygen. Several types of electrolyser exist and are categorised by the type of electrolyte they use. An overview of the function of an alkaline electrolyser is provided in Figure 11 and while the internal workings of other electrolyser chemistries differ, the general principles are common to all. The hydrogen produced is zero carbon and can form part of a carbon-free value chain.

Figure 11 Simplified annotated diagram of an alkaline electrolyser



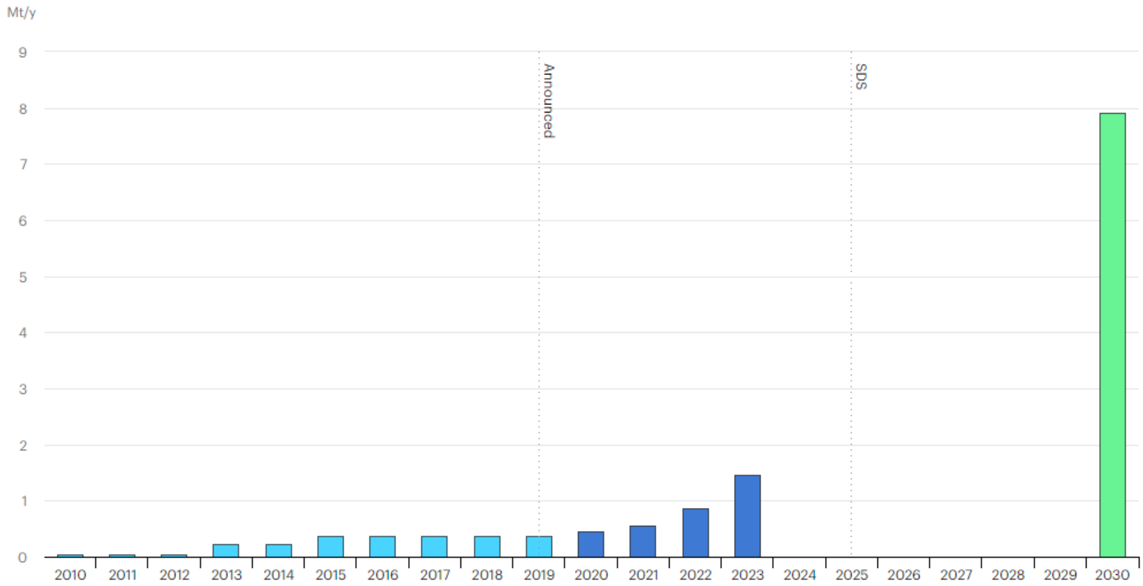
Source: E4tech

The water electrolysis process is rather mature, with large scale deployment of electrolysers first emerging in the early 20th century, but the three main electrolyser technologies are at different stages of development and would all require scaling up to meet forecast hydrogen demand: alkaline (AEL), polymer electrolyte membrane (PEMEL) and solid oxide (SOEL).

AEL is the most established technology and is effective for large scale electrolysis but suffers from poor dynamic response. Alkaline electrolysers use an aqueous alkaline solution for the electrolyte such as potassium hydroxide. They are the lowest cost technology and at present have higher efficiencies than PEMEL (65% and 60% respectively). However, PEMEL has many other advantages such as quicker start-up times and wider operating ranges (better for intermittent renewables), no corrosion, lower operating costs, and higher-pressure hydrogen output. PEMEL is more expensive owing to the catalysts used (e.g. platinum) in the cell stack but has become the most commonly used type of electrolyser. SOEL is the least mature technology and requires high operating temperatures for operation (>600°C) so that it does not require expensive catalysts. SOEL is therefore useful for applications where there is a large amount of waste heat but precludes its use in other applications. SOEL shows the best efficiency of 80% currently but to date there are few, if any, commercial deployments.

The IEA reported that 2020 was a record year for electrolyser capacity additions and many major announcements were made (Figure 12). The IEA's Sustainable Development Scenario outlines major transformations of the global energy system that would be needed to deliver the IEAs Sustainable Development Goals in a realistic and cost-effective way.

Figure 12 Global low carbon hydrogen production, 2010-2030, historical, announced and in the Sustainable Development Scenario, 2030



Source: IEA

The main determinant of renewable hydrogen cost is the cost of the renewable electricity, although electrolyser capital costs are not insignificant. The stack which is the core component at the heart of the electrolyser also needs periodic replacement and / or refurbishment and this also contributes to the overall lifetime costs. Economies of scale in production and learning rates will drive down the capital cost of electrolysers in the future but a critical factor will be reducing the operating costs through reductions in the cost of electricity and improvements to efficiency. The siting location of production facilities is therefore important to potentially leverage lower costs of high-capacity renewable sources as evidenced by the significant projects announced for the Gulf region which has high PV and wind capabilities. However, while the storage and transportation of hydrogen remains costly, the lowest cost value chain is a compromise between production and distribution costs which may favour more localised production in the near term. Although European renewable capacity may be limited, in the short term it will be sufficient to satisfy the lower levels of demand while a hydrogen economy is still developing. Although electrolytic hydrogen in theory can be produced using grid electricity, this can in some countries e.g. Germany be carbon intense and can even lead to the production of hydrogen with CO_2 emissions greater than those in the SMR process. To be considered 'renewable hydrogen' electricity derived from sustainable sources e.g. wind/ PV/hydro must be used.

3.2.2 SMR of natural gas with CCS

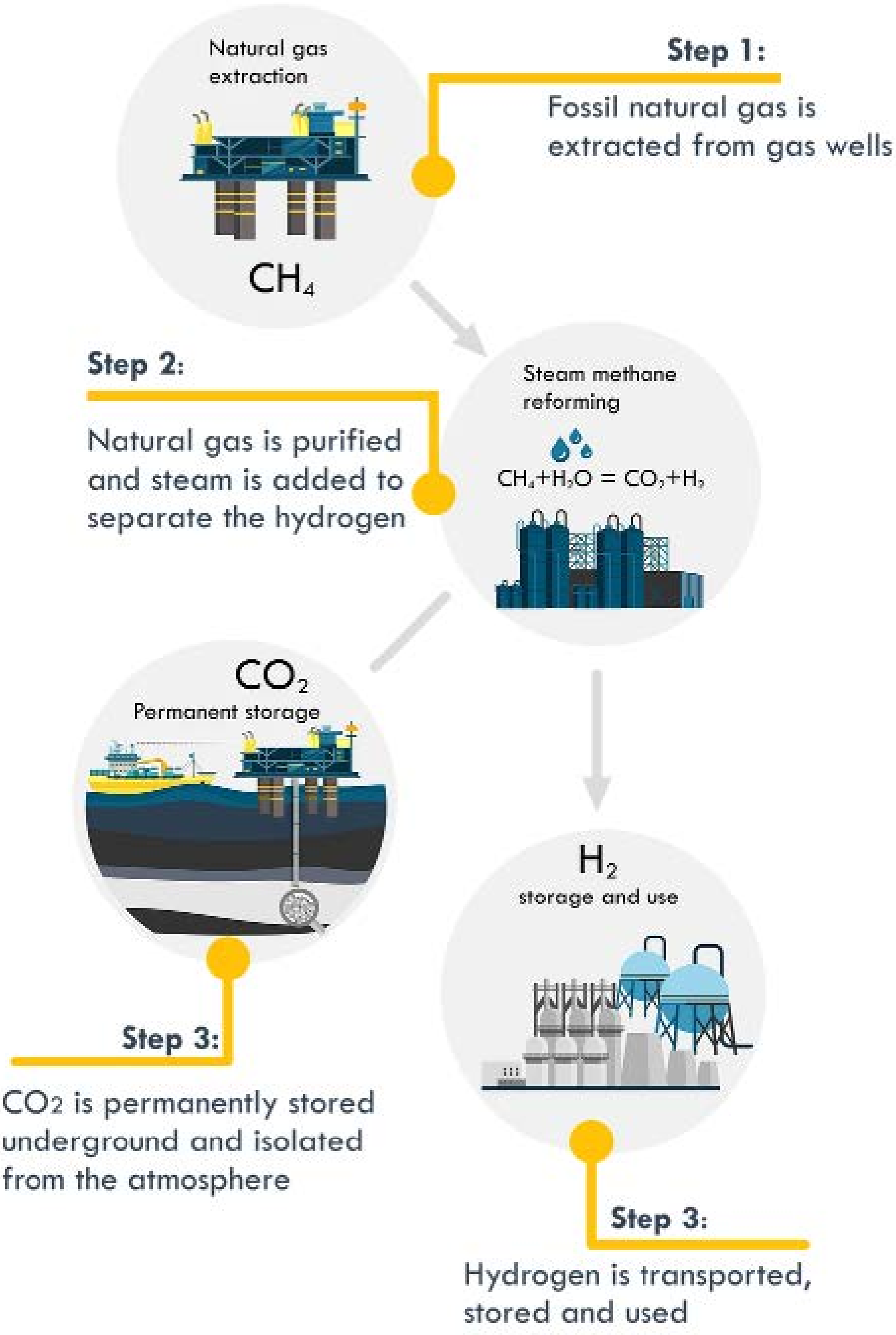
Currently 95% of hydrogen produced globally is from fossil fuels, primarily from natural gas via SMR but also through coal gasification. SMR involves the reaction of natural gas with steam to produce hydrogen and CO_2. In almost all installations today the CO_2 is allowed to escape into the atmosphere (high carbon hydrogen production).

The reforming process results in a concentrated stream of CO_2 so CCS technology could be applied in which case it is often referred to as "blue hydrogen" (in this study, we refer to this as low carbon hydrogen). As only 90% of the CO_2 emissions at best are captured, this is not a zero carbon and therefore long term solution. CCS is also not well developed; as of June 2020, there were only 21 CCS facilities in operation globally including the Snohvit CO_2 storage project in Norway which captures 0.7Mt/year from a natural gas plant[22]. CCS is in development for a wide variety of applications and this will support the reformer plus CCS technology. CCS adds cost to the hydrogen produced so is not commonly pursued, and the delivered cost of hydrogen is currently higher than those supported by carbon prices. This is likely to change with more stringent emission requirements and the potential implementation of carbon prices. It is recognised that this low carbon hydrogen will likely play a key short term role in developing a hydrogen economy and establishing the market for hydrogen until zero carbon, renewable hydrogen becomes cost competitive.

Adding CCS to existing fossil fuel based plants risks prolonging CO_2 emissions from these sites, for example through contributing to their financial viability and has led to concerns over "lock-in" to fossil sources. If the CO_2 from such point sources was to be used as a raw material instead of stored, it is not yet clear how these CO_2 emissions would be accounted but also whether in some regions policy may limit or disincentivise their use. Decarbonised technology such as renewable energy substitution in power plants, or fuel switching in industrial processes are therefore likely to be increasingly used to drive even low CO_2 production towards being carbon-free.

[22] IEA, Energy Technology Perspectives 2020, Special Report on Carbon Capture Utilisation and Storage, CCUS in clean energy transitions, Table 1.1.

Figure 13 Low carbon hydrogen production ("blue hydrogen")



Source: Bellona Europa https://www.frompollutiontosolution.org/hydrogen-from-smr-and-ccs

The cost of hydrogen production from natural gas consists of the cost of the natural gas (price if imported or the cost of extracting and processing natural gas if there is local production) plus a production premium. This premium relates to the process efficiency which is typically around

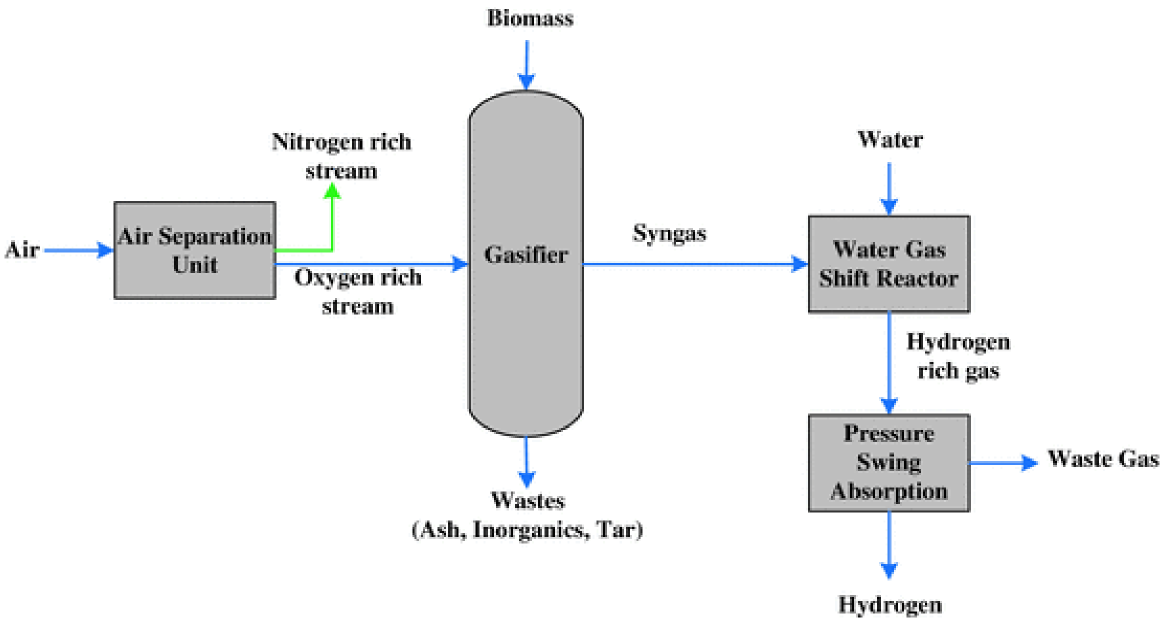
70% (the process is endothermic[23] and may not result in 100% conversion) and the costs of capturing, transporting and storing the CO_2, usually in an underground location.

As with renewable hydrogen, the feedstock costs are the main component of lifetime costs but unlike renewable electricity, the cost of natural gas is likely to increase as carbon pricing becomes more prevalent (it is assumed carbon pricing would be imputed on the unabated CO_2 emissions). In order to mitigate costs, low carbon hydrogen production plants will need to be located as near as possible to cheap natural gas production or import facilities as well as locations for CO_2 storage or use, in order to minimise the high costs of transporting hydrogen and/or CO_2.

3.2.3 Biological routes

Low carbon hydrogen can be produced from biomass (see Figure 14) although this has not been extensively investigated. There are two main routes; dry biomass can be gasified by being heated and combined with oxygen to produce syngas (a mix of mostly hydrogen and carbon monoxide), or syngas can be produced from anaerobic digestion of wet biomass.

Figure 14 Biogenic hydrogen production from gasification



Source: Production of Hydrogen from Renewable Resources [24]

This hydrogen-rich syngas is then purified, e.g. through the pressure swing absorption method, to produce a stream of hydrogen and a stream of waste gases, which include CO_2. This CO_2 is removed and vented or potentially stored (leading to negative CO_2 emissions) or reused to produce synthetic fuels which can displace fossil fuels. The process is carbon neutral since the CO_2 released was previously absorbed by the biomass as it grew, hence

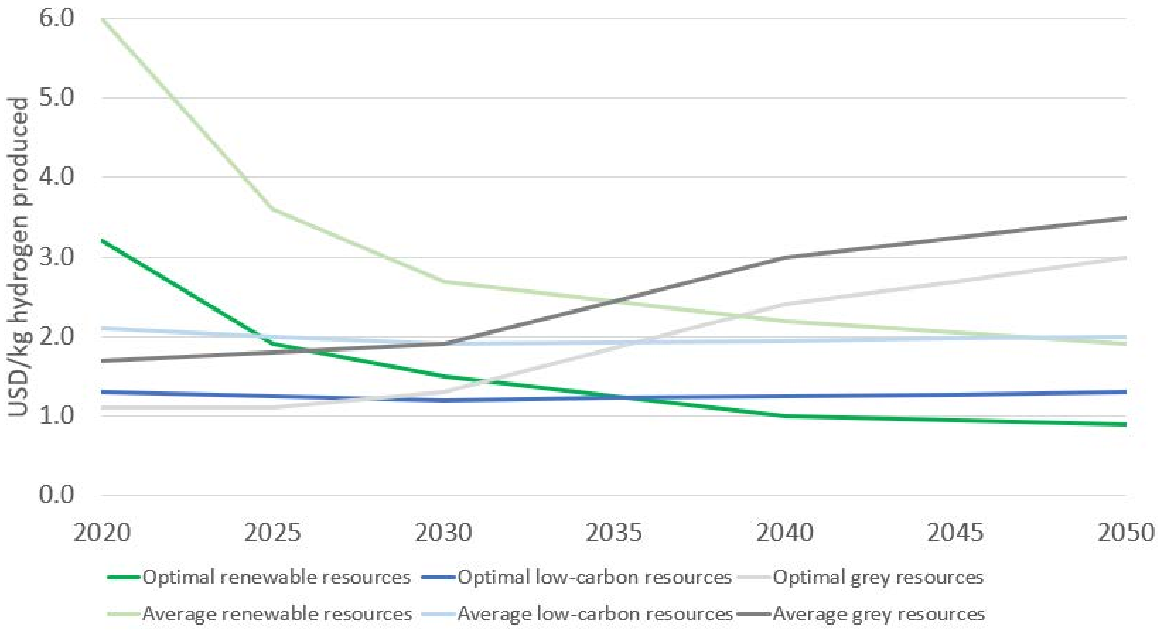
[23] An endothermic process is one which requires the input of heat.
[24] Karellas S. (2015) Hydrogen Production from Biomass Gasification. In: Fang Z., Smith, Jr. R., Qi X. (eds) Production of Hydrogen from Renewable Resources. Biofuels and Biorefineries, vol 5. Springer, Dordrecht.

negative emissions are also achievable if the resulting CO_2 is removed and stored. This process is more costly than SMR (see Section 3.2.4) and relies on a consistent supply of biomass which largely explains why the process has not been extensively explored. Additional concerns arise over the sustainability of the use of arable land for biomass growth over crop growth for food.

3.2.4 Production costs and cost evolution

Hydrogen production costs are critically dependent on the production method and production location, as estimates of future costs vary significantly. However, indicative production costs are provided in Figure 15.

Figure 15 Indicative costs of hydrogen production across different types of location



Source: Path to hydrogen competitiveness: A cost perspective[25]

The cost comparisons shown in Figure 15 across the different production methods and in varying locations are subject to high levels of uncertainty due to the immaturity of low carbon and renewable production routes, the lack of large scale production examples and currently no developed hydrogen markets. It is also hard to speculate on regional differences and so these values should only be taken as estimates as in reality there will inevitably be a large range of production costs. Recognising this uncertainty, it is perhaps more instructive to focus on the factors driving the costs, qualitatively how the routes compare to each other and how they are likely to change in the future. The lowest hydrogen production cost will vary both by time and location, for example electrolysis costs will have a different trajectory depending on the use case and region and the cost of CCS depends on availability, distance and scale.

'Optimal renewable' refers to places with good solar and wind resources such as the Middle East, Chile, Australia. Leveraging this low production cost provides the incentive for global

[25] Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf (hydrogencouncil.com).

hydrogen trading to benefit geographies with lower renewable capacity such as the EU. ‘Optimal low carbon’ refers to areas with particularly low cost natural gas and available CCS such as Russia and this will be one of the lowest cost options for hydrogen production, especially in the short term as renewable hydrogen production develops and scales up. ‘Grey resources’ refer to conventional fossil-based hydrogen production and becomes increasingly uncompetitive everywhere because of the rising cost of CO_2. The referenced study assumes a hypothetical carbon price of US$50 /Tonne CO_2 in 2030 rising to US$300 /Tonne CO_2 in 2050. For reference, the EU ETS price has been steadily increasing since October 2020 and reached a peak value of almost US$50 /Tonne CO_2 in May 2021..

The less mature technologies such as CCS and electrolysis in principle offer greater potential for cost reductions (compared to mature fossil-based routes such as SMR) as hydrogen systems are scaled up. Costs will inevitably fall in time as technologies, manufacturing and operations mature.

3.3 Transport and storage of hydrogen

3.3.1 Transportation

Hydrogen must first be conditioned for transportation into either compressed gas, a liquid or combined with other elements in a hydrogen carrier. In one of these forms it can then be carried in pipelines, trucks or wagons or waterborne vessels, either on inland waterways or the high seas. For hydrogen in its native state either as compressed gas or liquefied, transportation methods are briefly described in Table 2 .

Table 2 Transport methods for liquid or gaseous hydrogen

Pipeline	• Either blended with natural gas or pure hydrogen • Can use existing (retrofitted) or dedicated hydrogen grids • Variety of pressures up to 100 bar • Blending 20% v-v (volume-volume) hydrogen with natural gas can probably be achieved without the need for system modifications and the resulting blended gas will have up to 96% of the energy capacity of pure natural gas • A few dedicated hydrogen pipelines exist, usually in industrial complexes but there is now a plan for a European hydrogen backbone[26]
Truck	• As a gas in tube trailers typically at pressures of between 250 and 500 bar • As a liquid in insulated tanker trailers or rail wagons (gaseous hydrogen is liquefied by cooling it to below −253°C) • The phase preference is often dependent on the distance to be travelled, as the fixed cost of distribution is higher for a liquid value chain (liquefaction requires higher investment and more energy than compression), but the trucking of gaseous hydrogen is more costly due to significantly smaller capacity

[26] https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/.

	• Gaseous trucking is typically the lowest cost alternative for distances below ~300 km and liquid trucking the cheaper option for distances beyond this • Truck distribution of gaseous hydrogen is most common in Europe whereas in the US liquid hydrogen is more common
Ships / barges	• Liquid in vessels similar to LNG carriers (although different liquefaction temperatures will demand technology modifications) • Kawasaki has developed the world's first cargo ship to transport liquid hydrogen, expected to be fully operational in 2021 • Whole container racks of gaseous hydrogen / liquid hydrogen, made up of smaller mobile tank units could be loaded onto ships as cargo which would be beneficial if this were combined with onwards inland transport via road

Source: E4tech

It is expected that natural gas transmission and distribution pipelines will be the lowest cost option in moving hydrogen from production source to end user. The capital costs of building new transmission pipelines or a new distribution network is a significant investment and would only be viable where significant volumes were being transported. However, if the existing network could be converted then much of these costs could be mitigated.

Hydrogen has one-third of the energy density of natural gas at the same compression, but the volume flow of hydrogen can be higher than for natural gas, so the maximum energy capacity of a hydrogen pipeline is up to 80% of the energy capacity it has when transporting natural gas. Operating hydrogen pipelines at less than their maximum capacity gives much more attractive transport costs per MWh transported, as expensive high-capacity compressor stations and their high electricity consumption can be avoided and overcome the increase in fixed pipeline-related costs per MWh. The overall cost of delivered hydrogen gas via pipeline will depend on the ability to retrofit a pipeline, its diameter, the gas pressure and the cost of local electricity for compression amongst other factors.

Consequently, in regions where no existing pipelines exist it is more probable that the other methods of transport would be employed. Although transporting gas overland by truck or rail results in higher cost than pipelines, it offers much more flexibility and lower capital expenditure. In any case, it is entirely possible that end use applications like road transport will require truck deliveries for the "last mile" even if pipelines are used up to that point.

Other technical challenges exist for the distribution of hydrogen such as embrittlement[27] for hydride forming metals and hydrogen-assisted cracking for steels, which affect pipeline and trucking materials and compressor designs. Effective hydrogen infrastructure would therefore require significant capital investment to develop, build and maintain. Another complication is leakage owing to the very small molecule size.

Zero carbon hydrogen will be key to meeting decarbonisation targets, but insufficiencies in the current methods/infrastructure for efficient transportation and storage of large quantities of high density hydrogen are hindering the widespread implementation of the potential "hydrogen economy". The compression or liquefaction of hydrogen while easily reversible, are particularly expensive and energy intensive processes. Liquefaction at −253°C is particularly problematic

[27] Certain metals react with hydrogen to form hydrides which in turn leads the metal becoming more brittle and more at risk of fracture with the associated safety implications.

because of boil-off losses (1-3% per day) and heavily insulated reservoirs with thick or double-walled vacuum-insulated containers are needed. There are also safety concerns surrounding high pressure tanks of hydrogen given its high flammability range (4-75 vol %) and the backup systems required to maintain cryogenic temperatures of liquid hydrogen so distribution of hydrogen in its native form requires dedicated and specialist equipment.

Reversible chemical storage of hydrogen in carrier molecules provides most of the benefits of hydrogen as a fuel while allowing some of the challenges to be overcome. Ammonia can be easily liquefied at moderate temperature and pressure. Liquid ammonia has a very high hydrogen content, 17.8 % by mass, and volumetrically, liquid ammonia has over 50% greater hydrogen content than liquid hydrogen at cryogenic temperatures. Ammonia infrastructure is well established as it is already produced on an industrial scale (186 Mt/year). Ammonia storage and transportation is widely practised with optimised costs and can be scaled up; existing LPG infrastructure can also be leveraged for its distribution. Maturity of the industry means familiar handling and usage procedures exist as well as dedicated international markets. It is a flexible energy carrier that can be used as a direct fuel in a Solid Oxide Fuel Cell (SOFC) or combusted in an ICE/gas turbine with minimal modifications, cracked to produce hydrogen or as is currently the case, sold for its use as a fertiliser feedstock.

Liquid organic hydrogen carriers (LOHCs) absorb hydrogen (hydrogenation) by chemical bonding and release it again (dehydrogenation) when heated to high temperatures at the end use destination. Prominent examples of LOHCs are dibenzyl toluene (Hydrogenious) and methylcyclohexane (Chiyoda). Characteristics are molecule specific but generally similar; the main benefits are easy, safe and proven distribution technologies as liquids under ambient conditions. However, there are many unknowns with these systems; they have a limited energy density (only about 6.2 wt.% hydrogen), dehydrogenation is energy intensive, the requirement to return the carrier molecule to the point of production adds cost and complexity, and no specific infrastructure for them currently exists. The one area where LOHC may have a future use is in the case of combined shipping and long term storage given the ease and safety of store and transporting these liquids under ambient conditions e.g. by leveraging existing/redundant oil distribution technology.

Methanol is another potential carrier, but as a carbon containing molecule, its combustion releases CO_2 which adds complexity to ensure zero net emissions meaning this is often overlooked in light of more preferential alternatives.

3.3.2 Storage

Hydrogen can be stored in much the same ways that it can be transported (compressed gas, cryogenic liquid or carrier molecules), with the chosen method dependent on factors such as the space constraints and the length of storage time required. The volumetric energy density of hydrogen is low relative to fossil fuels (see Table 1), for example:

- The same energy content of cryogenic liquid hydrogen would require 2.6 times greater storage volume than LNG at -160°C; and
- Hydrogen gas requires at best five times more storage volume depending on compression pressure (<700 bar).

This is a particular issue for onboard storage of hydrogen for its use as a fuel where space is a critical factor to avoid loss of cargo and passenger space. An additional issue is that compressed gas and cryogenic liquid hydrogen tanks have fixed cylindrical shapes and so can only be accommodated in cuboid volumes, meaning that they are awkward to transport and may not pack efficiently onto the means of transportation in void spaces. Storage methods are outlined in Table 3.

Table 3 Hydrogen storage methods

Low pressure gaseous storage (100 bar)	• Static steel tanks • Pipelines (linepack) • Short or long term storage • Occurs at industrial facilities or refuelling stations
High pressure gaseous storage (700 bar) (The standard for light duty road vehicles)	• Composite tanks e.g. carbon fibre-wrapped aluminum • High pressure justified onboard to minimise space • Short term storage within fuel cell vehicles
Cryogenic liquid storage	• Double-walled vacuum-insulated containers • Low temperature justified onboard to minimise space • Very few liquefaction plants exist • Possible short term storage within fuel cell vehicles but this is less technologically developed than compressed hydrogen gas as a fuel
Underground gaseous storage	• Low pressure • Salt caverns, porous rock formations • Long term storage • Inter-seasonal energy storage
LOHC storage	• Bound in LOHC and stored in liquid tanks • Long term storage • Inter-seasonal energy storage

Source: E4tech

The cost of storing compressed hydrogen at low pressure in tanks is expected to be more expensive than underground storage on a per kg basis but not all regions will have access to suitable rock formations to accommodate underground storage. Europe has the potential to inject hydrogen in bedded salt deposits and salt domes, with a total storage capacity of 84.8 PWh, of which 42% belongs to Germany. This is followed by the Netherlands and the UK with 10.4 and 9.0 PWh of hydrogen, respectively.

Liquefied hydrogen storage has higher capital and operational costs than compressed hydrogen but as it has a higher volumetric density it is more likely to be used when space is a key concern e.g. to transport hydrogen on ships. However, currently very few liquefaction plants exist, and liquid hydrogen infrastructure is much less advanced than that of gaseous hydrogen. Hence, even if in the long term the use of liquid hydrogen is envisaged over gaseous hydrogen, initial applications such as demonstrating the use of hydrogen as a marine fuel are being proven with compressed hydrogen gas first.

3.4 Efficiency of transformation steps

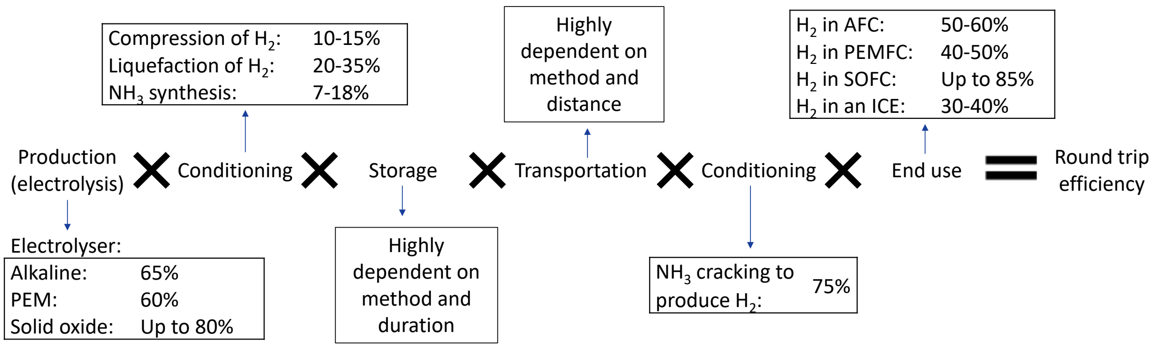
Every transformation step in the hydrogen supply chain has associated energy losses and reduces the efficiency of the overall chain, so roundtrip efficiency must include the entire chain of processes including production, conditioning, transportation, storage and utilisation. Conditioning hydrogen is energy intensive and compression or liquefaction have by far the largest efficiency losses if hydrogen is to be distributed in its native form. Compression typically requires 10-15% of the lower heating value (LHV) of hydrogen depending on the pressure to be reached and liquefaction requires 20-35% of the LHV energy content of hydrogen. Additionally, storage of hydrogen as a cryogenic liquid suffers from unavoidable boil-off losses. The boil-off rate strongly depends on the tank size because the surface area to volume ratio affects the heat influx. As an example, if liquid hydrogen were to be used as a marine fuel, boil-off losses could be kept below 0.5% of the total energy content of the vessel capacity per day.

The high aggregated efficiency losses for the distribution of either compressed gas or cryogenic liquid hydrogen may make liquid hydrogen carriers such as ammonia or LOHC seem comparatively favourable as a means to store and transport high density hydrogen at scale. The energy penalty of converting hydrogen to ammonia and back is roughly the same as liquefying hydrogen, but liquid ammonia is much less costly than liquid hydrogen to store for half a year (€0.4 /kg NH_3 compared to €12.5 /kg H_2) and at least three times less costly to ship on sea or on land. Therefore, in principle, renewable hydrogen can be produced in areas with low cost electricity from high renewable capacity, converted to ammonia, shipped elsewhere, reconverted to hydrogen (or used directly) and be economically competitive with domestically produced hydrogen, bypassing the challenges of distributing hydrogen.

The efficiencies of each of the end use cases for hydrogen are discussed by application in Section 3.5 where relevant (e.g. not applicable when considering hydrogen as a chemical feedstock). One example for varying efficiencies in the end use application is for the case when hydrogen is to be used as a fuel. Modified hydrogen ICE typically have efficiencies of 30-40%, but fuel cells have higher efficiencies which in turn is highly dependent on the type of technology (PEMFC 40-50%, alkaline FC 50-60%, SOFC 50-65% and up to 85% if waste heat is used). However, it is possible that next generation hydrogen combustion engines will approach the overall efficiency of a fuel cell.

Figure 16 shows some indicative efficiencies of different steps in the hydrogen value chain. These individual efficiencies must be multiplied across the value chain to obtain the overall round trip efficiency for a chosen pathway.

Figure 16 Some indicative efficiencies of each step in the hydrogen value chain



3.5 Present and potential uses of hydrogen

3.5.1 Industry

Direct substitution of high carbon hydrogen feedstocks

Most hydrogen today is used as a feedstock for industrial processes such as ammonia synthesis, oil refining and food manufacture (see Figure 2). As a feedstock, it is the molecular properties of hydrogen that are required rather than its energy carrying ability (when it is viewed as a hydrocarbon substitute e.g. as transport fuel). In these feedstock applications, high hydrogen production costs are required (regardless of any decarbonisation incentives) and are unavoidable (not just tolerated) as they are no longer in comparison with fossil fuels.

The widespread adoption of hydrogen as an energy carrier will develop from initial applications which have the most favourable economics, and these existing demand sectors where fossil-based hydrogen feedstocks can be replaced by zero or low carbon hydrogen (in potentially increasing quantities) offer such opportunities as little adaptation to the specific process technology would be required to facilitate the transition.

For example, renewable hydrogen could be used in ammonia synthesis to produce lower carbon fertilisers, or in refining to deliver lower carbon transport fuels in line with regulations included in Renewable Energy Directive (RED) II. Due to the ease of transition (from direct substitution), these are likely to be the first uses for clean hydrogen through which the development of the surrounding infrastructure will enable the subsequent proliferation of clean hydrogen into complementary applications by starting ‘virtuous cycles’.

While direct substitution offers short term industrial decarbonisation opportunities, the applications detailed in more detail below, will likely be adopted on a longer timescale as the use of hydrogen provides an alternative to the current approach and so require a reconfiguration of plant and process technology.

Methanol / olefin production

Conventional methanol synthesis involves reforming natural gas or coal with steam to produce syngas which is then converted to methanol. The use of fossil fuels for methanol synthesis is convenient because methanol is a carbon containing molecule, so a carbon source is required. However, alternative methods for methanol production are emerging which negate the use of hydrocarbon feedstocks by decoupling the hydrogen and carbon sources. These processes can therefore use renewable or low carbon hydrogen and to minimise the overall carbon footprint, the CO_2 used should be sourced from sustainable processes e.g. direct air capture (DAC). The independently sourced H_2 and CO_2 can then be converted to syngas via the reverse water gas shift reaction, and subsequently converted to methanol using the same conditions as for methanol production from fossil sources.

Alternatively, direct methanol synthesis involves the direct reaction of H_2 with CO_2 through catalytic synthesis and so unlike conventional synthesis does not proceed via syngas. This technology is being developed by Carbon Recycling International[28] which claims this process gives enhanced selectivity towards methanol and has a reduced overall energy consumption compared to the conventional process.

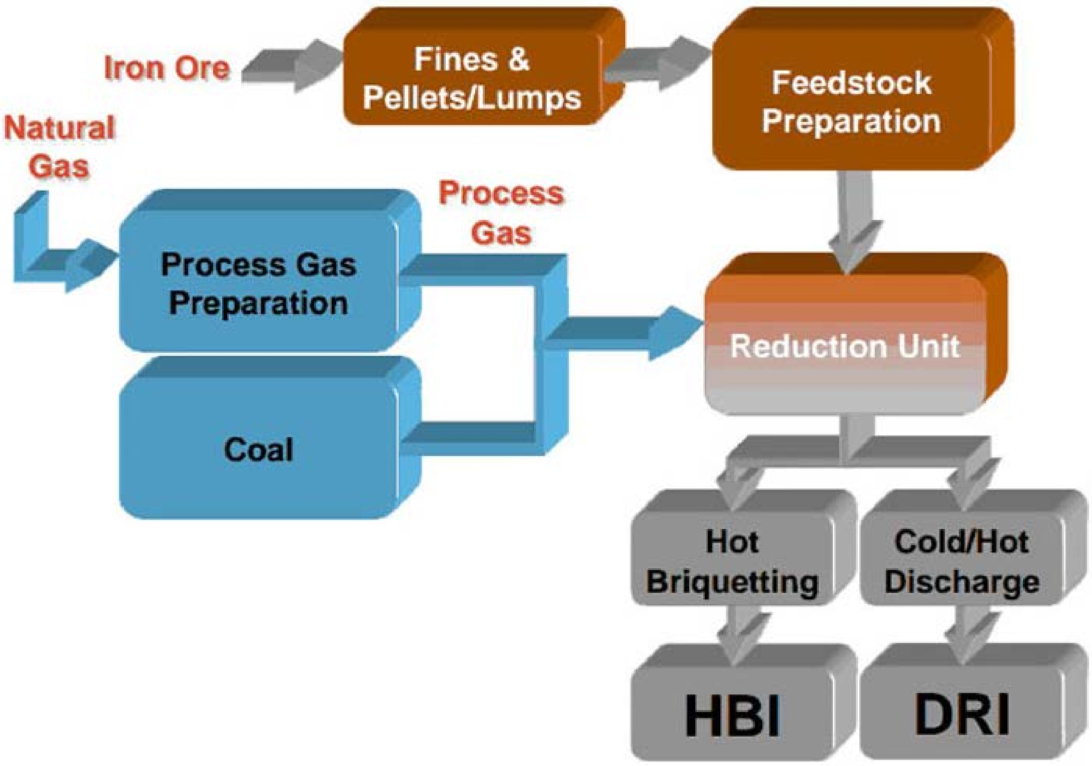
Steel production

Fossil-free steel is produced using HYBRIT technology which replaces the coking coal traditionally needed for ore-based steelmaking, with fossil-free electricity and hydrogen. In a HYBRIT pilot plant, hydrogen produced from the electrolysis of water is used to reduce iron ore to make direct reduced iron (DRI) (see Figure 14 below), also called sponge iron and no fossil CO_2 emissions are produced during production. Hydrogen can also be introduced into a blast furnace/Basic Oxygen Furnace (BOF) to improve the efficiency of the process by acting as an additional reagent. Using HYBRIT technology, SSAB (Europe's largest iron ore producer) aims to be the first steel company in the world to produce fossil-free steel (by 2026) and as a whole be practically fossil-free by 2045. A pre-feasibility study in 2016 concluded that fossil-free steel, given then current electricity and coal prices and the cost of CO_2 emissions, would be 20-30% more expensive but decreasing electricity prices and the increasing cost of CO_2 emissions (under EU ETS) means fossil-free steel will, in the future, be able to compete in the market with traditional steel.

SSAB is also converting the blast furnaces to electric arc furnaces at its industrial steelmaking production sites in Sweden and Finland. Fossil fuels used in rolling mills and heat treatment plants will be phased out throughout the company. Sweden has unique conditions for this kind of project, with good access to fossil-free electricity, the highest-quality iron ore and a specialised, innovative steel industry.

[28] https://www.carbonrecycling.is/.

Figure 17 Overview of direct reduction process types[29]



Unlike in materials synthesis in refineries where a portion of fossil fuel activities can be displaced by renewable hydrogen, its use in steel production requires major modifications to a whole plant so is likely to be a preferred application once the hydrogen economy has matured and there are fewer risks associated with adopting a new technology.

Other industrial applications

Hydrogen could also be used as a source of heat in industrial processes particularly where a high flame temperature is beneficial. Possible applications that have been considered include lime and cement production where high temperatures and significant input energy are required. Whereas coal, pet coke or gas are used today, hydrogen could be used as a substitute for these fossil fuels reducing the overall carbon footprint although this is not the most favoured option, at least in the short term.

Hydrogen can also be used in the production of medium or low-grade heat, replacing natural gas from the grid where it is used today in applications such as chemicals, food production and textiles. Electrification is expected to be an important heat source for this type of application but where natural gas infrastructure exists and is being replaced by, or blended with hydrogen, this may be a cost-effective solution.

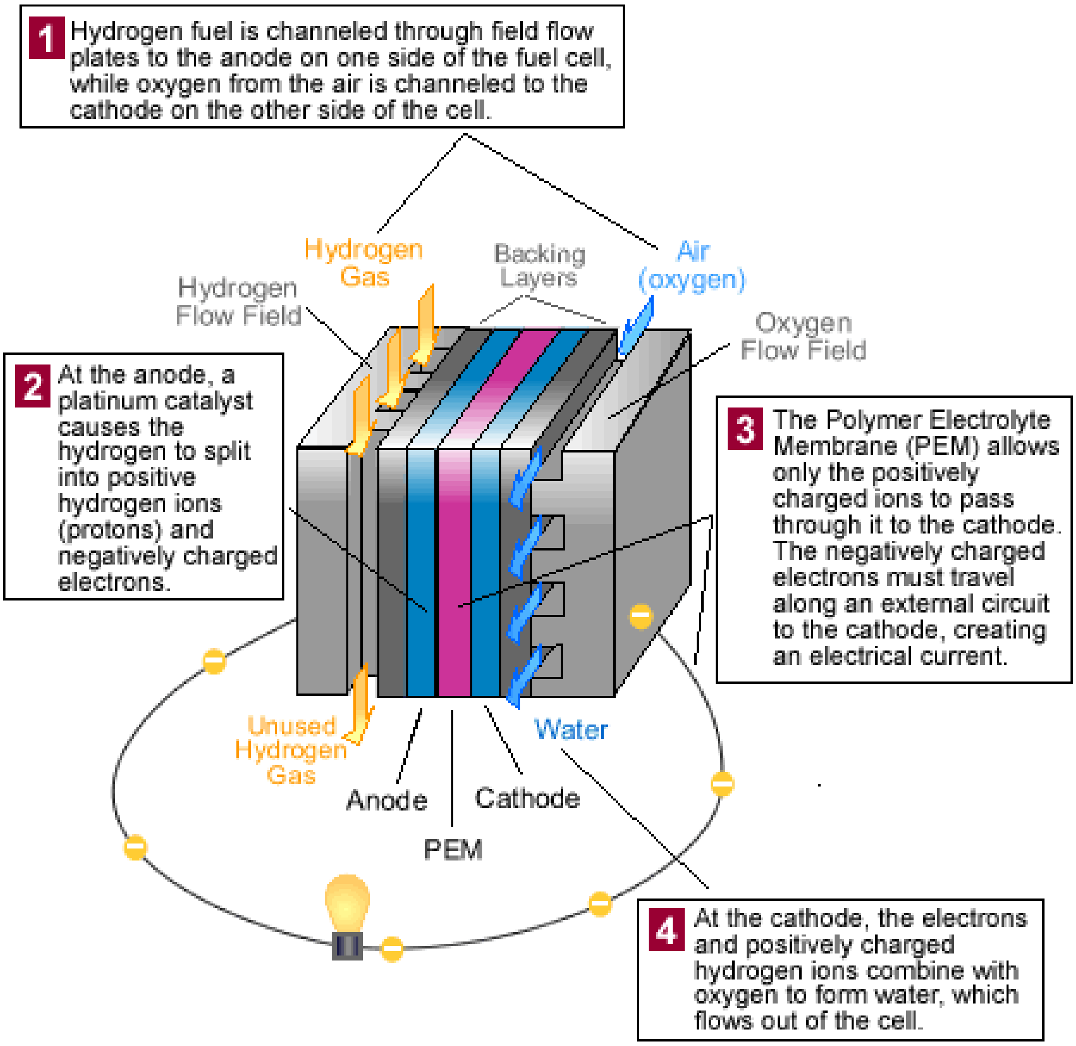
[29] https://www.metallics.org/dri-production.html.

3.5.2 Transport

Vehicles

Fuel cell electric vehicles (FCEV) use hydrogen as a fuel and convert it to electrical energy in a fuel cell (see Figure 18).

Figure 18 Diagram of a Proton Exchange Membrane fuel cell



Source: https://www.fueleconomy.gov/feg/fcv_PEM.shtml

Proton Exchange Membrane Fuel Cells are the most common and extensively researched type of fuel cell for transportation applications due to their compactness, favourable power-to-weight ratio (high power density) and low operating temperature (80°C) allowing them to start quickly. FCEVs can have common power trains with battery electric vehicles (BEVs) and benefit from being zero emission both from a greenhouse gas and air quality perspective. Overall, powertrain efficiency at around 60% (tank-to-wheel) is relatively high compared with the ICE of fossil-fuelled vehicles (30 – 35% efficient). **FCEVs compete with BEVs with the main advantages being range (500 km+ is likely to be achievable) and refuelling time**

which is roughly comparable with gasoline or diesel refuelling. The current constraint is the availability of hydrogen refuelling stations (HRS) at which hydrogen FCEVs could refuel.

Almost all road passenger vehicle automotive manufacturers have had hydrogen vehicle programmes at one time or another, mostly with a fuel cell focus although some have investigated hydrogen ICE. Development in passenger cars has been led by Toyota which now offers its Mirai saloon car for sale on a commercial basis in many countries. In the passenger vehicle market, a number of studies[13] have shown passenger FCEVs to be most likely to compete where range and refuelling times play a critical role. This tends to be larger classes of vehicle (e.g. SUVs) and / or fleet vehicles which have high annual utilisation rates.

Hydrogen-fuelled vehicles are expected to have further advantages over battery vehicles in heavy duty commercial applications such as buses and trucks. Both range and refuelling times are critical to making technology choices within these sectors and at present hydrogen is considered the most suitable carbon-free transport fuel for heavy duty trucks. A significant number of fuel cell bus trials have been completed or are ongoing, involving a wide range of vehicle manufacturers. Truck trials have been undertaken by Toyota in California, while Hyundai has begun delivery of fuel cell trucks to what is probably the world's most ambitious programme in Switzerland (Figure 19). As described in 5.2.2, this trial involves the eventual supply of as many as 1,000 trucks of different sizes to the Coop supermarket group together with a network of HRS. Fuel cell trucks are also being supplied to a number of users in Japan to coincide with the Olympic Games.

Figure 19 Hyundai Xcient fuel cell truck

Source: Hyundai

Challenges with electric vehicles include the limit on the global capacity to produce the Li-ion batteries required. Bloomberg has predicted that by 2028 there will be 1.1 TWh of Li-ion batteries produced. Taking an average of 50 kWh per BEV this allows for the production of 22 million BEVs per year. However, there are currently 100 million cars produced each year and demand for EVs is predicted to rise. Additionally, this only considers battery power for cars, not other applications such as trucks, maritime transport or grid-balancing.

Another concern is safety; a 100 kWh lithium-ion battery could cause a significant accident/fire as a result of all the stored energy and can give off toxic gases if damaged. These safety concerns would be slightly mitigated by future development of lithium-air batteries as oxygen does not reside in the battery itself (though there will probably need to be an oxygen tank onboard and these may not be able to be built on a large enough scale).

Cobalt and lithium are key components in the cathode of current lithium-ion rechargeable batteries. Cobalt is both scarce and expensive and the cost of cobalt (which reached an all-time high of $95,250 in March 2018) may make the mass production of >100 kWh batteries prohibitively expensive. There are also ethical concerns, as currently 60% of the world's cobalt is mined in the Democratic Republic of Congo where child labour still exists. There are also concerns surrounding the large scale use of lithium; large amounts of drinking water are used in lithium extraction and extraction techniques are becoming more energy intensive as lithium demand rises. At the end of their vehicular lifetime, batteries should be ideally reused or at least recycled to create a closed-loop system, and this is a growing market. Research into the use of second-hand batteries is looking at ways to reuse batteries in new technologies such as home energy electricity storage. Smelting processes can also be used to recover some of the expensive raw materials.

Trains

The use of hydrogen in trains is also being explored with ongoing trials in Germany of trains built by Alstom employing fuel cells supplied by Hydrogenics (see Figure 20). Similar trials are being undertaken in the UK and Japan where existing railway vehicles are being converted to use hydrogen fuel cells. Where train routes have already been electrified, hydrogen is unlikely to be competitive, as these routes can already be zero-carbon if a renewable source of power is used. However, in various parts of the world there are large portions of track that are not yet electrified and for some circumstances, conversion of diesel trains to hydrogen-powered trains may be less expensive and feasible than electrification because they do not require massive track overhauls and the existing diesel trains can be retrofitted.

Figure 20 Alstom Coradia iLint fuel cell train

Source: Alstom

Ships

The use of hydrogen to power ships is also under consideration with a number of trials underway to test their efficacy over short ferry routes. Projects in Norway[30], Scotland[31] and California[32] are all carrying out trials of seagoing ferries while fuel cells have also been tested on inland waterways in places like Germany[33].

For longer deep sea routes, liquid hydrogen may be an option for the main propulsion although hydrogen-based fuels (e-Fuels, see section 3.5.6 below), such as ammonia may be better suited to these applications. However, hydrogen could play a non-propulsion role on large vessels, especially cruise ships, where the energy demands of the hotel part can be supplied by fuel cells, replacing the current polluting auxiliary diesel generators.

[30] Norway's hydrogen powered car ferries https://www.rivieramm.com/news-content-hub/news-content-hub/norwayrsquos-first-hydrogen-powered-car-ferries-take-shape-55559.
[31] Scotland's hydrogen powered ferry in Orkney https://www.heraldscotland.com/business_hq/18789377.scotland-trial-worlds-first-hydrogen-powered-ferry-european-marine-energy-centre-orkney/.
[32] California's HFC ferry https://ggzeromarine.com/projects/.
[33] German HFC barge https://www.est-floattech.com/worlds-first-hydrogen-tug-in-kiel-with-ess-from-est-floattech/.

Aircraft

Hydrogen is being considered as a possible aircraft fuel in conjunction with fuel cells, particularly if the challenges of how to store high density hydrogen onboard can be overcome. Examples include Airbus targeting the use of renewable hydrogen to fuel its future zero emission aircraft through its ZEROe programme and HY4, a small passenger demonstration aircraft with a range of <1,500 km and an 80 kW motor. Airports are a possible ‘hub’ location for centralised hydrogen production given the plethora of localised possible uses for renewable hydrogen which would boost the economic case for hydrogen-fuelled aircraft. It is possibly more likely that this renewable hydrogen is combined with CO_2 (either captured from point sources or from the air via DAC) and via Fischer Tropsch synthesis are converted to a mixture of liquid hydrocarbons which are further processed in a hydrocracker to produce e-kerosene for aviation fuel.

3.5.3 Heating

Hydrogen can be used for space and water heating either blended with or as a substitute for natural gas. **Blends of hydrogen in natural gas up to a 20% volume-volume basis have been evaluated with the conclusion that this would not require any modification of the gas appliances** (see HyDeploy case study in Section 5.2.4)[34]. However, the greenhouse gas emissions benefit is limited given the low volumetric energy density of hydrogen, meaning that higher concentrations of hydrogen are being tested all the way up to 100%[35]. As explained in Section 3.3.1, the maximum energy capacity of a hydrogen pipeline is up to 80% of the energy capacity it has when transporting natural gas under the same compression. Therefore, if hydrogen is blended into existing natural gas on a 20% volume-volume basis, the resulting blended gas will have up to 96% of the energy capacity of pure natural gas.

Initial indicators of 100% hydrogen trials have been positive, suggesting relatively little modification of the gas network would be required and that very similar appliances could be used. Key considerations include the potential embrittling of steel pipework as well as the design of pumps, compressors and valves which can need modification to cope with the smaller molecule size.

Where pure hydrogen is available, this can either be combusted in boilers similar to those found in domestic and commercial properties today or used in stationary fuel cells that produce both power and heat in a combined heat and power (CHP) configuration. Existing gas boilers are expected to be able to cope with up to a 20% blend without modification but beyond that new appliances would be required. Hydrogen-ready models are already commercially available, and it is anticipated that these could be installed as part of the normal replacement cycle.

Fuel cell-based heating systems have been successfully trialled in Japan, albeit with natural gas as a fuel, and the country now has in excess of 150,000 such units in operation (see Figure 21). However, it should be noted that fuel cells require very high levels of hydrogen purity which presents challenges where hydrogen is delivered through a network where safety regulations are likely to require the use of odorants to allow rapid leak detection.

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[34] https://hydeploy.co.uk/hydrogen/.
[35] H100 project in the UK (https://www.sgn.co.uk/about-us/future-of-gas/hydrogen/hydrogen-100).

Figure 21 An example of a domestic Ene-Farm CHP unit in-situ

Source: https://earthbound.report/2017/08/11/why-have-i-never-heard-of-the-ene-farm/

While hydrogen could, in principle, be used off-grid in a similar way to Liquid Petroleum Gas (LPG), the cost of transporting and storing hydrogen is likely to make this uneconomic except under a certain specific set of boundary conditions, e.g. where fossil fuel costs are already very high and where environmental concerns are paramount, e.g. in the Arctic. Consequently, it is generally being considered where a gas network is already present.

It has been shown that hydrogen heating can be cost-effective relative to electricity-based solutions, especially where a highly developed gas network already exists, and may be a more effective form of heat for existing housing stock where insulation is poor (and difficult to ameliorate) or where housing density makes retrofitting with heat pumps difficult. Hydrogen networks, like gas networks, have one further benefit compared with electrical heating and that is the ability to store energy within the network and respond rapidly and effectively to changes in demand (known as linepacking). Hydrogen can also be stored in locations such as salt caverns or porous rock formations which can help to balance the inter-seasonal heating needs which vary considerably across the year.

While renewable hydrogen could be used in heating systems, it is more commonly expected that cheaper low carbon hydrogen from natural gas would be used in the first instance. Renewable hydrogen will likely be reserved for higher value applications like transport, where high purity hydrogen is required for use in conjunction with PEM fuel cells.

3.5.4 Power generation

Gas turbines are inherently fuel-flexible and can run on a variety of fuels that contain hydrogen using concentrations from 5% to ~95% by volume. The use of hydrogen as a gas turbine fuel has been demonstrated commercially, but there are differences between natural gas and hydrogen that must be considered (such as difference in combustion properties) to use hydrogen properly and safely in a gas turbine. Gas turbine manufacturers have set a target of being able to offer gas turbines capable of burning 100% hydrogen, but the challenge is to do this without compromising efficiency, start-up times, and emissions of NOx. Gas turbines can be upgraded to operate on renewable hydrogen/ blends even after extended service on traditional fuels, i.e. natural gas, but not all gas turbines will prove suitable for retrofit modifications to enable hydrogen combustion, in part or in whole. At low levels of hydrogen (up to 20% by volume), no changes to the fuel system or combustors are required, according to Siemens. Siemens has hydrogen capability at various levels across its gas turbine portfolio from 4 MW to 567 MW.

Technical challenges for the use of hydrogen fuel in gas turbines include having to avoid auto ignition in the fuel premix zone due to hydrogen's high flammability and flashback (where the flame moves from its desired position in the combustion and back towards the fuel injectors). As hydrogen has a higher flame temperature than natural gas, NOx emissions will be higher with hydrogen if no additional measures are taken.

Hydrogen can therefore be used to generate grid power using hydrogen turbines and could prove to be a viable solution for providing consistent power to the electricity system, allowing more effective integration of intermittent renewables. Hydrogen-powered combined cycle power plants could not only provide firm generation but also a variety of grid support services including spinning reserve, frequency response and voltage support (see illustration of a hydrogen turbine in Figure 22). It is argued that such power plant would provide inertia in the system rendering it more stable and secure.

As with heating, it is generally considered that in the short-term, low carbon hydrogen would be used in power generation over renewable hydrogen as it is generally lower cost. The roundtrip inefficiency of using electricity to produce hydrogen and then converting it back into electricity is poor, and so the benefit of being able to use a lower cost feedstock could make such a route for power generation more attractive (Figure 15). Such an approach represents an alternative to using combined cycle gas turbine (CCGT) plant in combination with post-combustion CCS. Pre-combustion carbon capture is arguably more cost-effective than post-combustion on the basis that SMR / ATR (auto thermal reforming) provides a more concentrated stream of CO_2 than is found in CCGT flue gas.

Figure 22 Ansaldo hydrogen turbine

Source: Ansaldo

In Japan, a project to demonstrate the use of blended hydrogen imported from Brunei became operational in 2020 at a refinery in Kawasaki City[36]. A large scale project has also been announced in the Netherlands which would see an existing CCGT plant being transitioned to blended hydrogen[37] using Mitsubishi Hitachi Power Systems technology.

Fuel cells could be used for grid power generation but are generally seen as less cost-effective than hydrogen turbines and provide fewer benefits (e.g. fuel cells cannot provide system inertia). Fuel cells have been shown to be an effective way of delivering distributed, off-grid and backup power although most of the demonstrations to date have seen the use of natural gas-based fuel cells.

3.5.5 Storage and sector coupling

One further potential application for hydrogen is in energy storage and system balancing. Much of the renewable electricity generation potential globally is intermittent and non-dispatchable and requires flexibility in the system in order to incorporate it. System flexibility can be delivered through storage, demand side response and greater interconnectivity, which can ensure that differences in load and generation in different regions balance out. The most

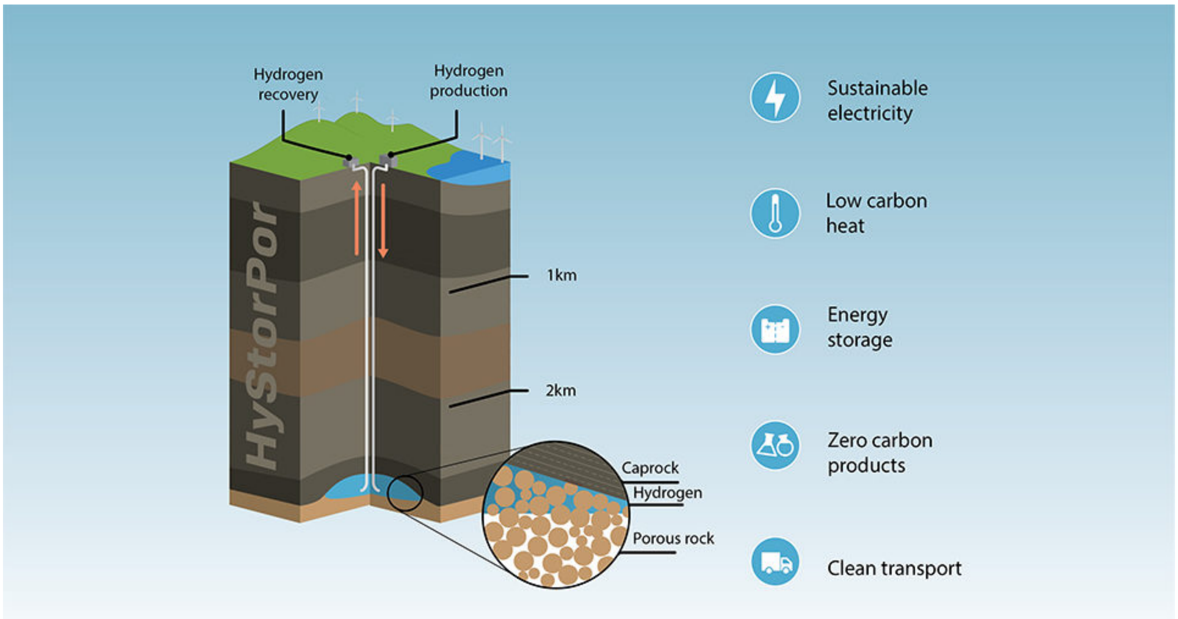
[36] https://energy.economictimes.indiatimes.com/news/oil-and-gas/japans-chiyoda-says-hydrogen-pilot-project-begins-to-fuel-power-plant/76624736.
[37] https://www.powermag.com/mhps-will-convert-dutch-ccgt-to-run-on-hydrogen/.

cost-effective solution for flexibility is likely to consist of a mix of these different measures, with hydrogen providing a possible means of storage or of demand side response, ramping hydrogen production up and down to take account of the instantaneous needs of the network. Increasing storage capacity can obviate the need for network capacity investment and vice versa, with the mix being selected depending on which is more cost-effective. Flexibility could also be provided by hydro plants in locations which have those resources, e.g. in Norway where 95% of electricity production capacity comes from hydropower plants. Additional flexibility is provided today through the provision of fast start-up peaking plant, usually in the form of open-cycle gas turbines. Hydrogen turbines could be used to replace existing gas turbines in these applications.

System inertia is another area where hydrogen thermal plant could be used to provide electricity system stability and security. This is currently assured through thermal plant including gas CCGT, nuclear and coal plant. In some countries, e.g. France which derives about 70% of its electricity from nuclear energy, system inertia is not likely to be a problem, but in others hydrogen turbines could take the role currently fulfilled by CCGT.

Hydrogen can be stored in many ways and at different pressures as discussed in Section 3.3.2. For the long term storage of energy on possibly an inter-seasonal basis e.g. to complement fluctuating energy demands between summer and winter, hydrogen storage in salt caverns or within porous rock formations, such as the HyStorPor concept in the UK (see Figure 23) has been investigated. This would allow very large quantities of hydrogen to be stored at relatively low cost and in a much wider set of locations.

Figure 23 The HyStorPor concept



Source: University of Edinburgh

Converting excess electricity into hydrogen through the application of PtH would couple the power and gas networks creating a more integrated energy system, allowing for energy to be stored and delivered flexibly across multiple sectors.

3.5.6 e-Fuels

A further application for hydrogen is in the production of electrofuels (e-fuels). These e-fuels are produced using electricity from renewable energy sources to make renewable hydrogen, which is then combined with CO_2, ideally from DAC but also biogenic sources, to produce synthetic hydrocarbons. Producing “drop-in” fuels that can be easily introduced into existing fuel networks in this way may seem appealing, but e-fuels have a number of disadvantages:

- Costs are high;
- The process is energy intensive leading to low efficiency;
- Fuels are not “clean” (i.e. they still produce CO_2 emissions at the point of use);
- If a waste CO_2 stream from fossil sources (point sources) is used, this could lock-in emissions producing technology and would preclude the achievement of net zero emissions; and
- If biogenic sources are used as the carbon source, there are sustainability concerns over land use re-allocation.

However, for some very hard-to-abate sectors like long distance marine or air transport, e-fuels do offer a promising alternative to fossil fuels due to their high energy density as in these applications tank space is at a premium. CO_2 from biogenic sources or DAC would be net zero, so combined with renewable hydrogen may represent a more scalable route to sustainable aviation fuel such as e-kerosene or marine fuel such as ammonia or methanol.

Hydrogen can be also reacted with either carbon monoxide or carbon dioxide to produce methane (i.e. synthetic natural gas (SNG)) in a process known as methanation. Thermocatalytic methanation is more efficient than photocatalytic methanation, but both are possible. SNG can be mixed and used interchangeably with natural gas in all applications and can be either liquefied (LNG) or compressed (CNG) for distribution. For example, CNG could be used in the gas grid or LNG could be used as a marine fuel.

3.6 Concluding comments

As a number of studies have shown, including the Hydrogen Council’s cost competitiveness report[13], for example, hydrogen could be competitive with other low carbon solutions over a large number of value chains. In some cases, it is expected to even be competitive with fossil fuels within a relatively short time frame (2030), although structural challenges will need to be overcome for hydrogen to realise its promise.

Sectors where hydrogen or its derivatives could be effective include:

- **Heavy duty transport** where many demonstration projects are underway.
- **Heavy industry** such as steelmaking in addition to the replacement of high carbon hydrogen in existing industrial processes.

- **Heating** where existing natural gas grids are already present.

- **Energy storage and transport** of energy over long distances. This has the benefit of facilitating energy trade and can also help with the integration of renewable generation which will increasingly require the deployment of inexpensive storage capacity.

- Thermal **power generation** or stationary power from fuel cells is also a promising area.

The efficiency of converting electricity or natural gas into hydrogen as well as the challenges associated with onboard storage and hydrogen delivery mean that the overall costs of hydrogen remain high. However, technology challenges have largely been overcome and the focus now is shifting to industrialisation of production which will allow cost reductions to be achieved, ensuring hydrogen's competitiveness relative to alternatives.

Hydrogen requires some major infrastructure changes, which in turn necessitates strong commitment from national and regional governments. This commitment is now in evidence, with many countries committing to hydrogen strategies, suggesting that the tipping point for hydrogen may have been reached.

4 Hydrogen policy frameworks and instruments

This section provides a review of hydrogen activities across Europe, supplemented where appropriate by information from other international countries. We provide an overview of the likely future landscape by outlining the current and planned policy frameworks being employed or being proposed at EU and national level, to incentivise the deployment of hydrogen. While policies already exist to support the use of low carbon fuels more generally, hydrogen-specific targets and support mechanisms are still nascent, but these are expected to expand to support the published hydrogen strategies. The review of national level policies includes an assessment of how hydrogen is being treated within the Member State NECPs, including investment support for hydrogen equipment and projects. We also outline hydrogen strategies at national and EU level which articulate a vision for the use of hydrogen as part of the decarbonisation agenda.

The measures, programmes, initiatives and policies provide insights into the range of actions that could be taken by the CPs if they decide to move towards using hydrogen as part of their energy system. To this end, the section also provides an overview of EU funding mechanisms that might become available to the CPs in pursuit of any hydrogen strategy that they may wish to pursue in the future.

4.1 Policy

4.1.1 Objectives

While the primary objective of policies to support hydrogen is decarbonisation, this is not the only aim. Other important drivers include the need to improve air quality by reducing particulate and other emissions, especially from the road transport sector[38], and economic development, through the establishment of hydrogen-related activities. The development of hydrogen technologies and systems offers opportunities for economic development in at least two ways.

Firstly, hydrogen technology manufacture and systems integration represent markets in their own right which if hydrogen takes off globally could grow into significant opportunities. **Hydrogen as part of industrial strategy features heavily in the hydrogen roadmaps** set out by countries like Germany, Japan and South Korea. In addition, the EU undertook a study of the region’s capabilities in this area under the auspices of the FCH-JU (The Fuel Cells and Hydrogen Joint Undertaking)[39]. Secondly, the use of hydrogen to reduce or eliminate carbon emissions from industrial production may allow these products to attract a price premium from buyers willing to pay extra to meet their corporate goals. A good example of this is IKEA which has been actively trying to source low carbon plastics.

[38] During the combustion of any fuel in an internal combustion engine, nitrogen and oxygen present in the air combine to form NOx, which when emitted contributes to the formation of fine particles and ground level ozone. The World Health Organisation has estimated this fine particulate matter caused over 4.2 million premature deaths worldwide in 2016 as a result of respiratory diseases, while the ozone formed adversely affects ecosystems and agricultural crops.
[39] FCH-JU ‘Value Added of the Hydrogen and Fuel Cell Sector in Europe’ study September 2019.

In recognition of these considerations, the analysis in the remainder of this section considers climate policy, environmental policy more generally and industrial policy.

4.1.2 EU Policy timeline for hydrogen related developments and legislation

The EU decided on a vision for its energy system in 2015 with the Energy Union Strategy, which the 2019 Clean Energy Package aimed to turn into action. Both the Green Deal (Section 4.1.3) in late 2019 and the EU Recovery Plan in 2020, updated this vision through higher climate ambitions. These entail both the revision of existing legislation and the definition of a new regulatory framework which in turn will have to be nationally implemented and transposed into law by Member States. These developments all offer many opportunities for clean hydrogen e.g., through subsidies to support its introduction.

The Governance Regulation outlines the framework for the EU's energy policy and sets an EU trajectory to reach Energy Union Objectives. It sits alongside the latest version of Member States' National Energy and Climate Plans (NECPs), released in summer 2020, which set out the framework by which they will integrate climate and energy objectives, targets, policies, and measures for the period 2021 to 2030. In these, hydrogen technologies are quasi-systematically considered and will steer national policy for the period 2021-2030 to reach EU's 2030 energy and climate targets.

There are several actions mentioned under the EU Hydrogen Strategy which are expected to be translated into **new legislative proposals** including:

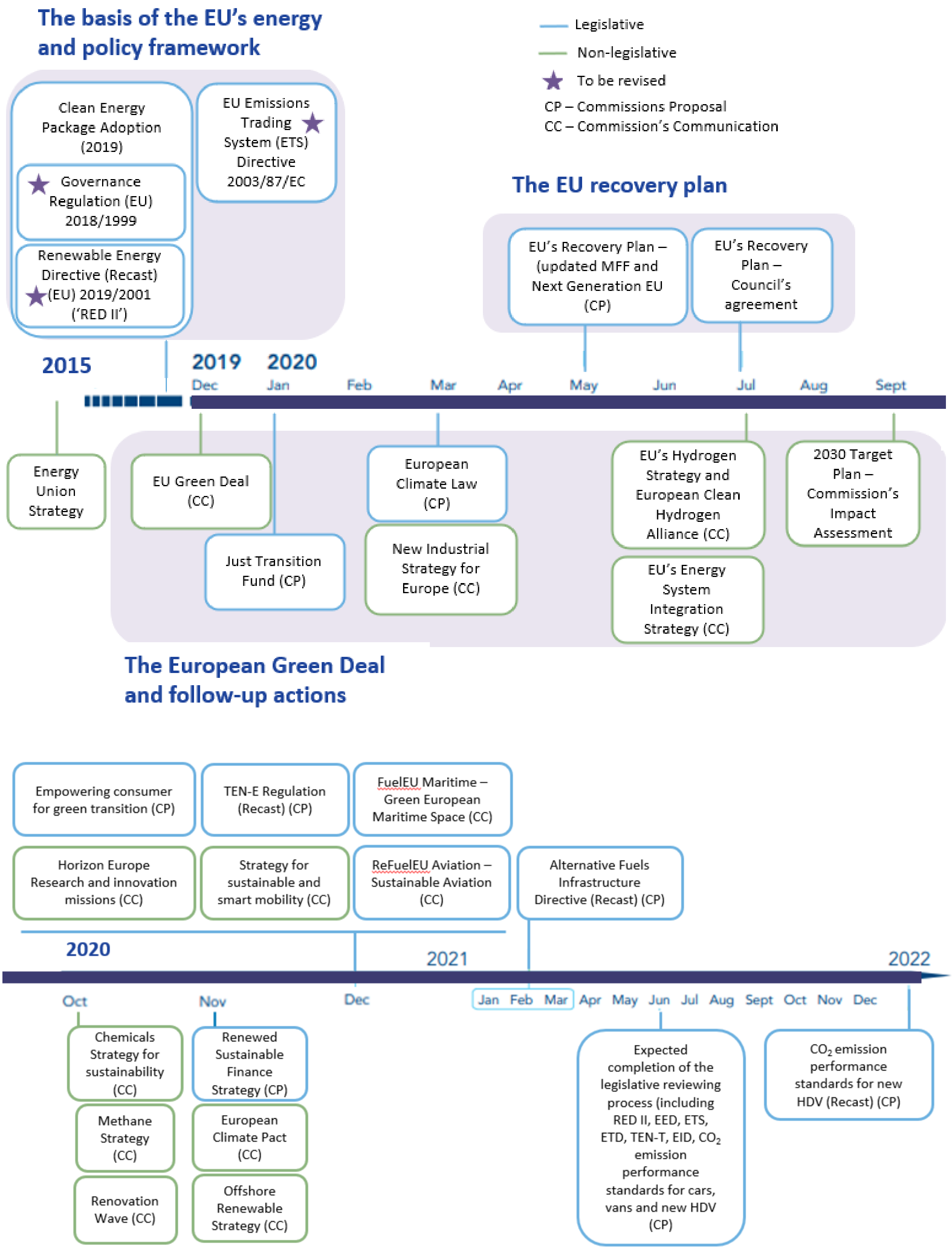
- Introduction of both a common **low-carbon threshold**/standard for the promotion of hydrogen production installations based on their full life cycle GHG performance;

- Introduction of comprehensive terminology and European-wide criteria for the **certification of renewable and low carbon hydrogen** (by June 2021) i.e., guarantees of origin; and

- Review of the legislative framework to design a competitive **decarbonised gas market** to be fit for renewable gases (2021) i.e., the gas *acquis* reform.

The development of an integrated hydrogen market is important and could include the development of a common regulatory framework and standards, as well as support mechanisms to reduce risk and coordinate the development of critical infrastructure. The basis for the EU energy policy framework is set out in Figure 24.

Figure 24 EU Policy timeline for hydrogen related developments and legislation



4.1.3 The European Green Deal

The European Green Deal (the Deal) was announced in December 2019 by the new European Commission and is a policy roadmap designed to represent the EU's new growth strategy towards greener pathways with targets for 2030 and 2050. The key features of the European Green Deal are shown in Figure 25. It provides a unifying umbrella under which other policy initiatives can be viewed, even if many of these were in existence before the Deal was envisaged or established. It outlines the investment tools needed to realise its climate objectives as well as the financing instruments available and has been used as a key funding channel .

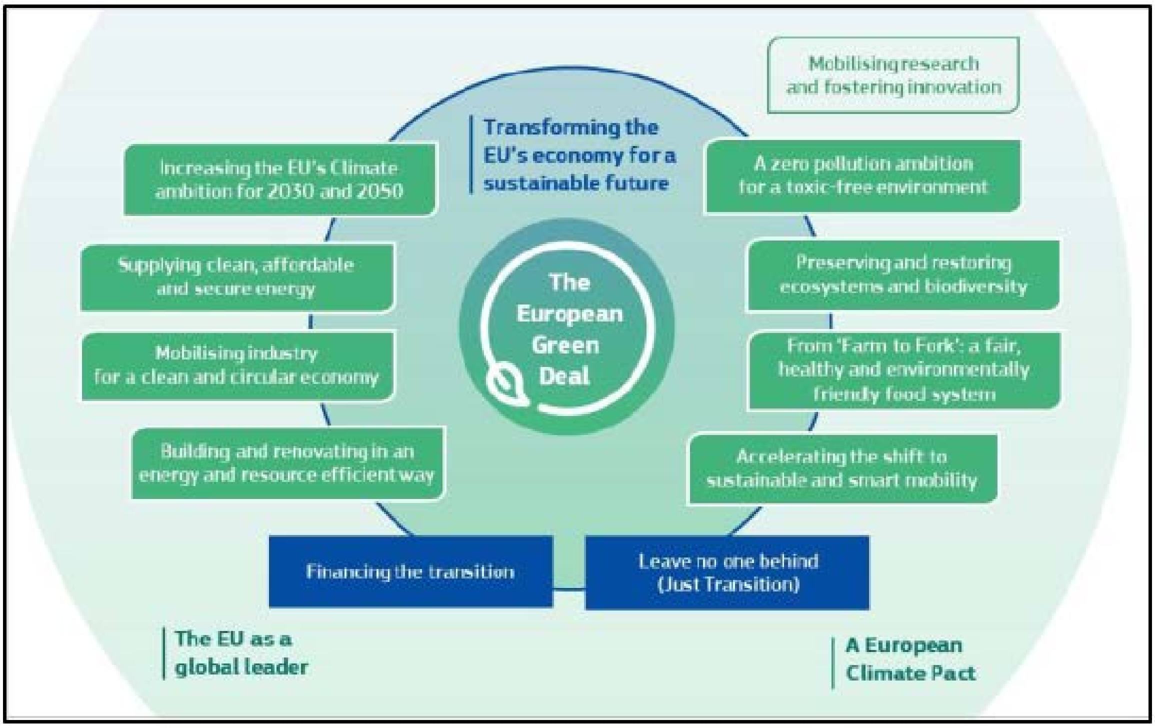
The Deal aims to introduce **a political and legislative framework to reach climate neutrality by 2050** and provides the strategy and means to achieve this objective. Under it, the Governance Regulation (which outlines the framework for the EU's energy policy) will be amended, and its climate ambitions will be reinforced, through the European Climate Law (ECL). Among many initiatives incorporated in the Deal, the ECL is expected to have greatest impact on the hydrogen industry as it:

- Sets higher greenhouse gas reduction targets for 2030 (from at least 40% to at least 55% by 2030 compared with 1990 levels); and
- Will make the 2050 target for carbon neutrality legally binding in the EU.

Aligning these updated ambitions with current legislation will require revisions to a substantial number of legal acts including, but not limited to, RED II, the Energy Efficiency Directive, which cover sectors offering business opportunities for hydrogen, TEN-E (discussed in Section 4.3.1), and potentially the Emissions Trading Scheme and the Carbon Border Adjustment Mechanism. The proposed revisions are expected to be tabled by the European Commission by June 2021. The adopted acts will likely impact the hydrogen industry and could boost the scaling up of renewable hydrogen, from an increased use of renewable fuels in transport to incentives for stationary hydrogen fuel cell systems, for example.

As mentioned above, the Deal outlines the investment tools needed to realise its climate objectives as well as the financing instruments available. The EU's budget for 2021-2027, originally known as the Multiannual Financial Framework, has been reduced but supplemented by the Next Generation EU (NGEU) recovery fund. These will both be incorporated in the 'EU Recovery Plan' (€1,850 billion) in light of the COVID-19 crisis. This will positively impact the hydrogen industry by providing extra funding under existing legislation (such as InvestEU and the Just Transition Mechanism) and by creating new financial support instruments such as the Recovery and Resilience Facility (Section 4.3.1).

Figure 25 The European Green Deal objectives and approach



Source: European Commission[40]

The European Commission has identified that hydrogen will be a key instrument for meeting the Deal objectives, citing several aspects of the legislation that point to hydrogen's role, including its ability to deliver greater energy system integration. An important pillar of the European Green Deal strategy to achieve a 'climate neutral' Europe is a plan for 'smart sector integration', bringing closer together the electricity, gas and heating sectors 'in one system'; hydrogen is at the heart of this system transformation. Meeting the objective will require increased cross-border and regional cooperation and may require a review of the regulatory framework relating to aspects such as gas infrastructure to accommodate hydrogen (e.g. through the gas *acquis*). Any new framework will be designed to foster the deployment of innovative technologies and infrastructure, such as smart grids, hydrogen networks or Carbon Capture, Utilisation and Storage, and energy storage, as well as enabling sector integration.

Priority areas for technological innovation include clean hydrogen and fuel cells and the Deal will seek to support 'climate and resource frontrunners' that will develop the first commercial applications of breakthrough technologies in key industrial sectors by 2030. This will be integrated with the full range of instruments available under the Horizon Europe programme which is already supporting innovation projects as discussed in Section 4.3. This recognises that clean hydrogen will be pivotal and that it is an area where Europe is already leading.

[40] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640&from=ET.

4.2 Strategies and targets

The European Commission has for some time recognised that clean hydrogen could play a pivotal role in achieving climate neutrality by 2050. The European Commission cemented this intent with the publication of its **Hydrogen Strategy in July 2020**, the high-level characteristics of which are set out in Figure 26.

Figure 26 Key features of the EU hydrogen strategy

Targets and commitments	Key Drivers	Challenges
• 2024: 6GW electrolysis • 2030: 40GW • Establish Clean Hydrogen Alliance to facilitate strategy and build project pipeline • FCH-JU to manage a funding scheme of €1.3bn to accelerate technology development	• Decarbonisation • Green Deal requires "just transition" • Mix of renewable and low carbon hydrogen although renewable is the priority	• Large scale system integration • Cooperation across Member States • Requires critical mass of investment

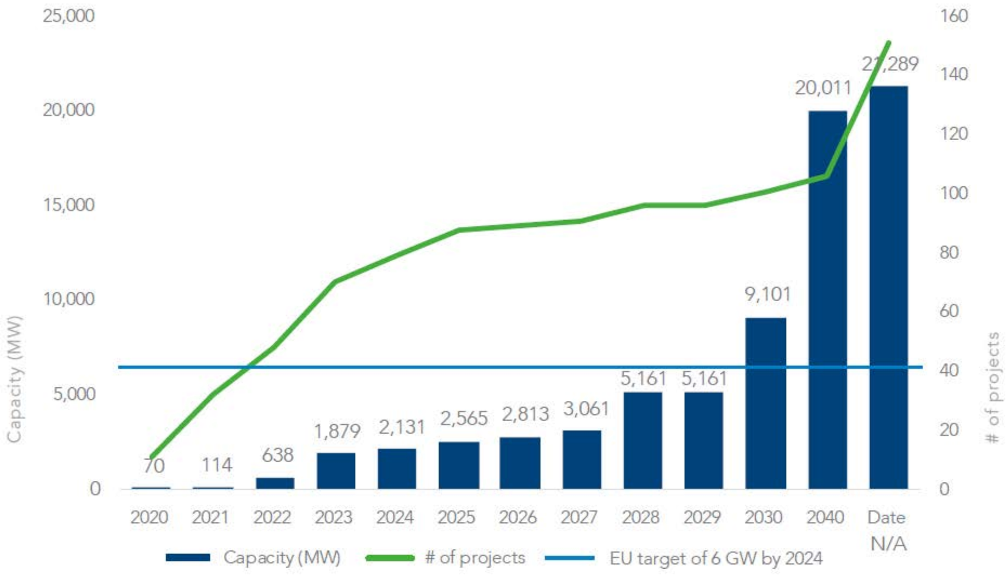
Source: E4tech

Two key production targets for the EU are the roll-out of 6 GW of electrolyser capacity and 1 Mt of production by 2024, increasing to 40 GW of installed electrolyser capacity and 10 Mt of production by 2030. The currently operational and announced list of power-to-hydrogen projects (Figure 27) would reach only 36% of the 2024 objective and only 23% of the 2030 objective. Low carbon hydrogen (e.g. from natural gas with CCS) may provide additional or complementary hydrogen supply, at least in the short term.

Since the total capacity of planned renewable hydrogen projects falls short of achieving the EU targets, a further boost to investment or more reliance on imports of hydrogen from outside the region (see Figure 27) will be required. As discussed below, renewable hydrogen imports form an integral part of the German hydrogen strategy, and it is probable that this will be replicated on a wider EU level.

A key action of the European Hydrogen Strategy is to promote cooperation with the Energy Community CPs, notably Ukraine on renewable electricity and hydrogen. The strategy notes that the Energy Community (and the Transport Community) will have a critical role to play in the promotion of EU regulations, standards and deployment of clean hydrogen, including the roll-out of new infrastructure, such as refuelling networks and the reuse, where relevant, of existing natural gas grids. Participation of the Western Balkans and Ukraine in the Clean Hydrogen Alliance is also to be encouraged under the strategy.

Figure 27 Cumulative planned renewable hydrogen projects by year, 2020-2040, in MW and number of projects



Source: Hydrogen Europe

As highlighted in Section 2, hydrogen strategies have been published at a national level in multiple EU countries and more detail on these is provided in Table 4. National level policies are being discussed to enable the achievement of the objectives in these hydrogen strategies. Specific regions in France, Germany and the Netherlands have also set out their own plans. For example, a Hydrogen Strategy for North Germany was published in November 2019 and there is the 'Hydrogen Valley Initiative' in Groningen (Northern Netherlands).

Table 4 Overview of national hydrogen strategies

Country	Targets and commitments	Key drivers	Challenges
Germany	• 2030: 5GW electrolysis • €7bn to develop domestic production + €2bn to develop production in partner countries	• Green decarbonisation • Prioritise renewable hydrogen although recognise potential role for low carbon during transition	• Lack of sufficient domestic production driving agenda for imports • Strong negative sentiment towards low carbon hydrogen restricts options
Norway	• Increase number of pilot and demonstrator projects • ENERGIX programme grant to provide NOK120m (€11m) with hydrogen having a central role	• Decarbonisation • Creation or replacement of economic value • Mix of renewable and low carbon production	• Achieving targets reliant on technological development

Country	Targets and commitments	Key drivers	Challenges
Netherlands	• 2030: 3-4GW electrolysis • 2040: 10GW from offshore wind • €35m p.a. Climate Budget Fund to support scale-up and technological advances including in hydrogen • Energy Innovation Demo scheme provides up to €15m per project including hydrogen • Renewable energy subsidy scheme supports hydrogen production by electrolysis	• Decarbonisation • Exploit large offshore wind resource • Transition from natural gas industry • Mix of renewable and low carbon production	• Decarbonising current high carbon hydrogen production cost effectively • Setting up value chains to capture hydrogen benefits
Australia	• Targeting exports to East Asia through projects in Phase 1 with full market activation in Phase 2 (post-2025) • AU$146m (€88m) already committed to projects • AU$15m (€9m) available for regional boost projects	• Large scale renewable resources • Existing supply chains (natural gas) to East Asia • Opportunity to decarbonise domestic heavy industry (mining) • Focus on renewable hydrogen although if suitable CO_2 storage available low carbon hydrogen could be an option too	• Demonstrating the safety case for long distance shipping • Realisation of early demand to justify investment
South Korea	• Mainly a transport focus although opportunity to decarbonise heat too • Targets 6.2 m FCEVs and 1,200 HRS by 2040 • US$18bn budget from Ministry of Trade, Industry and Energy to establish FCEV industry	• Economic opportunity in vehicle manufacture • Mix of renewable and low carbon hydrogen	• Planned rapid increase in domestic demand will not be met by domestic production requiring imports
Japan	• Mainly a transport focus although	• Security of supply and reduction in reliance on fossil fuels	• Maintaining competitiveness of industrial sector

Country	Targets and commitments	Key drivers	Challenges
	opportunity to decarbonise heat too • Targets 0.8 m FCEVs by 2030 • Builds on existing investment in fuel cell technologies	• Decarbonisation • Industrial strategy around automotive and fuel cell industries	
China	• Mainly a transport focus • Targets 1m FCEVs and 1,000 HRS by 2030	• Decarbonisation • Building automotive capability and competitiveness in this sector • Improving air quality • Mix of renewable and low carbon hydrogen	• Lack of domestic capabilities in manufacture of key components (although this is building)
USA	• Focused on fuel cells for transportation and to date mostly focused on California	• Decarbonisation • Air quality • Industrial strategy • Mix of renewable and low carbon production including SMR from biomethane	• Industry competitiveness • Development of safety case and building public awareness • Institutional barriers

Source: E4tech

4.3 Programs and measures promoting innovation through RD&D

As discussed in Section 1, a variety of mechanisms to support the development of hydrogen technologies and projects have been put in place across countries seeking to develop hydrogen. Supporting research and development aims to accelerate the process of bringing technologies to market or bridging the gap to commercial deployment by proving technologies in the field. The EU has led the way in this area, and we focus here on the mechanisms that have been put in place by the EU to support research, development and demonstration projects in renewable energy, many of which include hydrogen and in some cases are dedicated to hydrogen.

Two of the principal mechanisms for research and development projects are the Fuel Cell & Hydrogen Joint Undertaking (FCH-JU) and the Horizon 2020 (H2020) programme:

- The **FCH-JU** is a public private partnership supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. Its aim is to accelerate the market introduction of these technologies to realise their potential as an instrument in achieving a carbon-clean energy system. The FCH-JU is made up of the European Commission, Hydrogen Europe (which represents fuel cell and hydrogen industries) and Hydrogen Europe Research (which represents the research community). The FCH-JU aims to coordinate efforts across all sectors.

- **Horizon 2020** is the Framework Programme according to which all FCH-JU projects financed under the 2014-2020 call for proposals are funded. It is an EU research and innovation programme in which almost €80 billion of funding was made available, focused towards ensuring that Europe produces world-class science and technology, barriers to innovation are removed and it is easier for the public and private sectors to work together to help achieve smart, sustainable and inclusive economic growth.

- **Horizon Europe** is the next funding programme (from 2021) which will support "pilot applications, demonstration projects and innovative products, innovation for better governance of the green and digital transition, and social and value chain innovation." There are ten call areas. Call area 2 has a special focus on hydrogen as it will provide support for the development and demonstration of a 100 MW electrolyser. Call area 3 will look at the decarbonisation of industry, call area 4 is on improving buildings' energy efficiency and call area 5 is about the greening of ports and airports, all of which could be relevant for hydrogen technologies.

Among the principal funds that support demonstration projects are the EU Innovation Fund and InnovFin which provide support to projects that deliver carbon reductions.

- The **EU Innovation Fund** will provide up to €10 billion between 2020 and 2030 for innovative renewable energy generation and innovative low carbon solutions for pilot projects to scale up. It will support up to 60% of the additional capital and operational costs linked to innovation. The deadline for the first call for proposals was 29 October 2020.

- **InnovFin Energy Demonstration Projects** provides loans, loan guarantees or equity financing between €7.5m and €75m for innovative projects in the energy sector. The technologies must be at pre-commercial level or an early stage of commercialisation.

Examples of projects that have received funding under these and other nationally funded RD&D (research, development and demonstration) programmes are shown in Table 5.

Table 5 Example RD&D projects in hydrogen

Project name	Project description	Date	Funding pillar
BIG HIT The Orkney Islands (Scotland)	BIG HIT will create a 'Hydrogen Territory' by implementing a fully integrated model. 50 tonnes of hydrogen will be produced a year from 2 PEM electrolysers (1 MW and 0.5 MW) using wind and tidal energy and stored as high pressure gas in tube trailers which can be transported to the mainland. The hydrogen will also be used to fuel vessels, vehicles and for heat and power for buildings in the harbour.	2015	Transport
GRASSHOPPER Delfzijl (Netherlands)	GRASSHOPPER aims to create a next generation MW size PEM Fuel Cell Power Plant. It will be based on learnings from a 100 kW pilot plant design, implementing newly developed stacks and membrane electrodes which are more	2017	Energy

Project name	Project description	Date	Funding pillar
	cost-effective and flexible in power output. The CAPEX is estimated at < 1,500 €/kWe with a yearly production of 25 MWe. The aim is to validate operation flexibility and grid stabilisation capability via fast response.		
H2Haul Belgium, France, Germany, and Switzerland	16 new heavy duty hydrogen fuel cell trucks will be developed and deployed at sites in Belgium, France, Germany and Switzerland. Three types of fuel cell trucks will be certified for safe use on Europe's roads. In addition, six new high-capacity HRS will be installed to provide reliable, low carbon hydrogen supplies to the trucks.	2019	Transport
HEAVENN Northern Netherlands	By 2026, the Northern Netherlands region aims to become a fully integrated and functioning "Hydrogen Valley", a geographical area hosting an entire hydrogen value chain from production to distribution, storage and local end use. The aim is to develop a replicable business model for wide-scale commercial deployment of hydrogen across the entire regional energy systems.	2019	Energy
HY4ALL	Overarching communication strategy in 11 Member States to increase public awareness of hydrogen fuel cell technologies by delivering clear consistent messages.	2014	Cross-cutting
JIVE and JIVE2 Denmark, France, Germany, Iceland, Italy, Latvia, Norway, Sweden, the Netherlands and United Kingdom	Nearly 300 zero emission fuel cell buses will be deployed in 20 cities by the early 2020s to facilitate and expedite their full commercial viability in Europe. Clustering and group procurement will allow partners to achieve 30% cost reductions through economies of scale.	2017 and 2018	Transport
REFHYNE Wesseling (Germany)	A 10 MW PEM electrolyser which can produce 1,300 tonnes of hydrogen per year will be operated at the Shell Refinery. The decarbonised hydrogen will be fully integrated into refinery processes including the desulphurisation of conventional fuels.	2017	Energy

Source: E4tech

4.3.1 Financial support for hydrogen supply and infrastructure development

The hydrogen and clean energy related projects currently underway, are generally still demonstrating "first of a kind" technologies and so require some level of public funding. Multiple funds being made available, such as specific regional funds (e.g. West Balkans Investment Fund, Neighbourhood Investment Facility), specific sector funds (e.g. infrastructure TEN-T, or energy TEN-E), or specific project funds (FCHJU or Important Projects of Common European Interest). Support packages to help recover from the effect of the COVID-19 crisis have also been targeted towards green energy measures. For example, the ‘EU Recovery Plan’ (€1,850 billion) will provide extra funding under existing legislation such as the Just Transition Mechanism and by creating new financial support instruments such as the Recovery and Resilience Facility.

Through the **Just Transition Mechanism**, financial support will be available to all Member States, but focused on most vulnerable sectors and regions directly affected by the green transition, by being traditionally most heavily dependent on fossil fuels. It provides targeted support to help mobilise at least €150 billion over the period 2021-2027 to alleviate the socio-economic impact of the transition. Member States can get access by preparing territorial just transition plans that cover the period up to 2030, identifying the territories that should get the most support and outlining the best ways to address social, economic and environmental challenges. The three pillars of the Just Transition Mechanism are a new Just Transition Fund of €40 billion to generate at least €89-107 billion investments, the InvestEU “Just Transition” scheme mobilising €30 billion in investments and the EIB public sector loan facility of €10 billion in loans, backed by €1.5 billion of the EU budget, mobilising up to €30 billion of investments.

The **InvestEU programme** provides debt and equity financing to support the transition from scale-up phase to roll-out. The European Hydrogen Strategy envisions a doubling of the InvestEU fund, which already aims to mobilise €650 billion of investment, and to enable hydrogen projects to participate in the Strategic European Investment Window of Invest EU, expected to be available from 2021.

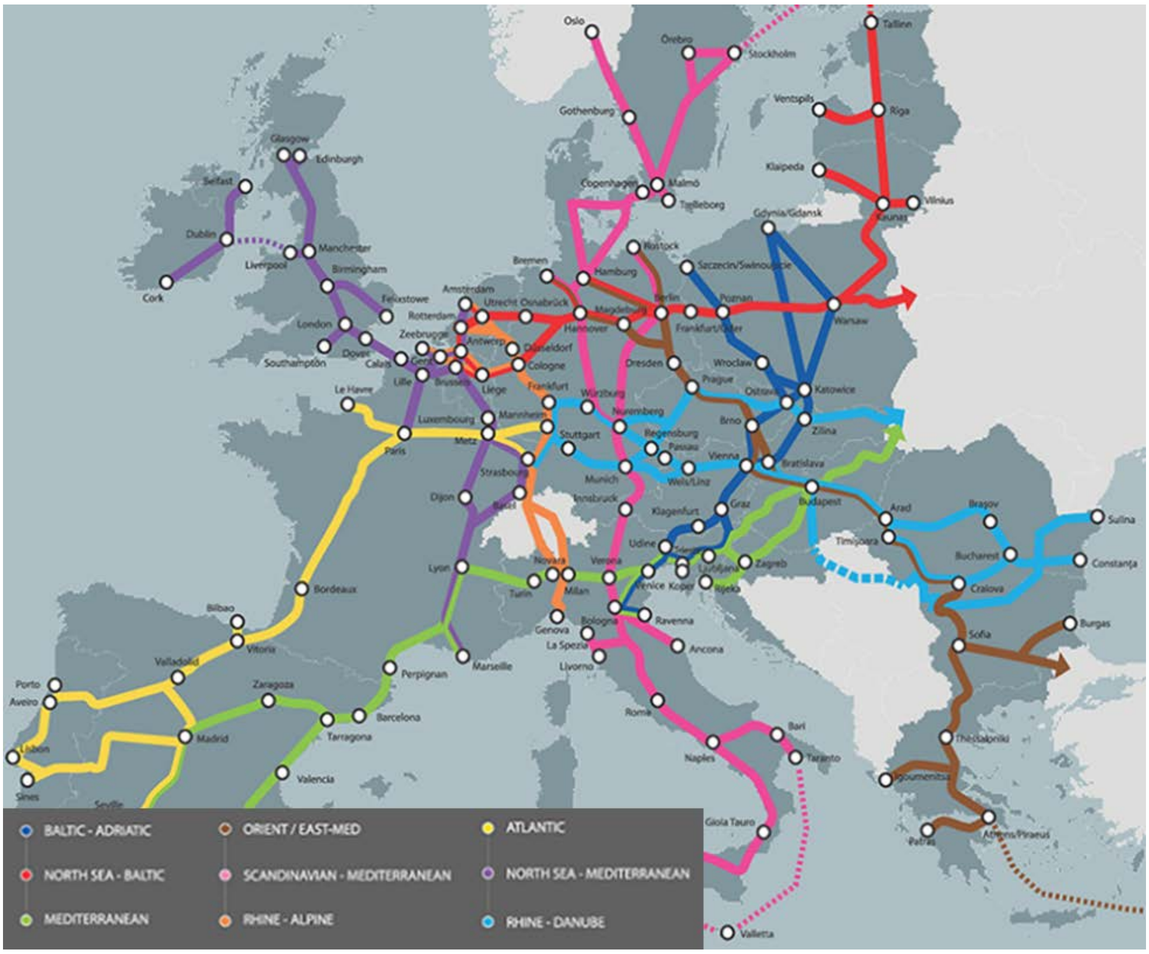
The **Recovery and Resilience Facility** will make €672.5 billion available in loans and grants to provide financial support to public investments and reforms undertaken by Member States. It will ‘support investments and reforms essential to a lasting recovery, to improve the economic and social resilience of Member States, and to support the green and digital transitions’. Hydrogen will be eligible for funding, provided the technology is integrated into national Recovery and Resilience Plans prepared by Member States which must be prepared by 2021 for approval by the EC. Funding would run until 2026.

The **Connecting Europe Facility (CEF)** is a funding instrument (through grants and subsidies) to promote jobs and competitiveness through targeted energy infrastructure investment. It supports the development of high performing, sustainable and efficiently interconnected trans-European networks (PCI projects) in the fields of transport, energy and digital services. The CEF benefits people across all Member States, as it makes travel easier and more sustainable, it enhances Europe’s energy security while enabling wider use of renewables, and it facilitates cross-border interaction between public administrations, businesses and citizens. Figure 28 shows that the priority corridors supported by the CEF will be of benefit to the CP’s, for example the Rhine-Danube corridor passes through Serbia and this and the Mediterranean corridor link to Ukraine. The deadline to submit a proposal for the fourth cut-off was 13 November 2020. The CEF is divided into three sectors, energy, telecoms and transport.

- The CEF supports the realisation of a **Trans-European Energy Network** through the **TEN-E** policy which is focused on linking the energy infrastructure of EU countries. Through it, the EU helps countries in 9 priority corridors and 3 thematic areas to work together to develop better connected energy networks and provides funding for new energy infrastructure. It was revised under the European Green Deal and explicitly supports the use of low carbon gases and hydrogen, in line with the EU hydrogen strategy. It envisages the creation of a new investment category (smart gas grids) to enable the introduction of new clean gases into the grid to replace natural gas. That is, it is aimed at supporting the conversion of the existing gas grid to enable the integration of renewable and low carbon gases. At the same time, PCI support for new natural gas and oil transmission has been removed.

- Similarly, the **TEN-T** (Trans-European Transport Network) is a policy that supports market-side development of innovative and new technologies that will play a key role in facilitating the mobility of goods and passengers within the EU, and into neighbouring countries. One such project completed under this policy was HIT (Hydrogen Infrastructure for Transport) which aimed to understand how hydrogen hotspots can become local markets for Hydrogen Refuelling Stations (HRS) and how these can enable long distance transport along the TEN-T corridors.

Figure 28 Priority corridors supported by the Connecting Europe Facility



4.3.2 Specific support available to the Contracting Parties

The EU has an interest in seeing greater economic development and better governance in adjacent countries. The **European Neighbourhood Policy (ENP),** operational since 2007, applies to the EU's immediate neighbours by land and by sea and provides a support framework. The Neighbourhood Investment Facility (NIF) is a financial instrument under the

ENP designed to maximise the impact of EU funding. Of the Contracting Parties, this currently applies to Ukraine, Moldova and Georgia.

The **Neighbourhood Investment Framework** has for many years financed projects accompanying the clean energy transition (alongside the transport, social and environment sectors) of partner countries. One objective is to establish better energy and transport infrastructure interconnections between the EU and its neighbours as well as between neighbouring countries themselves. It pools grant resources from the EU budget and the EU Member States and uses them to leverage loans from European Financial Institutions as well as contributions from the European Neighbourhood Policy partner countries themselves.

To support investments in clean hydrogen and new hydrogen-related project proposals in the European Neighbourhood, the Commission will also be mobilising financing instruments including the **Western Balkans Investment Framework (WBIF).** This supports socio-economic development and EU accession across the Western Balkans through the provision of finance and technical assistance for strategic investments in the energy, environment, social, transport, and digital infrastructure sectors and supports private sector development initiatives. It is a joint initiative of the EU, financial institutions, bilateral donors and the governments of the Western Balkans.

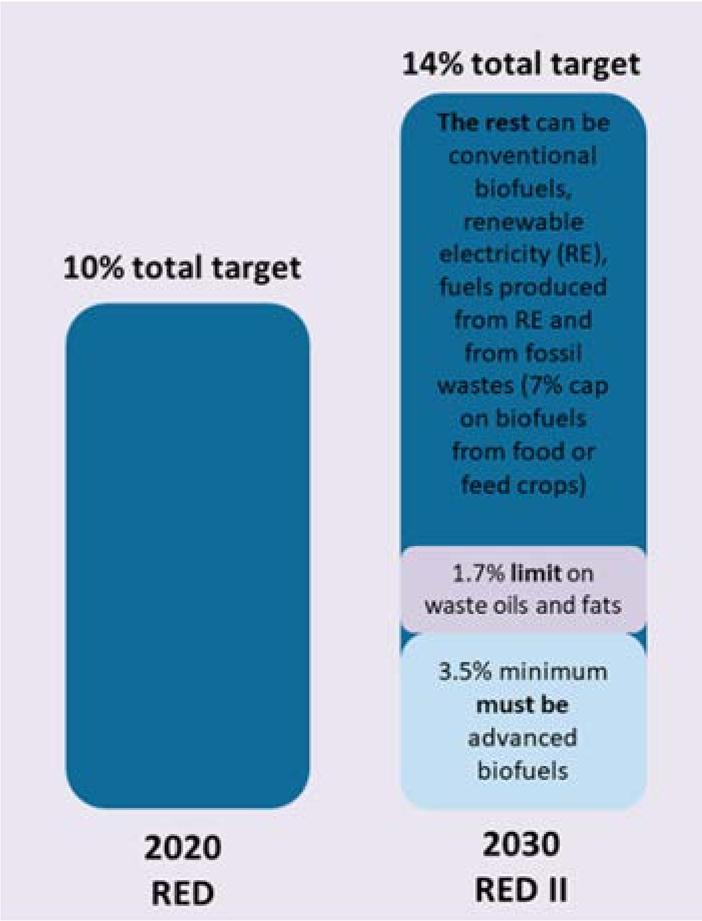
4.4 Support schemes

4.4.1 Demand creation

The main legislation supporting the transition in the EU away from fossil fuels and towards low carbon alternatives is the RED, now in its second iteration (RED II). It sets an overall target for countries to provide 32% of their energy supply from renewable sources by 2030 and includes a sub-target of 14% renewables in transport. RED II will be reviewed by June 2021, and current renewable energy targets are expected to be reinforced in light of the new EU minimum 55% GHG reduction target by 2030. Member States independently develop national frameworks and policies to achieve these targets. Most of these frameworks are technology agnostic, meaning that hydrogen will be included but will need to compete against other technologies such as batteries and biofuels.

At present, this transport sectoral target within RED II is the only substantial piece of legislation that specifically supports the use of hydrogen and in addition to the overall target, it sets specific thresholds and limitations for certain types of renewable energy sources. This is illustrated in Figure 29.

Figure 29 Characteristics of the RED II targets for transport in 2030



Source: E4tech

Key items of note are:

- The cap on the use of waste oils and fats, which must not exceed 1.7% of energy supplied and is designed to reduce dependence on these sources;
- The floor on advanced biofuels which must represent at least 3.5% of energy supplied and seeks to encourage development of these new fuels; and
- The cap on the number of conventional biofuels derived from food or feed crops of 7% aimed at reducing competition between food and fuel land uses.

Hydrogen-based fuels could contribute to the 8.8% sub-category under RED II referred to as "the rest" in the chart above. However, it should be emphasised that hydrogen will compete with conventional biofuels which are significantly lower cost than hydrogen and direct electrification. It is possible that specific support for renewable fuels of non-biological origin (RFNBOs), which includes hydrogen and hydrogen-derived fuels, could receive additional support in future legislation. For example, as noted above, the EU hydrogen strategy envisages additional support for hydrogen-specific initiatives.

RED II is supported by other transport legislation designed to ensure that the overall carbon intensity of road transport remains within certain thresholds. For example, Regulation (EU) 2019/1242 establishes the first CO_2 per tonne kilometre emissions reduction targets for heavy duty vehicles of 15% in 2025 and 30% in 2030 compared to 2019/2020 levels. Furthermore, Regulations (EC) No 443/2009 and (EU) No 510/2011 (revised in April 2019) establish CO_2 emissions performance requirements for passenger and light commercial vehicles.
From 1 January 2020, it sets an EU fleet wide target of 95 g CO_2/km average emissions for new passenger cars and 147 g CO_2/km average emissions for new light commercial vehicles. Further reductions will be applied in 2025 and 2030.

Similar support mechanisms can be found elsewhere, notably in California, where the Zero Emissions Vehicle (ZEV) percentage credit requirement is set to become increasingly stringent and ranges from 4.5% in 2018 to 22% in 2025. Credits are awarded upon the delivery of a ZEV for sale in California. This legislation covers FCEVs. The California Air Resources Board also recently extended the Low Carbon Fuel Standard and aims at a carbon intensity reduction target of 20% compared to 2011 levels. Furthermore, California also committed to reduce GHG emissions by 40% compared to 1990 levels. There is also federal legislation covering low emissions vehicles, the Renewable Fuel Obligation but this does not specifically support hydrogen vehicles and has mostly underpinned the roll-out of biofuels, especially ethanol blending with gasoline.

Since the inception of California's ZEV programme, nine additional states (Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island and Vermont) now have similar mandates. The objective is to deploy 3.3 m ZEVs by 2025 across these states.

4.4.2 End user applications

As end use applications have begun to mature, subsidy programmes have been developed to drive early adoption to reflect the gap which exists between the cost of ownership when compared with fossil fuel equivalents. For example, in the road vehicle sector, China's new energy vehicle subsidy programme has been running since 2016. This has supported consumers in the purchase of low carbon vehicles, including both battery electric and FCEV. It led to the purchase of 1.4 million New Energy Vehicles (NEVs) in 2020, including several thousand light and heavy duty FCEVs, and China has the aim of 20% market share for NEVs by 2025. Although these subsidies were halted in 2020, they have been replaced by a new four-year pilot program focused on research and development and application demonstrations of FCEVs which is to be launched in select cities.

In the UK, meanwhile, the FCEV fleet support mechanism[41] provided funding to cover 75% of costs over a four-year period starting in 2016. This competition fell into two streams:

- Stream 1 (Public Sector Fleets): this provides support to public sector bodies for deployment of FCEVs in public sector fleets that are not in competition with commercial activity. It funds up to 75% of the total cost of procuring FCEVs, insurance, fleet management, vehicle servicing, user training, fuel, project reporting and dissemination;

41 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/521147/supporting-fleet-uptake-of-hydrogen-fuel-cell-vehicles-guidance-note.pdf.

- Stream 2 (private enterprise): this provides support to private enterprises, up to a maximum of €200,000 per enterprise, for up to 75% of the total cost of procuring FCEVs, insurance, fleet management, vehicle servicing, user training, fuel, project reporting and dissemination.

In the heating sector, Japan has led the way with its Ene.farm subsidy programme for domestic fuel cell CHP. The programme, launched in 2009, has seen the deployment of well over 150,000 domestic CHP units based on fuel cells but fuelled by natural gas. A similar support programme, Ene.field, was launched in Europe with more modest ambitions and has seen the deployment of approximately 1,000 units, mostly in commercial buildings. Meanwhile, Germany has its own micro-CHP subsidy package (which, in practice, applies to gas fuelled CHP), KfW433, and this has also seen an uptake of a few thousand units.

4.5 Projects

The **Important Project of Common European Interest (IPCEI) framework** enables state aid funding for large cross-border projects. The European Hydrogen Strategy foresees the uses of the IPCEI framework for hydrogen-related projects. A significant number of IPCEI[42] projects already incorporate hydrogen as a central aspect and a number of these are outlined in Table 6[43]. However, EC will only subsidise four of these projects in the context of the Hydrogen Europe programme, so they are in competition with each other, vying for funding. The White Dragon project is explained in more detail in Section 5.2.1 due to its links to the CPs.

Table 6 Example IPCEI projects involving hydrogen[44]

Project name	Partners (# involved)	Description of project
Green Hydrogen@Blue Danube	Verbund (electric utility), ElringKlinger (tier 1 auto supplier), DB Schenker (logistics), ÖBB (rail), Siemens (industrial), Hydrogenious (LOHC), Chemgas Shipping (inland barges and sea), Danube Commission (river management)	2 GW wind and solar-based hydrogen production, transportation by barges on River Danube, supply to industry and mobility hubs in the InterReg Danube Transnational Region. Serbia would be one of the participating countries in this project
Black Horse	Bioway (green truck fleet), UNICRE (bank)	Hydrogen filling station infrastructure, production and operation of a heavy duty vehicle fleet in SK, CZ, PL and HU
Green Octopus	WaterstofnNet (hydrogen project developer), ENGIE (utility), Gasunie (gas utility), Fluxys (gas transmission), Port of Antwerp (authority), Salzgitta AG (steel), DEME (port infrastructure), Exmar (shipping), Port of Zeebrugges (seaport)	Creating a 2,000 km hydrogen backbone by re-purposing existing pipelines, producing 6 GW of wind-based hydrogen to transport it through the pipeline to multiple users including major regional port areas and industrial clusters

42 https://www.hydrogen4climateaction.eu/whats-an-ipcei.
43 Legal references: Community framework for state aid for R&D and innovation (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014XC0620(01)&from=EN), Criteria for the analysis of the compatibility with the internal market of State aid (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52006XC1230(01)&from=EN), Community guidelines on state aid for environmental protection (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52008XC0401(03)&from=EN).
44 https://www.hydrogen4climateaction.eu/projects.

Project name	Partners (# involved)	Description of project
White Dragon	DEPA (LNG), SOLIDPower (solid-state batteries), Public Power Corporation (electric utility), Hellenic Republic Region of Western Macedonia (authority), Demokritos (research centre), Hydrogenious (LOHC), MBN Nanomaterialia (ball-milling)	1 GW solar-based hydrogen production using Solid Oxide Cell technology including storage, compression, transportation of hydrogen and usage for fuel cell buses and CHP. This project is explained in more detail in Section 5.2.1.
Silver Frog	Hydrogenics (fuel cells), Meyer Burger (solar engineering), EcoSolifer (Photovoltaic (PV) manufacture), SolarPower Europe (events), European energy (wind, solar, storage developer)	10 GW solar-based hydrogen production, transportation through pipelines for use in steel and chemical industry
Blue Dolphin	Fincantieri (shipbuilder)	50 ships and ship power generation systems, from liquid hydrogen cargo to passenger ships, powered by hydrogen and the required port infrastructure

Source: E4tech

4.6 Concluding comments

Reflecting the growing maturity of hydrogen technologies and the recognition that it can form part of a broader set of decarbonisation objectives, strong strategies at EU and country level are now supporting hydrogen development. **Strategies and targets help provide overall commitment and direction but also provide roadmaps for the development of hydrogen and also set targets and objectives for its deployment**.

A combination of policies is needed to ensure the potential of hydrogen can be achieved and governments have established multiple policy mechanisms designed to support decarbonisation in general which can and are being used to underpin hydrogen technology development and projects. Given the relative early stage of development and level of maturity that hydrogen has reached, the focus of these efforts has been more on supporting innovation and pre-commercial testing. However, targeted policies to bridge the gap to commercialisation are starting to emerge as hydrogen gets closer to commercial readiness. Existing instruments should be used as much as possible (e.g. RED II), but cannot necessarily be relied upon, so more targeted approaches are being used to ensure that hydrogen develops.

The European Green Deal and similar industrialisation policies in other countries like Japan and South Korea in addition to climate change-focused policies are likely to further boost the hydrogen sector. It will also be critical to remove existing barriers and support 'losers' from the energy transition, factors which are key aspects of the European Green Deal.

The policies and strategies set out by the EU and its Member States provide opportunities for the CPs to become involved in development of hydrogen energy, even at this relatively early stage. Several projects are already underway or are being discussed that involve the CPs in different roles and more funding opportunities exist that could support regional development of hydrogen. Figure 28 shows that the priority corridors supported by the Connecting Europe Facility under the TEN-E and TEN-T policies will be of benefit to the CP's, for example the Rhine-Danube corridor passes through Serbia and this and the Mediterranean corridor link to

Ukraine. The Western Balkans investment Framework and/or the Neighbourhood Investment Framework could be of relevance to the Contracting Parties. Policy targets and incentive mechanisms will also be available to support the transition to hydrogen in areas like heavy duty transport.

5 Lessons and benchmarks

In this section we provide **three specific country case studies and four project case studies which** provide relevant insights for the CPs.

The country case studies highlight how hydrogen strategies and policies are supporting overall energy system objectives, such as energy security and decarbonisation, as well as other objectives like industrial strategy.

The project case studies were selected from the EU and provide insights across the hydrogen value chain. A range of projects was chosen to reflect the full spectrum of hydrogen development.

At both the country and project levels, the case studies highlight success stories, describe the lessons learned, and exemplify the promise and limits of current technologies. The examples chosen show where regulatory and/or policy frameworks may help surmount barriers to further scaling up the hydrogen economy in the regions chosen. These have been summarised within each individual country or project case study where relevant and brought together more holistically with specific consideration for the CP's in Sections 5.1.4 and 5.2.5.

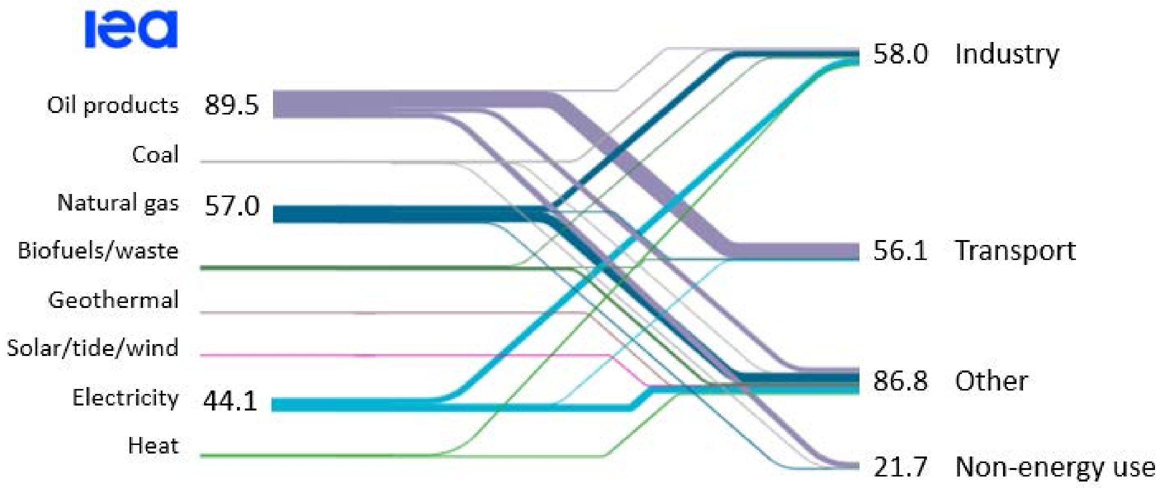
5.1 Country case studies

5.1.1 Case study 1: Germany

Germany is the world's fourth largest economy with very positive socio-economic indicators, such as levels of car ownership. Per capita energy consumption is accordingly relatively high although Germany benefits from relatively good energy efficiency.

Final energy demand in Germany stood at 223mToe in 2019 and despite a strong push for decarbonisation, Germany is still largely reliant on fossil fuels with nearly 80% of primary energy supply coming from fossil sources. Germany retains a strong industrial sector with 58mToe of final energy consumption coming from industry (see Figure 30).

Figure 30 Sankey Diagram for Germany, 2018 Final Energy Consumption (m Toe)



Source: IEA

The country benefits from highly developed electricity and gas networks which should serve to facilitate the transition to low carbon energy based around the electricity and hydrogen vectors.

Recognising the importance of its industrial sector and its leadership position in many sectors of manufacturing, Germany has identified hydrogen as both an element of its Energiewende, or energy transformation, and as a part of its industrial strategy. Germany's national hydrogen strategy[45] was approved in June 2020 in order to set out its vision for the sector. The strategy has some overarching objectives:

- Assume global responsibility in emissions reductions by establishing hydrogen as a decarbonisation option;
- Make hydrogen competitive by pushing cost reductions into a fast-moving international market ramp-up;
- Establish hydrogen as an alternative energy carrier to decarbonise hard-to-abate sectors;
- Support research and train qualified personnel;
- Strengthen the German economy and secure global market opportunities for German companies; and
- Understand global cooperation is an opportunity and establish international hydrogen markets, as sizeable imports will be required in medium and long term.

Key aspects of the strategy are captured in Table 7.

[45] https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html.

Table 7 Features of the German Hydrogen Strategy

Production	Transport	End use
• Focus on renewable hydrogen with low carbon hydrogen only allowable on an interim basis • Dual strategy emphasising both local production and imports • Target of up to 14TWh of hydrogen production by 2030 • Focus on securing imports, e.g. signing of MoU with Australia and Morocco to develop international supply chain	• Emphasise the use of the existing gas transmission and distribution infrastructure and extending or building new dedicated hydrogen networks • Recognising that Germany will have a net hydrogen deficit, alternative means of hydrogen transport from overseas are being explored, e.g. liquid hydrogen, ammonia or LOHC	• Identified demand 90 – 110TWh • In road transport, Germany has a target of 100 HRS stations by 2020 and 400 by 2025. • No specific target for fuel cell vehicles, but several subsidy schemes provide incentives to buy ZEVs. • E-fuels are expected to play a strong role in long distance / heavy transport sector.

Supporting funding and policy
• The Hydrogen Strategy foresees €9bn of investment for hydrogen, including €7bn for market ramp-up of hydrogen technologies and €2bn for international partnerships. Other funding streams include: - “Hydrogen Republic of Germany” is a competition to implement the national hydrogen strategy; - “Hydrogen Technologies 2030” is designed to fund large scale Power-to-X (PtX) projects and hydrogen projects for steel and chemical industries; - The Environment Ministry also has a Decarbonisation Industry Fund, with €445mn earmarked for industrial scale pilot projects; - KfW433 subsidy scheme for fuel cell-based micro-CHP will continue. • Policy mechanisms in place or envisaged: - A 2% blending obligation target is being considered for sustainable aviation fuels, and a strong deployment of low carbon fuels is envisioned in the shipping sector. - Carbon Contract for Difference to support decarbonisation of heavy industries. To support advanced fuels, Germany already has a GHG-based policy, with the goal of achieving a 6% GHG reduction in the transportation fuel mix by 2025 – this could support RFNBOs.

Key takeaways

- Germany represents a good example of **ambitious strategy-setting** for hydrogen;
- Like other major industrialised nations, Germany wishes to **remain competitive** and is seeking to leverage hydrogen imports to do that as required;
- The **strategy is comprehensive and outlines policy and funding** to support the objectives, setting out explicit goals for production and import, for example;

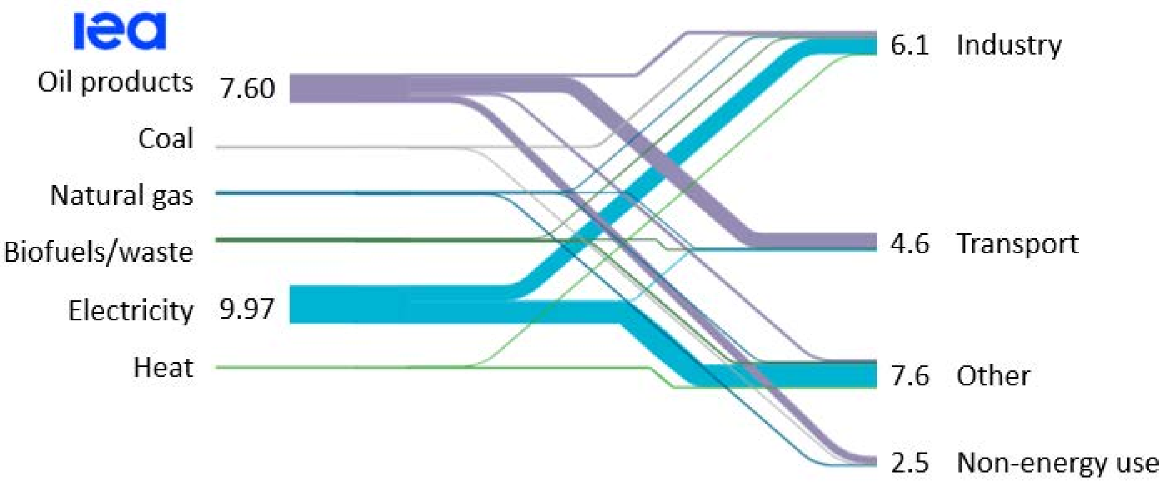
- These policies recognise that **hydrogen has a role to play in decarbonisation, environmental policy and industrial strategy**;
- Germany's economy is large and complex and energy demand is high, highlighting the need for complex solutions which **draw on as wide a selection of technologies as possible**;
- Germany's challenge will be to remain competitive while at the same time ensuring **secure supplies** of green energy.

5.1.2 Case study 2: Norway

Norway is an energy-rich nation with a small population and a high standard of living. This is reflected in typical socio-economic indicators. While energy demand per capita is high – Norway's per capita consumption is exceeded only by Iceland and Luxembourg in Europe - its electricity sector is almost completely decarbonised being reliant on abundant hydroelectric resources. This means that while its energy consumption is higher than the European average its carbon emissions were close to the EU average.

Total energy demand was 21 m Toe in 2018, while energy production was 218 m Toe with the remainder being exported. Exports of natural gas reached 101 m Toe while crude oil and refined products made up the remainder.

Figure 31 Sankey diagram for Norway, 2018 Final Energy Consumption (m Toe)



Source: IEA

Heat demand was largely fulfilled by electricity with a very small amount of natural gas feeding limited heating networks in major urban centres. Similarly, the industrial sector which is dominated by non-ferrous metals and chemicals relies predominantly on electricity. As a result, the heat and industrial sectors in Norway are already significantly decarbonised and the likelihood of transitioning to hydrogen relatively lower than in the other focus countries. By contrast, the transport sector relies on fossil fuels and accounts for roughly half of Norway's fossil fuel demand.

The Norwegian government has strong decarbonisation targets, as set out in the National Climate Act and other recent announcements, aimed at reducing greenhouse gas emissions by 50-55% by 2030 (compared to 1990) and by 90-95% by 2050. These ambitious targets will call for new technology and system change.

Given the significance of the transport sector in achieving the overall decarbonisation goals, Norway´s 12-year framework National Transport Plan 2018-2029 sets out tightened national ambitions for zero and low emission vehicles uptake in Norway:

- From 2026, all new private cars, buses and light commercial vehicles should be zero emission;
- By 2030, all new heavier distribution vans, 75% of new long distance buses and 50% of trucks should be zero emission; and
- By 2030, all goods distribution in the largest cities shall be virtually emission free.

In the maritime sector, similar strong measures have been formulated to decarbonise short sea shipping routes within the same timelines as for road transport. A national target of 50% reduction in the emissions from domestic shipping by 2030 has been set and the government's recent ban on all carbon emissions in Nærøyfjorden and Geirangerfjorden from 2026 onwards is a further driver for zero emission domestic maritime transport.

A number of mechanisms have been put in place to support transition of the transport sector including both road and marine transport. These include:

- the PILOT-E scheme which has the objective of promoting fast-track development and deployment of energy technology products and services to stimulate and assist the maritime sector’s shift towards zero emissions;
- the ENERGIX programme, which provides funding for research and innovation to achieve sustainable development of the energy system.

On the demand side, several incentives for zero emissions vehicles exist such as:

- The removal of purchase/import taxes;
- Exemption from 25% VAT on purchase;
- no annual road tax;
- Access to bus lanes;
- Exemption from 25% VAT on leasing; and
- Fiscal compensation for scrapping of fossil-fuelled vans when converting to a zero emission van.

Enova SF, a public enterprise owned by the Ministry of Climate and Environment (from 2018), manages the Energy Fund in Norway and also provides support for the wider transformation of the energy sector. In June 2019, Enova committed around 2.1bn NOK (~€0.2bn) to direct support for energy and climate projects including those in hydrogen. The Ministry for Climate and Environment recently announced that Enova would establish a Zero Emission Fund for business transport.

Given the importance of the transport sector, when Norway issued its hydrogen strategy in May 2020 its primary focus was on how hydrogen could help Norway to achieve its decarbonisation goals in that sector. Key features of the Norwegian strategy are shown in Table 8.

Table 8 Features of the Norwegian Hydrogen Strategy

Production	Transport	End Use
• Focus on both renewable hydrogen from hydro and offshore wind resources and low carbon hydrogen from the significant North Sea natural gas assets • Leverage capabilities of existing domestic electrolyser manufacturers, e.g. NEL • Participate in low carbon hydrogen projects such as Northern Lights[46]	• Very limited domestic gas grid but extensive network of offshore gas pipelines serving offshore oil production • Norway sees a potential opportunity for the export of zero or low carbon hydrogen via this network	• Focus is strongly on decarbonisation of transport with strong policies to encourage the use of zero carbon fuels in road transport • Extensive ferry network which encompasses activities in the Arctic is driving push to use CO_2 free fuels in marine transport • Industrial use of low carbon hydrogen to replace high carbon hydrogen also a factor as is potential use in steel making

Supporting funding and policy
• The Norwegian Parliament has a national goal that all new cars sold by 2025 should be zero emission (electric or hydrogen). • Financial sponsorship is available for renewable hydrogen-based maritime transport projects under the PILOT-E scheme, which is overseen by the Norwegian Research Council, Innovation Norway and Enova SF, an agency of the Norwegian Ministry of Climate and Environment. • The Innovation Norway programme has €11mn dedicated to hydrogen. • Enova SF, a public enterprise owned by the Ministry of Climate and Environment, which is tasked with managing the Energy Fund in Norway to support pilot and demonstration projects related to industrial development connected to hydrogen in all sectors of the economy. The Enova fund has earmarked 1bn NOK (~€0.1bn) for allocation to climate-friendly vehicles, including FCEVs, before the end of 2020. • A resolution by Parliament in 2016 encourages the use of development contracts for hydrogen ferries.

Key takeaways

- Norway is an energy-rich country which is **seeking to manage the decline of fossil fuels in an affordable way**;
- Strong credentials in low carbon and now in renewable hydrogen technology also provides Norway with industrial development opportunities;

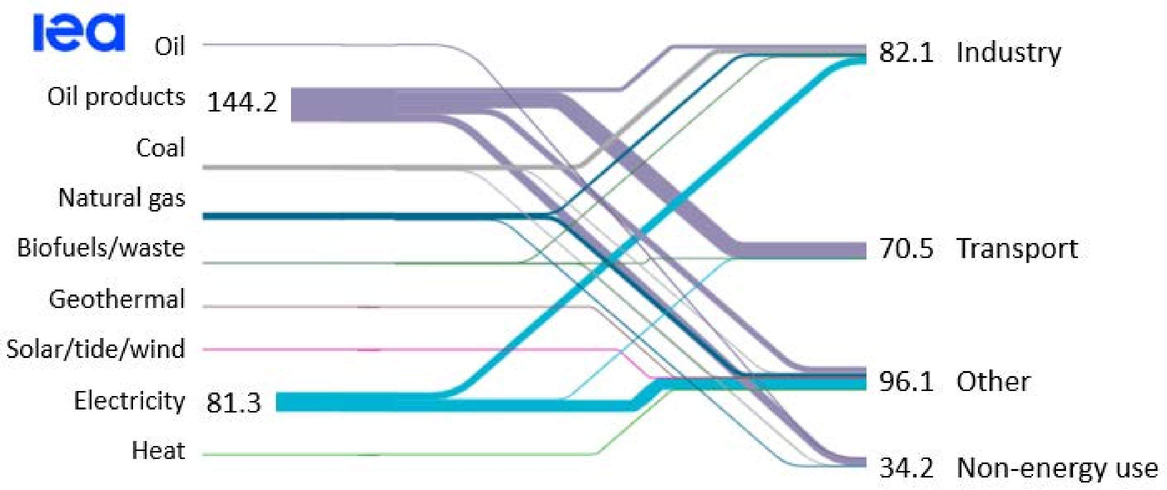
[46] https://northernlightsccs.com/en/about.

- Norway is fortunate to have a completely decarbonised energy system using only renewable energy for electricity generation due to extensive hydropower and wind resources. This abundant low cost electricity means Norway has the third lowest hydrogen production costs using grid electricity in the EU (€3.4/kg) and the carbon intensity of this grid electricity is low enough that even without power purchase agreements and Certificates of Origin the produced hydrogen's carbon footprint would be low enough to meet all hydrogen emission benchmarks set at the EU level. This means that Norway has been able to extend the use of hydrogen to hard-to-electrify sectors such as both heavy duty and light duty vehicles. (BEVs have gained more traction in the light duty sector).
- It has strong policies to support decarbonisation, with **targeted policies** to support hydrogen; and
- Critical to Norway will be ensuring that it manages the **transition away from fossil fuels effectively given the importance of oil and gas to the economy**.

5.1.3 Case study 3: Japan

Japan is the world's third largest economy with a high per capita income and a strong industrial base. It has very limited domestic energy resources and relies on imports for over 90% of its energy needs. This reliance increased significantly with the closure of its 42 nuclear reactors following the meltdown of the Fukushima plant in the wake of the Great Tsunami. While nine of these reactors have since reopened, Japan continues to be heavily reliant on fuel imports, with coal, oil and natural gas all contributing heavily to its energy needs (see Figure 32).

Figure 32 Sankey diagram for Japan, 2018 Final Energy Consumption (m Toe)



Source: IEA

Like Germany, Japan benefits from highly developed electricity and gas networks which should serve to facilitate the transition to low carbon energy based around the electricity and hydrogen vectors.

Energy consumption per capita is at a similar level to other developed economies such as the UK, France and Germany. GHG emissions per capita, while similar to those in Germany, were considerably higher than in the UK and France owing to the heavy reliance on fossil fuels across all sectors and the low nuclear capacity in operation[47]. Japan is targeting a reduction in carbon emissions of 80% by 2050 and sees hydrogen as one part of the strategy to achieve this reduction.

Japan has been one of the most long-standing advocates of hydrogen and fuel cells and the first country globally to announce a holistic hydrogen strategy in 2017. The country has led the way in fuel cell vehicle development through Toyota and the use of fuel cells in domestic heating through the "ene.farm" programme.

The hydrogen strategy has six overarching objectives:

1. Diversify supply sources to fundamentally reduce supply risks – reduce dependence on specific sources.
2. Reduce carbon in power generation, transport, heating and industrial processes – focus on both low carbon and renewable hydrogen.
3. Contribution to the 3E+S policy for energy as a whole[48] – hydrogen energy seen as a means to an end.
4. Contribute to the international community through world-leading innovation – Japan will extend its technologies overseas.
5. Industrial promotion and competitiveness enhancement – seek to capitalise on its strong position in fuel cell and other hydrogen technologies.
6. Leading hydrogen initiatives abroad – Japan will position itself as the first hydrogen-based society.

A plethora of hydrogen-related projects have been launched many of which have received government support. These include:

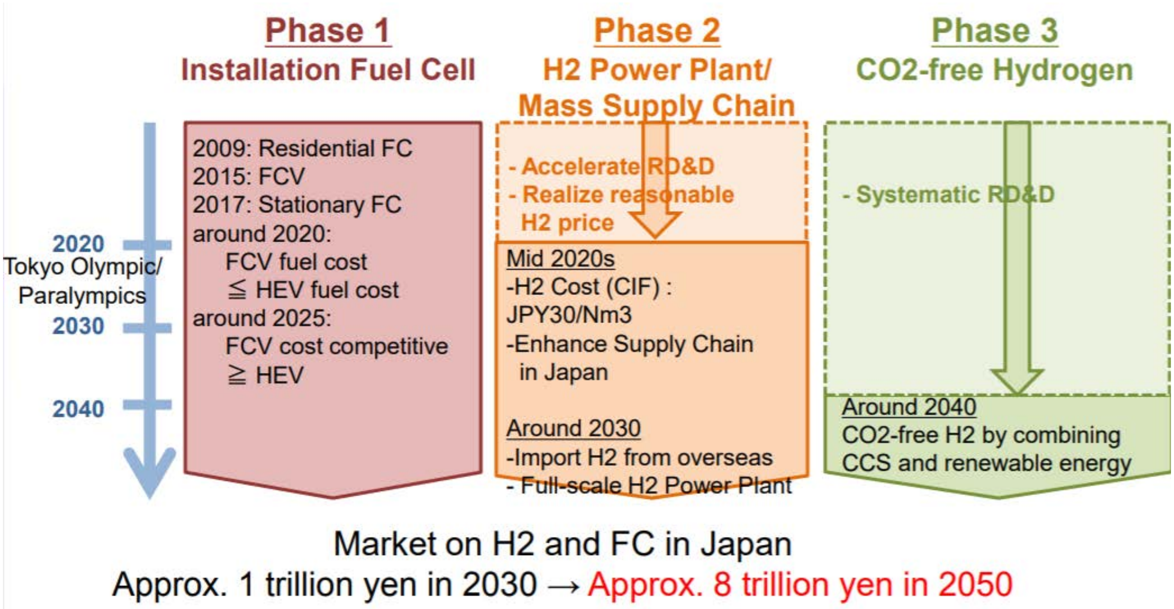
- Supply using LOHC – supply of by-product hydrogen from Brunei to Japan using LOHC for use in power generation. Project partners include Chiyoda Corporation, Mitsubishi Corporation, Mitsui & Co. Ltd., and Nippon Yusen Kabushiki Kaisha.
- Supply using LH2 – supply of hydrogen from Australia to Japan via liquid hydrogen carrier. Partners include KHI, Shell, J-Power, Iwatani, Marubeni, and JXTG Nippon Oil & Energy Corporation.
- Hydrogen power generation – project to demonstrate hydrogen blending in CHP plant at Kobe Port Island. Partners include Obayashi Corporation and Kawasaki Heavy Industries, Ltd.

[47] https://ucsusa.org/.
[48] The 3E+S energy policy refers to energy security, economic efficiency, environmental protection and safety http://www.en-2050-low-carbon-navi.jp/assets/onepage/3epluss.pdf.

- Renewable hydrogen production – the world's largest renewable hydrogen production plant is nearing completion in the Fukushima region of Japan. Partners include Toshiba, Tohoku Electric Power and Japan's New Energy and Industrial Technology Development Organisation[49].

The Japanese government has set out a roadmap (see Figure 33) for the implementation of hydrogen which they expect to reach a market size of Yen1 trillion ($9 billion) by 2030, rising to Yen 8 trillion ($75 billion) by 2050.

Figure 33 Japanese hydrogen roadmap



Source: Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry

Table 9 provides an overview of some of the key features of the Japanese strategy. As can be seen, there is a major focus on securing supplies of hydrogen to replace the existing fossil fuel (oil, NG, coal) supply chains. This draws on both imported supplies and domestic production although the former is expected to dominate. Given the importance placed on imported hydrogen, Japan also has a major focus on the means of hydrogen delivery with efforts to support innovation in LH2 and LOHC. Moreover, the existence of a developed natural gas network in Japan means that blending and an eventual shift to hydrogen networks is a realistic possibility. In the end use sectors, a combination of industrial strategy considerations and the need to transform power generation and industrial production to be cleaner is driving policy. Japan wishes to secure its position as a leading provider of hydrogen and fuel cell-based technologies especially in the automotive and stationary fuel cell sectors.

Table 9 Features of the Japanese Hydrogen Strategy

Production / import	Transport	End use
• Combine inexpensive unused energy from	• Develop international hydrogen energy supply	• **Power generation**: Commercialise hydrogen

[49] https://www.rechargenews.com/transition/japan-opens-worlds-largest-green-hydrogen-plant-near-fukushima-disaster-site/2-1-769361.

Production / import	Transport	End use
overseas with CCS to procure massive amounts of hydrogen from inexpensive renewable and international supply chains • Innovation to reduce costs of water electrolysis to 50,000Yen/kW (~$470/kW) locally • Aim to commercialise Power-to-Gas (PtG) by 2032 and cost parity with imports thereafter • Innovate in production from alternative sources, e.g. sewage sludge or waste plastics as a steppingstone to regional revitalisation	chains by innovating in transport and storage technologies • Focus on LH2 and LOHC technologies • R&D around ammonia to address NOx issues through combustion – aim to introduce ammonia as a fuel by mid-2020s • Investigate methanation of CO_2-free hydrogen	power generation with target generation cost of 17Yen/kWh (~$0.16) and ultimately as cheap as LNG-based power. Could involve use of ammonia or syn-methane • **Transportation**: Strong focus on promoting fuel cell cars and other road vehicles as well as materials handling and marine applications • **Heat**: Promote hydrogen as heating fuel, where electrification not practical. Expand ene.farm to 2030; promote hydrogen CHP over long term • **Industry**: Focus on replacing fossil hydrogen with CO2 free hydrogen in industrial processes

Supporting funding and policy
• Aim to access supplies of 300,000 tonnes of hydrogen by 2030 at a target cost of 30Yen/Nm3 (~$0.28) rising to 5-10mT in power sector alone. • Target 40,000 FCEVs by 2020 rising to 200,000 by 2025 and 800,000 by 2030. Target 160 HRS by 2020 with 320 in 2025 and beyond that allow commercial development. Additional targets for buses (1,200 by 2030) and forklifts (10,000). • In order to promote the uptake of renewable hydrogen, the construction of a scheme to enable trading of the environmental value of hydrogen is being considered, e.g. use of existing J-credit scheme.[50] • Focus on working internationally in the development of standardised codes and practices.

Key takeaways

- Japan has strong intent with regards to hydrogen with **a clearly set out and articulated strategy**.
- It has an **existing track record in deploying hydrogen-related technologies**, e.g. stationary fuel cell heat and power and fuel cell vehicles.
- Although Japan is anxious about the competitiveness of its industry and has been reluctant to embrace technologies which might adversely affect this, **it sees an opportunity to be a leading innovator in hydrogen fuel cell technologies**.

[50] https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/japan#:~:text=In%202017%2C%20the%20government%20formulated,the%20period%20up%20to%202030.

- Its strategy is therefore as much driven by industrial policy considerations as it is about decarbonisation and to date has been quite **supply-side driven**.
- **Energy security** is another critical consideration for Japan as it imports most of its energy and the hydrogen strategy is aimed at providing greater energy security.

5.1.4 Overall takeaways

It is evident from the country case studies that the drivers for hydrogen deployment vary widely according to the country-specific context. While decarbonisation represents a common theme across all countries, this is not the only consideration.

The need to achieve net zero has resulted in increased focus on hydrogen within overarching climate policy but existing policy is largely technology agnostic with hydrogen only one among a plethora of means to achieve this goal. It is yet to be seen how stated intentions towards hydrogen will translate into future policies and what will be put in place to realise the ambitious hydrogen targets announced.

Industrial strategy is also a critical driver, especially in countries like Germany and Japan with significant manufacturing capability. Here the development and use of hydrogen can be at once defensive, ensuring that the manufacturing sector remains competitive as GHG emissions targets tighten, and opportunistic, seeking to take advantage of new markets which will emerge along the hydrogen supply chain.

Another driver from the policy perspective is air quality incentives which have resulted in changes at both the national and local level. Announcements from cities banning emitting vehicles have spurred many fleet operators to work with OEMs to develop hydrogen alternatives. For example, in Hamburg, from the beginning of the 2030s onwards, only emission-free and low-noise buses will be allowed to operate and this is supported by procurement initiatives.

Finally, energy security is a preoccupation for many countries and the potential to produce and use hydrogen domestically is an attractive proposition for large importers of fossil fuels. Where local production is not an option, e.g. in Japan, ensuring access to imported low carbon or zero carbon hydrogen is a critical aspect of its energy transition.

5.2 Project case studies

5.2.1 Project case study 1: White Dragon

Aims and objectives

The White Dragon is a project which will see the gradual replacement of coal-fired power production in Western Macedonia, to clean energy production and transmission, with the goal of fully decarbonizing Greece's energy system. Whilst the project has yet to be accepted by the EC, it has been included here to demonstrate project viability outside the most affluent countries in the EU. The anticipated electrolytic hydrogen production is 250,000 ton per year using solar energy. This will be used to:

- Feed heat into the local district heating system serving some 120,000 citizens; while
- Excess hydrogen will be exported via injection into the Trans-Adriatic Gas Pipeline, which crosses Greece and Albania and goes sub-sea to connect to Italy, for applications such as transport refuelling.

Figure 34 Trans-Adriatic Pipeline

Source: https://www.tap-ag.com

Description

The Region of North-Western Macedonia has supplied a large proportion of electricity to Greece since 1960 via coal (lignite) fired generation. While domestic lignite resources have underpinned low cost electricity generation, requirements of legislation such as the EU's Large Combustion Plant Directive and the application of the EU Emissions Trading System (EU ETS) have seen lignite-fired power generation decline in the region. In 2019, for example, the capacity factor of the 11 lignite-fired units across Greece still in operation only ranged between 5% and 31%. This has resulted in job losses and the Greek government has been seeking a new, more sustainable production model for the Region of North-Western Macedonia based around low carbon electricity production. The White Dragon project site will cover 1.5 million m^2 in Western Macedonia and see the deployment of PV parks with a capacity of 1.5 GW.

Reflecting the growing interest in hydrogen, the project has the goal of producing more than 250,000 tonnes per year hydrogen via a reversible solid oxide electrolyser using solar energy from the PV park. The hydrogen produced will have multiple uses and will be stored in hydrides, in LOHCs and as compressed hydrogen. The project is expected to trigger investments of €2.5 billion and create 5,000 direct jobs.

Partners

Eight companies from four countries (Greece, Italy, Belgium, Germany) are involved. The Regional Authority of Western Macedonia is coordinating the project and the other project partners are DEPA (the Greek natural gas supply company), gas grid operator DESFA, Hellenic Petroleum (Balkan oil company), Motor Oil Hellas (petroleum refining and trading), Mytilineos (Greek energy and EPC conglomerate), Terna Energeiaki (Greek renewable energy company), Polish company Solaris (producer of public transport vehicles), the Demokritos National Centre for Scientific Research and the Centre for Research and Technology Hellas. Hellenic Petroleum and Motor Oil are participating in White Dragon for the production of renewable hydrogen in the context of their obligation to reduce their environmental footprint.

Lessons (to be) learned

At its heart, the project will allow the commercial viability of very large solar generation combined with hydrogen production to be tested. However, the project will also allow certain specific and novel technologies to be tested, notably the reversible SOFC is relatively new technology, and an important outcome of the project will be to understand how it performs under realistic operational conditions. Furthermore, this will be an opportunity to test the viability of solid hydride and LOHC storage technologies, again under realistic conditions.

Challenges encountered (if known)

On 19 May 2021, the consortium submitted the proposal to the Greek government and the European Union so is still awaiting multiple levels of approval. It hopes to be one of the four projects Brussels will subsidise in the context of the Hydrogen Europe programme under the IPCEI umbrella. This funding would be vital for the planned implementation. The combined budget for the project, if approved in its entirety by the European and Greek authorities, is €8.063 billion. The proposal already has the support of the Region of Western Macedonia and the Cluster of Bioeconomy and Environment of Western Macedonia.

5.2.2 Project case study 2: Carbon-free e-mobility system in Switzerland driven by Coop

Overview

This Swiss system unites various players in the energy and mobility sector in a joint, private sector system. Each element in the e-mobility system, from the energy source and production to the use in the electric vehicle, is completely free of CO_2 emissions.

The production of renewable hydrogen, its storage and its delivery to filling stations will be managed by Hydrospider. Hydrogen fuel cell trucks will be imported by Hyundai Hydrogen Mobility (HHM). Members of the H2 Mobility Switzerland Development Association will use these vehicles and establish the nationwide refuelling infrastructure. H2 Energy will operate the central platform for implementing the mobility system (skills centre for technology and business).

Aims and objectives

The carbon-free e-Mobility project in Switzerland is a pre-commercial trial aimed at testing all the elements of a hydrogen-based heavy duty road transport system with the ultimate aim of reducing CO_2 emissions from road transport. It is the largest trial of its kind taking place in Europe currently, with the aim of deploying 50 trucks initially and several hundreds of trucks in later phases. It will provide the evidence base necessary to understand the commercial case for hydrogen-fuelled transport and bridge the gap to full commercial deployment through driving costs down.

Description

The initial phase of the project will see the deployment of 50 Hyundai Xcient Fuel Cell hydrogen-powered electric vehicles (36 tonne trailer trucks) in Switzerland from the end of 2020. Expansion will take place from 2021 to 2023 with a total of 1,600 fuel cell trucks to be on the road by 2025. Hyundai's heavy duty truck will be powered by a 190 kW fuel cell using two 95-kW stacks connected in parallel. They have seven high pressure hydrogen tanks providing a storage capacity of almost 32 kg of hydrogen so will have a range of 400 km per refuelling operation. Hyundai says that the refuelling process should be as short as eight to 20 minutes. Each vehicle will save 80 tCO_2/year (average emissions of the diesel trucks they are replacing).

The hydrogen supply, infrastructure, and a small filling station network have already been rolled out. There are three filling stations in operation (Hunzenschwil (Coop), St Gallen (Avia) and Zofingen) and five more are currently being planned over the route between Lake Constance and Lake Geneva to promote hydrogen mobility in Switzerland. These filling stations will offer renewable hydrogen (H2 ZERO) for commercial vehicles (350 bar) and passenger cars (700 bar). The network of filling stations will be expanded over the coming years to supply the growing number of trucks with renewable hydrogen. Over 10 years, Hyundai estimates the assumed investment of 1.3 million Swiss francs (~€1.2 million) in a pump could be recovered if 15 trucks visited it exclusively for their annual fuelling needs.

Production of renewable hydrogen, managed by Hydrospider, takes place at a new 2 MW electrolysis facility at Alpiq's hydroelectric power plant in Gösgen. Hydropower provides more than half of Switzerland's energy today and is a ready source of energy for hydrogen production. As more hydrogen trucks go into service it will boost capacity to between 70 MW and 100 MW by 2023-2025.

The trucks will be leased by HHM to member companies of H2 Mobility Switzerland Association, transport and logistics companies which distribute goods throughout Switzerland. Pay-per-use contracts will give the leasing companies mileage, warranty, service, insurance and access to sufficient hydrogen in a system that does not require any initial investment. One thousand of these fuel cell trucks have been ordered by Coop alone (one of Switzerland's largest supermarkets (wholesale distribution) with over 900 sales points, CHF 30.7 billion (~€28.4 billion) turnover in 2018 and around 90,000 employees.

Coop has already been using fuel cell trucks produced by ESORO (but not built in commercial capacity). In June 2017, the Zurich engineering company ESORO received road approval for the world's first fuel cell heavy duty vehicle (35-tonne - the necessary load capacity able to fulfil Coop's logistical requirements). It had 100 kW fuel cell capacity (made by Swiss Hydrogen), 31 kg hydrogen storage at 350 bar and 2x60 kWh batteries. The project partners were Coop, H2 Energy, Swiss Hydrogen, Powercell and Ceekon/Emoss.

Switzerland was chosen for the programme as it features challenging terrain with steep elevation and is known for high road taxes on commercial vehicles to reduce emissions and prevent trucks from crossing through the country as they traverse Europe. Depending on weight and distance driven, the annual tax can cost up to $50,000 per vehicle. Fuel cell trucks are exempt from mineral oil tax and are not subject to road charges; the potential savings from the tax exemption alone contribute to a total cost of ownership that Huber expects will be equivalent to operating a conventionally powered truck.

Partners

The project's sponsors are:

- Hydrospider (a joint venture between Alpiq, H2 Energy and Linde founded in early 2019).
- HHM (a joint venture between the Hyundai Motor Company and H2 Energy).
- The H2 Mobility Switzerland Association is a consortium of private companies (service station operators and transport and logistic companies) created at the initiative of Coop in 2018 with the objective of setting up a network of hydrogen service stations covering the whole of Switzerland by 2023. Jointly, the member companies operate more than 2,000 traditional refuelling stations and over 5,000 heavy duty commercial vehicles on the road, an ideal combination to establish a nationwide hydrogen infrastructure. The association does not itself intend to pursue any commercial gains and particular investments for vehicles and infrastructure are funded by the individual member companies at their own expense.

  The H2 Mobility Switzerland Association was founded by seven companies in May 2018 - Agrola, AVIA, Coop, Coop Mineraloel AG, the fenaco cooperative, Migrol and Migros Cooperatives. Additional service station operators and transport and logistic companies have joined; SOCAR Energy, The Emil Frey Group, hell Galliker Transport & Logistics, Camion Transport, G. Leclerc Transport, F. Murpf, Tamoil, Christian Cavegn, Emmi Schweiz, Schöni Transport, Gebrüder Weiss, Streck Transport and von Bergen SA.
- H2 Energy, which will produce and distribute the renewable hydrogen.

Lessons (to be) learned

The project provides an opportunity to test the commercial viability of hydrogen as a fuel for heavy duty transport and to allow learning to be applied to the manufacturing process, driving down cost, improving reliability and underpinning the development of new models. It will allow operators to learn lessons regarding the operation of fuel cell trucks and to gain confidence with the refuelling network.

Hyundai has ambitious plans to build on what it views as a test case in Switzerland, and the company plans to expand internationally. Within Europe the focus lies on the development of solutions and partner networks in Germany, the Netherlands, Austria and Norway with the aim to launch similar projects in at least two more European countries this year. Green H2 Norway is a joint venture with H2 Energy, Greenstat and Akershus Energi to establish renewable hydrogen production facilities in Norway to supply hydrogen to Hyundai trucks which are expected in Norway from 2020. Hyundai expects more than 25,000 hydrogen fuel cell trucks to operate in Europe by 2030 by which point it will have to increase its annual capacity for fuel cells to 700,000.

Production capacity of the Xcient Fuel Cell will reach 2,000 units per year by 2021 to support its expansion into Europe, the US and China as demand for clean mobility grows. The increase in capacity will be backed by a $1.3 billion investment in addition to the previous $6.4 billion used to establish the hydrogen ecosystem. By 2030, Hyundai expects more than 12,000 fuel cell trucks to hit the US roads. Hyundai is also working with various parties in China, which aims to get 1 million hydrogen vehicles on its roads by 2030.

Hyundai is planning a semitrailer tractor in addition to the Xcient, which will have a range of 1,000 kilometres as well as other fuel cell trucks in development.

Supermarket chain Migros is taking delivery of three Xcient trucks and plans to measure their performance against a Mercedes-Benz (DAIGn.DE) battery powered truck, three biogas-fuelled trucks from Italy’s Iveco (CNHI.MI) and their current diesel trucks.

Figure 35 Hyundai XCient Hydrogen fuel cell heavy duty truck leased to Coop

Source: https://dhl-freight-connections.com/en/fuel-cell-truck/

Challenges encountered (if known)

Currently, Hyundai relies on government tax breaks for fuel cell trucks and internal subsidies to help make them economically viable for its partners. Hyundai has declined to say how much its own subsidies amount to but recognises that while this new technology is being introduced it is initially a subsidised business model.

Subsidies can be expected to decrease over time as reductions in fuel and capital costs decrease. By 2030, the expectation generally (i.e. not for this project alone) is that hydrogen fuel cell trucks will be comparable with all the trucks running on combustion engines when it comes to fuel costs[51].

[51] See, for example, Hydrogen Council (February 2021), Hydrogen Insights – A perspective on hydrogen investment, market development and cost competitiveness,

5.2.3 Project case study 3: H2Future

Aims and objectives

H2FUTURE aims to prove the industrial production of renewable hydrogen as a means of replacing fossil fuels in steel production at the Voestalpine steel manufacturing site in Linz, Austria. It seeks to demonstrate that an industrially integrated PEM electrolyser can produce renewable hydrogen and supply grid services at the same time. The project will investigate the potential to provide network services, and potentially compensate for fluctuations in the power grid. The renewable hydrogen will be fed directly into the internal gas network, allowing the testing of hydrogen use in various process stages of steel production to meet future needs of low carbon manufacturing value chains. In addition, the potential for "breakthrough" steelmaking technologies will be investigated which replace carbon with renewable hydrogen.

Description

H2FUTURE is currently the world's largest and most advanced hydrogen pilot facility using PEM electrolysis technology to produce renewable hydrogen. The project began on 1 January 2017 and has a duration of 4.5 years. It has a project budget of €18 million funded through the EU Horizon 2020 programme, the EU's largest research and innovation programme through FCH-JU.

The project involves the installation of a Siemens Silyzer 300 PEM electrolyser, with a capacity of 6 MW and able to generate 1,200 cubic metres of renewable hydrogen per hour, at the Voestalpine steel plant in Linz Austria.

The next step in the project will be to test the integration of the electrolyser with steel production at the Linz plant. Voestalpine is taking a stepwise approach to decarbonisation of steel production by hydrogen; in the short term, it is primarily focused on natural gas as a bridge technology in the direct reduction process in addition to the conventional route. In the long term there will be a full transfer to process routes like direct reduction based on the use of renewable hydrogen and electric arc furnaces.

Approximately 7% of global CO_2 emissions are related to the steel industry, mainly resulting from carbon that is necessary to extract the oxygen from the iron oxide. The scope to reduce CO_2 emissions by optimising the dominant blast furnace/BOF steelmaking route, based on coal/coke, is limited but this route represents 70% of global steel production. Renewable hydrogen could become a major lever to speed up decarbonisation in industry.

Figure 36 The Voestalpine steel production plant in Linz, Austria

Source: https://www.h2future-project.eu/

Over the long term, Voestalpine is striving to successively increase the use of renewable hydrogen in the steel production process, allowing the Group to reduce its CO_2 emissions by a total of over 80% by 2050. Voestalpine is currently investigating the practicality of a hybrid technology to bridge between the existing coke/coal-based BF route and electric arc furnaces powered with green electricity partly generated using renewable hydrogen. If economically feasible, from today's perspective, this option would reduce Voestalpine's CO_2 emissions by around a third sometime between 2030 and 2035.

Partners

This project brings together energy suppliers, the steel industry, technology providers and research partners:

- The utility Verbund is coordinating the project. It is Austria's largest electricity provider covering around 40% of electricity demand in Austria of which 90% comes from hydropower. Verbund will provide the electricity for this project from renewable energy sources and is responsible for developing and testing grid services with the electrolyser.
- The steel manufacturer Voestalpine.
- Siemens is manufacturing the PEM electrolyser being used.
- Austrian Power Grid, the transmission operator of Austria will provide support in integrating the plant into the power reserve markets.

- The Netherland's research centre TNO is responsible for the scientific analysis of the demonstration operation and the transferability to other industrial sectors.
- K1-MET (Austrian metallurgical competence centre) will provide its expertise in the operation of the plant and will demonstrate potential applications in the European and global steel sector.

Lessons (to be) learned

The demonstration is split into five pilot tests and the quasi-commercial operation so far shows that the PEM electrolyser can:

- Use timely power price opportunities to provide affordable hydrogen for current uses of the steel making processes;
- Help to compensate fluctuations, using demand side management, in an increasingly volatile power supply and enable higher shares of wind and solar energy; and
- Attract extra revenues from grid-balancing services which improves the hydrogen price attractiveness from a two-carrier utility like Verbund.

The Netherland's research centre TNO will study the replicability of the experimental results at larger scales in the EU for the steel industry with inputs from Transmission System Operators in Italy, Spain and the Netherlands.

A dedicated H2FUTURE work package aims to quantify and benchmark the technical, environmental, economic and grid-related performance of the electrolyser plant using the CertifHY tools. This will provide the background for developing, scaling and replication scenarios not only for the steel industry, but also for other industrial sectors requiring large volumes of hydrogen such as the fertiliser industry and in refineries.

The regulatory framework will be assessed regarding barriers and bottlenecks that might prevent the acceleration of deployment. The respective findings will be communicated to and discussed with the relevant stakeholders on national and EU levels.

Future, bigger electrolyser projects are also underway elsewhere including:

- A 10 MW PEM electrolysis plant, REFHYNE, which is under construction at Shell's Rhineland refinery in Wesseling, Germany, that was due to be completed by the end of 2020; and
- A 30 MW pilot, part of a 700 MW project which is expected to be up and running in northwest Germany by 2025.

It is hoped this project will provide the basis for further upscaling to industrial dimensions and decarbonising industrial processes. H2FUTURE provides an opportunity to address regulatory challenges that need to be solved to create a sustainable environment for European industry players.

5.2.4 Project case study 4: HyDeploy

Aims and objectives

HyDeploy is an energy trial to establish the potential for blending up to 20% hydrogen into the natural gas supply. It aims to prove that blending up to 20% volume of hydrogen with natural gas is a safe and greener alternative to the gas used today.

Description

The HyDeploy project is the UK's first grid-injected hydrogen pilot to heat homes and businesses and the first ever live demonstration of hydrogen in homes. The nationwide network of gas pipes consists of 176,469 miles (284,000 km) of pipework, is connected to 23 million homes, fuels all industrial sites and supplies gas turbines which in 2018, generated over half of the UK's electricity supply. Finding a low carbon alternative to put into the gas network is a research area of growing importance to meet UK net zero targets by 2050. If a 20% hydrogen blend were rolled out across the country, it could save around 6 million tonnes of CO_2 emissions every year.

HyDeploy is the first stage of this three-stage programme. In November 2019, the UK Health and Safety Executive (HSE) gave permission to run a 16-month live demonstration to test the efficacy of blended hydrogen and natural gas on part of the private gas network at Keele University campus in Staffordshire. The University owns and operates its own private gas network feeding 100 homes and 30 faculty buildings which can be safely isolated from the wider UK gas network making it a good location for the pilot project.

Across Europe, permitted levels of hydrogen in the gas supply vary, from 0.1% in the UK to up to 12% in parts of the Netherlands. In 2018, HSE granted the HyDeploy consortium an exemption to the current limit of 0.1% hydrogen in the UK gas network. The hydrogen content has so far reached a blend of 15% added to the existing gas supply and will eventually be 20% which is the highest in Europe, together with a similar project being run by Engie in Northern France. The use of the blended gas requires no change to appliances and customers do not notice any difference to their gas supply.

Once the Keele stage has been completed, HyDeploy will move to larger demonstrations on public networks in the North-East and the North-West in the early 2020s. These are designed to test the blend across a range of networks and customers so that the evidence collected is representative of the UK as a whole. The North-East trial starting in early 2021 will involve 670 houses in Winlaton and will include the church, primary school and several businesses and will be the first public network to receive a 20% hydrogen blend for 10 months.

The hydrogen for HyDeploy is being generated on the Keele University site using a grid connected electrolyser supplied by ITM.

Partners

HyDeploy is a £6.8 million (€7.6 million) project, funded by Ofgem and the HyDeploy consortium is led by Cadent (the UK's largest gas distribution network business). The partners include Northern Gas Networks, Progressive Energy Ltd, Keele University, HSE Science

Division and ITM Power is supplying the electrolyser system. The first HyDeploy live demonstration is being hosted on the Keele University campus in Staffordshire.

Lessons (to be) learned

Currently, 30% of carbon dioxide emissions in the UK are generated from the natural gas used to heat the 85% of homes which are connected to the gas network. To achieve net zero emissions by 2050 will require significant changes to the gas supply or a switch to alternative forms of heat. Some ‘low carbon’ gases are in use today such as biomethane, but this type of gas cannot meet demand and this project will allow the technical and commercial viability, reliability and safety of hydrogen blending to be tested.

A number of the elements of the hydrogen production, blending units, and other supporting equipment are first-of-a-kind and so their performance is being monitored closely. The project will allow the learning from these experiments to be more widely disseminated. Furthermore, the University is working with businesses, academics and graduates to create Europe’s first ‘at scale’ multi-energy-vector Smart Energy Network Demonstrator, where new energy-efficient technologies can be researched, developed and tested in a real-world environment.

HyDeploy will help to determine the level of hydrogen which can be used by customers safely and with no changes to their existing domestic appliances which means less disruption and cost for them. It is also confirming initial findings that customers do not notice any difference when using the hydrogen blend.

Social acceptance is a key part of technical energy transitions and it will be important to understand the views and perceptions of people using a hydrogen blend in their homes as part of the pilot.

Challenges encountered (if known)

In the run-up to the demonstration project starting, there were varied attitudes towards cost implications, with several participants mentioning this as an area of initial concern for the future, although those taking part in the pilot project are not being charged for the hydrogen. It was also found that people wanted reassurance about safety aspects of accepting the blend into their homes.

Blending for the HyDeploy project was temporarily suspended when the Covid-19 lockdown was introduced but has now resumed at Keele University.

Figure 37 Gas grid injection of hydrogen as part of the HyDeploy project

Source: https://www.itm-power.com/news/hydeploy-uk-gas-grid-injection-of-hydrogen

5.2.5 Key takeaways for CPs

The foregoing project case studies were selected to demonstrate the wide range of experimentation being undertaken for the possible production and utilisation of hydrogen. Hydrogen can potentially represent a new and separate energy vector requiring a reconfiguration of how energy is produced, stored and consumed. Accordingly, projects were chosen that examine this reshaped producer-consumer relationship for different possible hydrogen applications (in the energy, transport and industry sectors). All projects ultimately aim to prove the technical and commercial viability of hydrogen and reduce the risk of scaling up their respective technologies, but they also hold broader lessons of relevance to stakeholders (including the CPs) such as the following:

- As with any project, **clear objectives and outcomes are essential** – the selected project case studies are all centred around very specific applications of hydrogen, together with a clear definition of the roles and responsibilities of the parties involved and well-defined outcomes.

- **Collaboration among varied stakeholders is critical** – this includes players along the entire hydrogen value chain, the government and private sector, technology providers, research institutes and others. Such cooperation is necessary given the system reconfiguration required and the need to ensure that the solutions (and their constituent elements) that emerge meet the needs of all affected parties. It also allows the various stakeholders to contribute according to their expertise and abilities. All selected project case studies are characterised by such collaborative efforts, for example:

- **White Dragon** brings together international partners (offering their expertise); a mix of private companies such as oil companies wishing to reduce their carbon footprint, gas companies that want to invest in and secure a future that would involve less or no natural gas, and companies with renewables portfolios that are seeking diversification; and academic institutes that can contribute latest knowledge and innovation.

- **e-mobility Switzerland** entails the collaboration of stakeholders across the whole value chain, from source to distribution to use, and with expertise in all the required areas to realise end-to-end transportation using hydrogen, e.g. vehicle manufacture, hydrogen production, goods distribution and logistics, fuelling station operation, etc. It also highlights the global considerations around hydrogen, bringing together partners in Europe and South Korea.

- **H2Future** which is exploring the use of hydrogen in steel production also involves a varied group of partners, including energy suppliers, a steel manufacturer, technology providers, research outfits, electricity transmission system operators from various countries, etc.

- **If hydrogen is to play a significant role, it will need to be considered a safe, reliable, efficient and low cost fuel by consumers**, or put differently, social acceptance is important – the HyDeploy project in the UK which is blending hydrogen into existing gas networks is a good example of this as part of the project is to understand the views and perceptions of people using a hydrogen blend in their homes

- **Lessons can be learned from ongoing amendments to regulation and from updates to national rules that have enabled these projects.**

  - Hydrogen technology ISO standards are developed by the ISO/TC 197 technical committee and ensure standardisation in the systems and devices for the production, storage, transport, measurement and use of hydrogen. They are continuously being amended to keep pace with ongoing developments. For example ISO 14687:2019 is the hydrogen fuel quality product specification for use in vehicular and stationary applications and is being updated reconsidering the new tolerances of hydrogen impurities within PEM fuel cells.

  - As above, the UK Health and Safety Executive granted the HyDeploy consortium an exemption to the current limit of 0.1% hydrogen in the UK gas network. Across Europe, permitted levels of hydrogen in the gas supply vary, from 0.1% in the UK to up to 12% in parts of the Netherlands. The HyDeploy project aims to prove that blending up to 20% volume of hydrogen with natural gas is a safe and effective alternative.

- **Given that the adoption of hydrogen can entail a wider systemic transition, the social and economic consequences of this change need to be recognised and managed** – this is demonstrated by the White Dragon project, for example, which is focused on a region with a very high dependence on coal and a local economy that was built over decades around coal mining and coal-fuelled power generation. The inevitability of adopting cleaner fuels and decarbonising can be seized as an opportunity to ensure the region may continue to play a significant role in a ‘greener energy future’ thereby also helping manage the negative consequences (social and economic costs) of the transition.

- **The outcomes of these projects can provide broader lessons** that could apply to other countries and/or sectors – the H2Future project explicitly provides for using insights gained from this project to other industrial sectors and sharing information and findings widely (at the EU level), while also identifying any regulatory challenges that need to be overcome beyond assessing the technical and commercial viability of the project.