Government of the Netherlands

CATAPULT Energy Systems

Market Study

Hydrogen in the United Kingdom

An overview for SMEs and Research Institutes on the ambitions, activity and opportunities in the British hydrogen sector.

March 2021

Colophon
This market report has been written by the Energy Systems Catapult and commissioned by the Netherlands Innovation Network UK and the Embassy of the Kingdom of the Netherlands.

Authors
Eveline Sleiman, Energy Systems Catapult
Abdulrahman Elgalassi, Energy Systems Catapult

Editors
Tessel van Essen, Senior Commercial Attaché, Embassy of the Kingdom of the Netherlands in the UK
Marjolein Bouwers, Chief Innovation Advisor, Netherlands Innovation Network UK
Lara Neervoort, Innovation Advisor, Netherlands Innovation Network UK

Contributors
Inès Tunga, Practice Manager – Renewables, Energy Systems Catapult
Susanna Elks, Energy Policy Advisor, Energy Systems Catapult
Sanjay Mukherjee, Energy Systems Engineer, Energy Systems Catapult

Contact details
Embassy of the Kingdom of the Netherlands
38 Hyde Park Gate
SW7 5DP London
United Kingdom
T +44 20 7590 3259

Energy Systems Catapult
7th Floor, Cannon House
18 Priory Queensway
Birmingham
B4 6BS

es.catapult.org.uk
info@es.catapult.org.uk
+44 (0)121 203 3700

Energy Systems Catapult supports innovators in unleashing opportunities from the transition to a clean, intelligent energy system.

Contents

1. Introduction 3

2. Context 4

2.1. Policy and ambitions 4

2.1.1. Looking Ahead 7

2.1.2. Devolved administrations 8

2.2. Public and private investments 9

2.3. The bigger picture: other low-carbon alternatives in the UK 11

3. Industry Overview 14

3.1. Industry structure and key sectors where hydrogen is applied 14

3.2. Research and Innovation 20

3.3. Funding 24

3.4. Key Stakeholders 25

3.4.1. Industry, Research and Knowledge Centres 26

3.5. Opportunities and barriers to hydrogen in the UK 29

4. Opportunities for collaboration 31

4.1. Platforms promoting collaboration 31

4.2. Relevant public-private partnerships 32

4.3. Potential commercial opportunities 32

5. Recommendations and suggestions 34

6. References 36

1. Introduction

On the 18th of November 2020, the UK Prime Minister, Boris Johnson announced his Ten Point Plan[1] for a green industrial revolution in the UK. This plan covers clean energy, transport, nature and emerging technologies and aims to create and support up to 250,000 jobs in the UK.

Hydrogen is one of the key priorities of the ten point plan, which outlines that the government will be "working with industry aiming to generate 5GW of low carbon hydrogen production capacity by 2030 for industry, transport, power and homes, and aiming to develop the first town heated entirely by hydrogen by the end of the decade."[2]

Currently, there is no large-scale production of low carbon hydrogen in the UK. Therefore, the aim of the UK government set out in the Ten Point Plan signals a clear ambition to "build back better" after the COVID-19 crisis and aims to illustrate global leadership ahead of hosting this year's COP26 summit.

Given the UK's investment in the development of the hydrogen sector, from both the government and industry, new policy incentives being developed, and similar challenges faced by the Netherlands, the UK is a highly attractive candidate for comparisons in policy and collaboration in this field.

As a result, the Embassy of the Kingdom of the Netherlands in the United Kingdom has indicated an interest in learning from the UK about deploying hydrogen for both the industrial and urban environments, as well as identifying areas for collaboration. This market study was commissioned to support this agenda. This report aims to:

- provide an overview of the UK hydrogen landscape including government ambitions and activities to support these, current policy and sectors for hydrogen use
- identify commercial opportunities for Dutch SMEs and knowledge institutes in the application of (low carbon) hydrogen across transport, power generation, heating (grid blending) and the industrial sector
- identify opportunities for collaboration between the Dutch and the British hydrogen industry and ecosystems

To support this agenda the report below is broken into four key sections to provide a high-level overview of the Hydrogen sector in the UK. It provides context in terms of the UK Government's ambitions as announced in the Ten Point Plan and recently published Energy White Paper[3]. The report highlights various investments and funding plans being announced and strategy documents being published in 2021 and 2022 that will be provide further guidance and policy measures. The report also provides some insight into the key areas of focus for hydrogen end use, recent activity, research and innovation, as well as key sector stakeholders.

Please note, this report is not intended to provide a detailed nor comprehensive view across any of the sections below but act as a starting guide in navigating the UK hydrogen sector landscape.

2. Context

This section provides an overview of the current UK Government ambitions in achieving net zero and specific ambitions across hydrogen and other relevant sectors as highlighted in the Ten Point Plan and Energy White Paper. It captures some of the policy, investment plans and incentives being put in place in the UK, as well as upcoming plans that will enable scale-up of hydrogen and a low carbon economy.

2.1. Policy and ambitions

The Prime Minister's Ten Point Plan for a Green Industrial Revolution[4] sets out the approach government will take to build back better, support green jobs, and accelerate the UK's path to net zero. The UK government aspires to lead a new Green Industrial Revolution by investing in clean technologies such as wind, carbon capture, hydrogen and others. The second point addressed in the plan focuses on 'Driving the Growth of Low Carbon Hydrogen'. This section lays out the following targets:

- Commitment to publish a hydrogen strategy in early 2021
- Target of 5GWs of low carbon hydrogen production capacity by 2030 – supported by up to £500 million for low carbon hydrogen production to 2030 with £240m committed out to 2025
- Conduct a Hydrogen Neighbourhood trial by 2023, and support for a Hydrogen Neighbourhood by 2023 and ambition for a Hydrogen Town before 2030
- Commitment to support new business models for industry Carbon Capture and Storage (CCS) and low carbon hydrogen
- Address constraints regarding potential to blend hydrogen into the gas grid to allow for up to 20% blending of hydrogen
- Setting ambition to capture 10Mt of carbon dioxide a year by 2030, supported by up to £1 billion investment to create two carbon capture clusters by the mid-2020s and another two by 2030

Building on this the Government is developing a hydrogen strategy which will be published in 2021. It is intended to set out business models and revenue mechanisms to promote private sector investment. There will also be a consultation on the Government's preferred support mechanism for hydrogen in 2021 with the aim to finalise in 2022.

The Ten Point Plan also includes wider plans on other sectors and end uses relevant to hydrogen such as offshore wind, carbon capture, buildings and transport. These ambitions and targets have been captured in Table 1 below.

Following the Ten Point Plan the UK government released the Energy White Paper[5] in late 2020, which sets out the government's policies and commitments that will put the UK on course to net zero. The White Paper includes some of the following key commitments:

- consult on the role of 'hydrogen ready' appliances in 2021. Using hydrogen as a heating source requires household appliances to be hydrogen 'ready'. As a result, the government is supporting the testing of hydrogen-ready boilers (gas boilers which can be easily changed to burn hydrogen) through the Hy4Heat programme. The government will issue a call for evidence in summer 2021 based on the findings of the programme. Hy4Heat is also developing prototypes for cookers and fires to integrate hydrogen further into domestic

use. The plan is to work with industry on the testing necessary to boost hydrogen in gas distribution grid up to 20% (blending) by 2023.

- support carbon capture and storage infrastructure in four industrial clusters in the areas which are the North East, the Humber, North West, Scotland and Wales (creating what is being called 'SuperPlaces'). As mentioned above to be supported by investing up to £1 billion to facilitate the deployment of CCUS in industrial clusters.
- support at least one power CCUS project, to be operational by 2030. More details will be brought forward in 2021 of a revenue-mechanisms to bring through private sector investment into industrial carbon capture and hydrogen projects. Following the publication of the government response to CCUS business models consultation last year[6] the UK will introduce a business model based on the existing Contracts for Different (CfD) framework adapted so that price signals incentivise power CCUS to play a role in the system.
- 40GW of offshore wind by 2030, including 1GW floating offshore wind, alongside the expansion of other low-cost renewable technologies. The UK will continue to hold regular CfD auction rounds every two years with the next auction open in late 2021 that will be open to onshore wind, solar photovoltaics and other established technologies. In addition to growing UK offshore wind capacity, the UK has set a target of 60 per cent UK content in offshore wind projects by 2030 using more stringent requirements for the CfD supply chain process.
- support the UK oil and gas sector to repurpose its existing infrastructure in support of clean energy technologies, recognising the potential for cost savings particularly in relation to deployment of CCUS. In 2020, the government published their response to a consultation on the re-use of oil and gas assets for CCUS projects[7]. This review identified assets which could have the greatest potential for re-use in CCUS. Next steps involve working with industry and regulators on regulations and development of technical guidance on how this can be done safely and securely.
- commitment to establishing a new UK Emissions Trading System to replace participation in the EU ETS.

It is also worth noting the Renewable Transport Fuel obligation[8], which commenced on 15 April 2008 and is intended to deliver reductions in greenhouse gas emissions from fuel used for transport purposes by encouraging the supply of renewable fuels.

Table 1: Summary of milestones from the Ten Point Plan

Year	Sector	Target Milestones
2021	**Hydrogen**	Publish the Hydrogen Strategy and begin consultation on Government's preferred business models for hydrogen
	Offshore Wind	Consult on the introduction of more stringent supply chain requirements Support up to twice the capacity of renewable generation in the next CfD round, with onshore wind and solar projects eligible to bid for CfD contracts
	CCUS	Execute a process for CCUS deployment, working in collaboration with industry and set out further details of a revenue mechanism for industrial carbon capture and hydrogen projects
	Green public transport	National Bus Strategy and first electric bus town Deliver 4,000 new zero-emission buses
	Jet Zero & Green Ships	Consult on the Aviation Decarbonisation Strategy Run a £15 million competition for fuel plants and support production of sustainable aviation fuels
	Zero emission Vehicles	Deliver a Green Paper on the UK's post EU emissions regulations and the car and van phase out dates Launch a consultation on the phase out of new diesel HGVs
	Greener Buildings	Set out the Heat and Buildings Strategy
	Finance & Innovation	Launch remaining priority innovation challenges within the Net Zero Innovation Portfolio
2022	**CCUS**	New CCUS business models finalised
	Hydrogen	Finalise Hydrogen Business Models
	Finance & Innovation	Start vessel trials in Orkney, work towards a hydrogen port in Tees Valley, and launch feasibility studies for several clean maritime clusters across the UK
2023	**Hydrogen**	Work with industry to complete testing necessary to allow up to 20% blending of hydrogen into the gas distribution grid for all homes on the gas grid
	Hydrogen	By 2023 support industry to begin hydrogen heating trials in a local neighbourhood
2025	**Hydrogen**	1 GW of Hydrogen production capacity Support industry to begin a large village hydrogen heating trial, and set out plans for a possible pilot hydrogen town before the end of the decade
	Jet Zero & Green Ships	Consult on a Sustainable Aviation Fuels mandate to blend greener fuels into kerosene
2030	**Zero emission vehicles**	End of sales of new petrol and diesel cars and vans
	CCUS	Two clusters operational by the mid-2020s, subject to relevant value for money and affordability considerations and a further two clusters operational by 2030
	Offshore Wind	Aim to produce 40GW of Offshore wind including 1GW of floating offshore wind

Source: Ten Point Plan

2.1.1. Looking Ahead

Whilst the UK Government has set out targets and strong ambitions there are no specific policies in place yet and as mentioned above, the hydrogen strategy is currently being developed. However, there have been some relevant work and other initiatives that promote hydrogen use in the UK. For example, work has been done in identifying the business models and enablers to support carbon capture and hydrogen production. Some of these relevant reports are:

- Business models for low carbon hydrogen production[9]
- CCUS: an update on business models for CCUS[10]
- Hydrogen Blending and the gas commercial framework[11]
- Britain's Hydrogen Plan – Gas Goes Green[12]
- Pathways to Net-Zero: Decarbonising the Gas Networks in Great Britain[13]
- Clean Maritime Plan[14]

Below are various strategy papers that will be published between 2021 & 2022 which will set out further details and mechanisms to support the UK government's ambitions and plans:

1. Energy White Paper – published
2. Hydrogen Strategy – to be published in 2021 outlining ambitions for the hydrogen economy and short-term actions
3. Transport Decarbonisation Plan setting out Government's vision
4. Heat & Buildings Strategy to include immediate actions for reducing emissions in buildings
5. Industrial Decarbonisation Strategy on how infrastructure can support economic recovery
6. National Infrastructure Strategy
7. Net Zero Strategy to be published in 2021 with details on how the UK will meet net zero
8. Biomass Strategy to be published in 2022
9. North Sea Transition deal in first half of 2021, which includes key deliverables to support delivery of CCUS and development of hydrogen production
10. National Bus Strategy
11. Greening Government Commitments to be published in 2021, to feed into the Net Zero strategy to support COP26
12. The CCC's 6th Carbon budget recently published to feed into the Net Zero strategy to support COP26

Upcoming Government consultations:

- ending gas grid connections to new homes being built from 2025 including reviewing updates to the Gas Act established 1995
- on the role of 'hydrogen ready' appliances in 2021.
- on how the CfD scheme could evolve beyond the 2021 auction, including how longer-term changes to the CfD or wider electricity market design can enable the effective integration of increasing renewables capacity
- ending the sale of new diesel buses – currently open

Source: Ten Point Plan, Energy White Paper and Achieving Net Zero, National Audit Office[15]

UK Hydrogen Advisory council

The UK government has also recently launched a Hydrogen Advisory Council[16] as part of its decarbonisation efforts. The Hydrogen Advisory Council will be the primary forum for the Department of Business, Energy and Industrial Strategy (BEIS) ministerial engagement with representatives from the hydrogen sector.

The Council will consider the relationship between production and end use, including strategic considerations for where and when hydrogen is deployed, alongside coordination with potential demand volumes and cost implications.

The Council and associated working groups will engage with existing industry and government led groups where the remit covers hydrogen or has implications for the development of hydrogen, to ensure alignment as required.

A series of four workstreams with corresponding working groups have been established with participation by application and invitation. These four workstreams comprise:

1. 2020>2030 deployment roadmap
2. Business Models
3. Standards and Regulation
4. Sector and supply chain development

The council is co-chaired by Kwasi Kwarteng, Minister of State for BEIS, and Sinead Lynch, UK Country Chair of Shell. The Advisory Group also includes Government observers from: BEIS, Department for Transport (DfT), Department for International Trade (DIT), Her Majesty's Treasury, Engineering and Physical Sciences Research Council (EPSRC), Northern Irish Government, Scottish Government and Welsh Government. The Energy Systems Catapult (ESC) is also a member of the council. A full list of member organisations can be found on the website as referenced above.

2.1.2. Devolved administrations

The devolved administrations in the UK are also setting out their own decarbonisation strategies and outlining the possible future role for hydrogen in their regions.

The **Scottish Government** published its Hydrogen Policy Statement[17] last year which stated that through policy, they will support the development of at least 5GW of renewable and low-carbon hydrogen production capacity by 2030 and 25GW by 2045.

In 2021 Scotland will publish a Hydrogen Action Plan which will set out the actions to implement hydrogen policies. This will be accompanied by £100 million funding to boost excellence in research, innovation development and demonstration of secure, low-cost clean hydrogen production between 2021 and 2026.

The **Welsh Government** are also considering ways to maximise the potential of hydrogen as they shift reliance away from fossil fuels.

In January the Welsh government launched a consultation seeking views on a hydrogen pathway, based on the findings of a report[18] published back in December to baseline the current situation in Wales with hydrogen-related industries and technologies.

Within the consultation, the Welsh government set out a proposed pathway with the aim of informing activities to take place in the short-term – to 2025. Through ten key objectives (figure 1), it is aiming to build momentum and lay the foundations for scale-up and commercial deployment from the end of the 2020s.

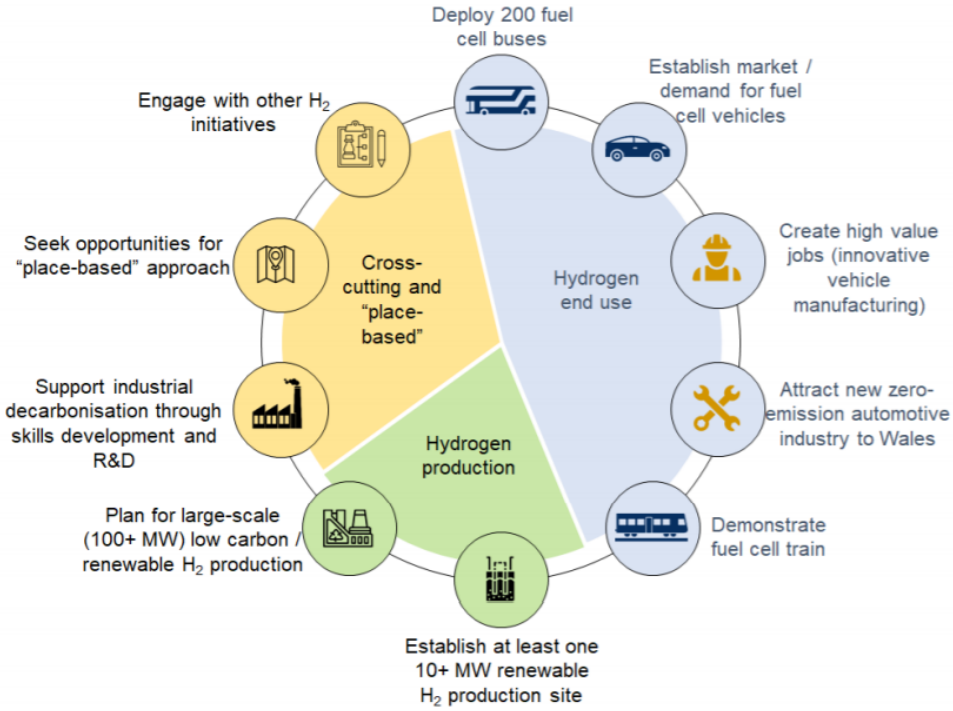

Figure 1: Recommended actions to generate momentum in the Welsh hydrogen sector (Source: Welsh Government Consultation Document[19])

In **Northern Ireland** the Department for the Economy has begun the process of developing a new energy strategy to decarbonise the Northern Ireland energy sector by 2050. This new energy strategy is due to be published by the end of 2021. The first step in the development of the Energy Strategy was a Call for Evidence, which closed on 3 April 2020[20].

Last year the Economy Minister set out new ambitions for renewable energy. Whilst there is still ongoing work to gather the required evidence in setting the new target, the Minister's comment suggested the target should not be below 70% by 2030. As part of the statement, she mentions hydrogen, which is seen as a key enabler of the decarbonisation pathways to net zero emissions. To support this, she plans to bring key players together across the public sector at a senior level to provide government oversight and co-ordination on the development of the hydrogen economy in Northern Ireland.

A series of energy strategy e-bulletins are also currently being published and available online[21] which will keep key stakeholders up to date on progress with developing the new energy strategy.

2.2. Public and private investments

To support the scale up of hydrogen more investments are required to achieve ambitions by 2030. In the Ten Point Plan the government mentions plans to mobilise £12 billion with which it sees potential for three times as much investment from the private sector. The plan mentions the potential to deliver over £4bn of private investment by 2030 as a result of driving the growth of low carbon hydrogen. One of the key support mechanisms will be the Net Zero hydrogen fund which will provide £240 million of capital co-investment for hydrogen production out to 2024/25. Below are some of the key investments being planned over the next decade and refenced in the Energy White Paper.

1) £1 Billion Net Zero Innovation Portfolio focussing on ten priority areas (figure 2) that correspond with the Ten Point Plan. This succeeds the BEIS Energy Innovation Programme (EIP) which ran from 2015-2021 and is intended to accelerate the commercialisation of low-carbon technologies, systems and business models in power, buildings, and industry.

2) £240 million Net Zero Hydrogen Fund to deliver a major boost to production capacity, ensuring that clean hydrogen can be utilised for decarbonising industrial clusters and play its role delivering net zero. The Fund will help establish the technology and will ensure that existing mechanisms, such as the Renewable Transport Fuel Obligation, provide an appropriate level of support for renewable hydrogen. Government will be engaging with industry on design of the Net Zero Hydrogen fund, and more details on the delivery of the scheme will be published in 2021.

3) Up to £100 million funding in brand-new Greenhouse Gas Removals including Direct Air Capture, which captures carbon dioxide emissions directly from the air. Phase 1 has already been launched (November 2020). [22]

4) £100 million for Energy Storage and Flexibility innovation challenges which will be launched in spring 2021 as one of the key priorities in the £1 billion Net Zero Innovation Portfolio.

5) £20 million in freight trials using hydrogen and other zero emission truck technologies. The government is exploring methods to decarbonise large, long haul, road freight transport pioneering hydrogen and zero emission truck technologies to support industry to develop cost effective, zero emission HGVs in the UK.

6) £120 million of investment in 2021/22 to start the delivery of the 4,000 zero emission buses as reiterated in the White Paper. The government will be funding towns/cities to switch to low-carbon buses (mostly electric for now but hydrogen is also considered).[23]

7) £20 million investment into the Clean Maritime Demonstration Programme to support feasibility studies including £3 million for development of a hydrogen port in Teesside (Tees Valley Hydrogen Transport).

8) £122 million of funding towards a new Heat Network Transformation Programme to support the creation of clean heat networks. There is existing funding (£320 million) on the Heat Networks Investment Project (HNIP), using grants and loans to accelerate the growth of the market – to end in 2022. As part of the new Heat Network Transformation Programme, government will support funding to the Green Heat Network Fund as the successor to HNIP.

9) A £160 million scheme and a competitive process (launched in early December)[24] to support the development of major portside hubs, strengthening UK offshore wind manufacturing and creating employment and investment in coastal communities and the supply chain.

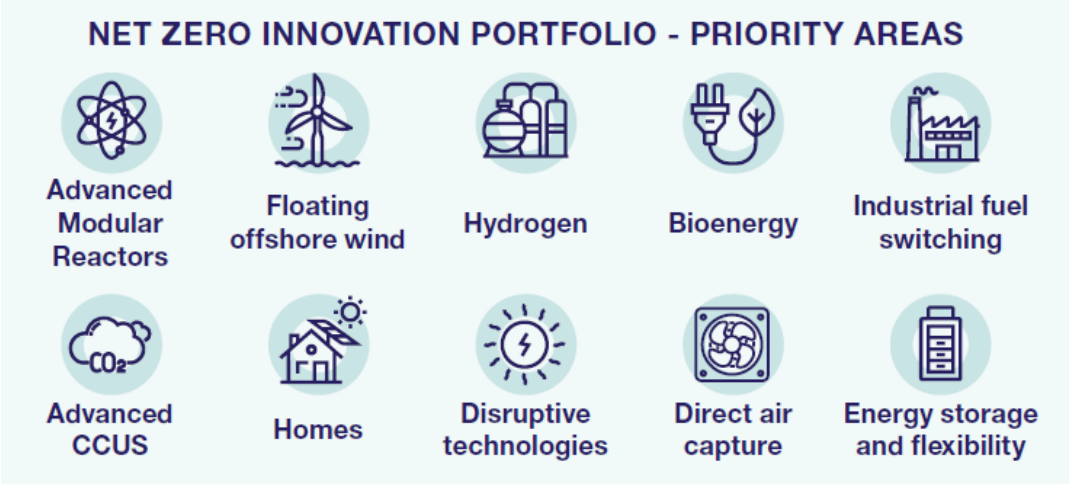

Figure 2: Net Zero Innovation Portfolio priority areas (Source: Ten Point Plan)

In addition to government, industry is showing their support and endorsement for hydrogen. The Hydrogen Strategy Now campaign was launched in June 2020 and is made up of fifty-four major businesses and trade bodies. Collectively, Hydrogen Strategy Now campaign partners employ around 100,000 people and have a value of over £100bn in the UK. They stand ready to invest up to £3bn in hydrogen projects in the UK, creating thousands of jobs across the country.

2.3. The bigger picture: other low-carbon alternatives in the UK

In 2019, UK parliament passed legislation requiring the government to reduce the UK's net emissions of greenhouse gases by 100% relative to 1990 levels by 2050[25]. This would mean achieving net zero emissions by 2050. ESC's Innovating to Net Zero report[26] which considers pathways for the UK to achieve net zero, indicates that electricity, district heat and hydrogen will play a key role in a low carbon future and achieving net zero. The report outlines a significant increase in the role of hydrogen, as well as district heating. Currently there are no energy related uses of hydrogen, and nationally the share of energy delivered by district heating is negligible. In the future they will be used in place of electricity where they provide a more practical or low-cost approach. Additionally, the report expects to see significant increases in electrification driven by renewable energy. Below are some of the key low carbon alternatives that are expected to contribute to achieving net zero in the UK, in some cases complimenting hydrogen and in others providing alternatives.

Offshore wind will play a key role in achieving net zero emission by 2050 with significant innovation throughout the supply chain, technology and market aspects, potentially becoming the largest source of zero-carbon energy in the UK. In 2019, the Committee for Climate Change (CCC) set an ambitious target of reaching 3 GW of offshore wind capacity by 2030, a number that will increase further to 75GW by 2050. More recently, as part of the Ten Point Plan, the UK Government announced a production of 40GW of offshore wind by 2030, including 1GW of innovative floating offshore wind. Additionally, the latest report by OREC[27] predicts that in the next 55 years, offshore wind LCOE will cost less than wholesale electricity. The UK government has also launched the offshore wind manufacturing investment scheme to support the delivery of manufacturing investment in the offshore wind supply chain.

The UK has the largest **Marine Renewables** in Europe, with the wave and tidal energy representing the two most advanced technologies in the sector. Despite 80%[28] of the UK public supporting wave and tidal development, the technology is still at the early stages of developments

Wave energy is still at the demonstration level despite significant research, with an installed capacity of 2.31MW in Europe since 2010. Cumulative capacity has been increasing steadily as technology advances and devices survive longer in the water. However, wave energy has not seen a convergence towards standardised designs, as with other technologies such as wind energy. These technologies require further research, development and Innovation (RD&I) efforts to advance demonstration projects and partake in grid power's highly competitive markets. The high-up front costs and the embryonic stage of some ocean energy technologies make their development challenging[29].

Tidal energy has significant potential for power generation in the UK, as the world's second highest tidal range[30]. Tidal stream technologies are still at a pre-commercial stage with 10.6MW installed capacity globally. Expansion beyond the pre-commercial stage requires an increase in deployment, reduction in costs, scale-up production and market support. With tidal generation being predictable (two high and two low tides each day), the UK, through projects such as ITEG[31], Invinity Energy Systems[32] , explores unique combinations of tidal power with flow batteries and electrolysers to power hydrogen production plants and commercialise green hydrogen from renewable generation.

Solar PV is also seen to be one of the key building's blocks in the future generation mix and the CCC's 6th carbon budget estimates 75-90GW of solar capacity to reach net zero by 2050. Supporting increase in solar will be the next round of CfD auctions planned for 2021.

Biomass will also play a role in supporting the UK to net zero in a variety of applications, particularly given its unique qualities such as the ability to deliver negative emissions which makes it a valuable contribution to the energy system. A key aspect of the UK Government's upcoming biomass strategy will consider the role of Bioenergy with carbon capture and storage (BECCS) in the energy system, which can deliver negative emissions by capturing the carbon released during biomass combustion, gasification and other processes. BECCS can play a role in a number of areas including clean hydrogen production, power generation, waste management and in heat for industrial processes.

Table 2: Cumulative installed capacity - 2020

Source	Cumulative Installed Capacity (GW)	Generation (TWh)
Onshore Wind	14.3	34.9
Offshore Wind	10.4	40.6
Solar PV	13.6	12.8
Biomass	4.7	27.5
Other Renewables*	5.2	18.4

Source: UK government[33]

**Note: Other renewables includes hydro, energy from waste, landfill gas totalling 48.1 GW and 134.3 TWh*

Nuclear is also expected to play a role in meeting the demand by 2050 considering large-scale nuclear, as well as Small Modular Reactors and Advanced Modular Reactors (AMR). The White Paper commits to bringing at least one large scale nuclear project to final investment decision by end of this Parliament in 2024. As mentioned in the Ten Point Plan, the UK are planning investment through the Advanced Nuclear Fund to enable investment into SMRs to develop a domestic smaller-scale power plant technology design. Small modular nuclear reactors (e.g., 300 megawatts) offer the potential for combined heat and power and an option for district heat networks. The UK is also committing to support funding for a research and development programme on AMRs which could play a role in decarbonising Industry, heat and transport due to the nature of high-grade heating, from the high operating temperatures, that can help unlock efficient production of hydrogen and synthetic fuels. The UK aims to build an AMR demonstrator by the early 2030s at the latest to prove the potential of this technology.

District Heating will play a key role in the decarbonisation of heating in the UK, either via direct electrification or via hybrid heat pumps, which considers use of a heat pump and a boiler – this can be a fuel-based boiler or hydrogen. The extent to which district heating is deployed in the UK depends on different scenarios when modelled. Some scenarios consider more extensive heat networks, whereas others consider lower shares, where low-cost hydrogen is used in gas networks. Additionally, different measures might be better suited to different applications for example with retrofits, new builds or homes on and off the gas grid. Nonetheless, the Prime Minister's Ten Point Plan also sets an ambition to reach 600,000 electric heat pump installations per year by 2028.

3. Industry Overview

This section provides an overview of the hydrogen landscape in the UK, considering current use of hydrogen and potential end use applications considering shorter- and longer-term scenarios. In this section we also consider some of the key research and innovation projects and programmes in the UK demonstrating production and end uses of hydrogen. Finally, we capture some of the key stakeholders across government, research and industry.

3.1. Industry structure and key sectors where hydrogen is applied

Currently, the UK produces around 0.7 Mt (27 TWh)[34] of hydrogen. Current use of Hydrogen is primarily in industry as feedstock for production of Ammonia for fertiliser and in the petroleum industry for production of petroleum or petroleum-based products. The rest, which is a smaller proportion is used in other industries such as food, methanol, metals and electronics.[35] These are all primarily dominated by a fossil-based supply of hydrogen, produced primarily from coal.

ESC's Innovating to Net Zero Report[36] estimates that by 2050, around 200- 300TWh of hydrogen could be needed to meet demands for industry, space heating, flexible power generation and heavy-duty transport (including shipping). This represents a significant increase from current production levels.

Hydrogen can potentially have valuable roles in these sectors and in replacing current energy sources such as natural gas such as in heating buildings on colder winter days, industrial process heat and back-up power generation and liquid fuels such as in heavy transport. For the end uses of low carbon hydrogen, we will consider four main sectors which are currently being considered in the UK: industry, the built environment, transport, and power.

Figure 3, taken from a report by Regen[37] on building the hydrogen value chain provides a snapshot of the hydrogen supply and value chain. It considers the various markets for hydrogen, showing the potential for hydrogen across the energy supply chain and alternative fuels and solutions.

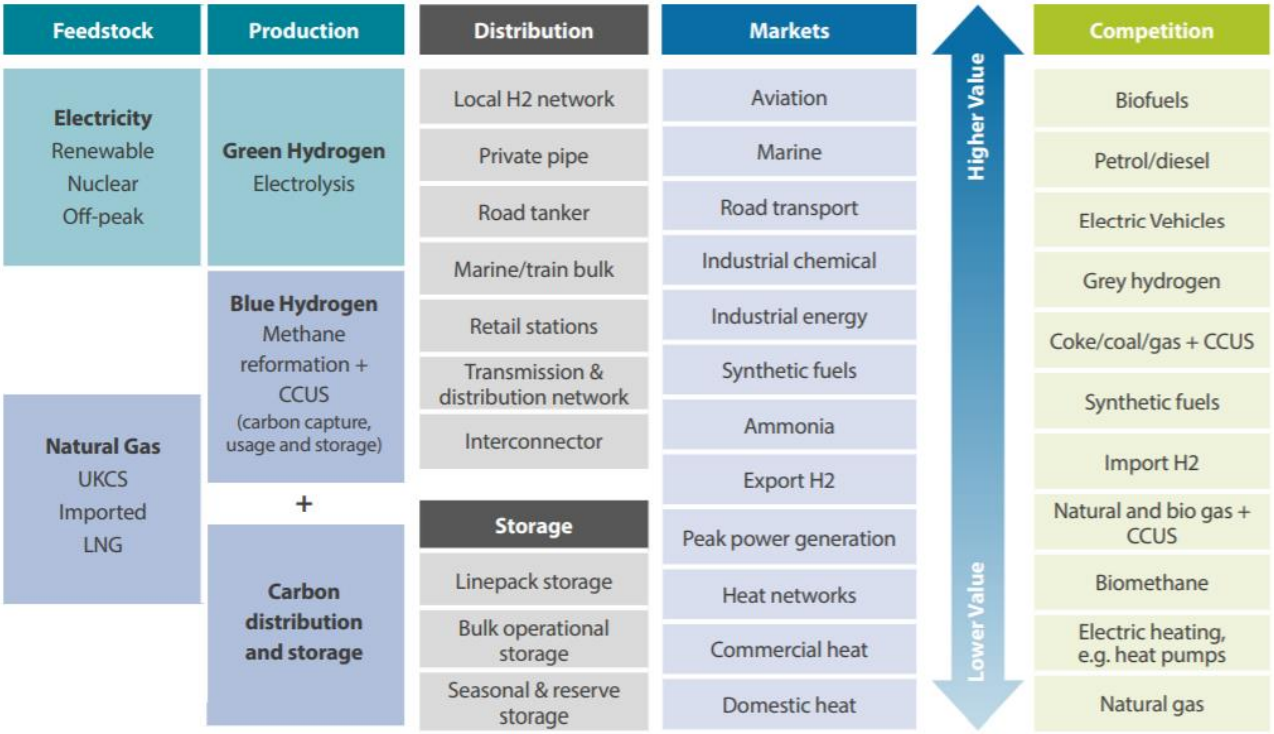

Figure 3: UK Hydrogen value chain (Source: Regen)

i. Hydrogen production

Hydrogen can be produced in a variety of ways and whilst current production is primarily based on fossil-fuels, future low carbon options currently being tested in the UK include:

- use of Carbon Capture and Storage (CCUS) with existing process via natural gas reformation
- bioenergy with carbon capture and storage, an attractive option given its potential for negative emissions
- electrolyses using renewables, of which there are two key technologies (see figure 4)

Table 2 provides an overview of the colours of hydrogen and associated processes and sources, and Figure 4 provides an overview of different technologies and their maturity.

Table 2: Colours of hydrogen and related sources

Colour	Process	Source
Grey	Steam methane reforming or gasification	Natural gas or coal
Blue	Steam methane reforming or gasification with CCUS	Natural gas or coal
Green	Electrolysis	Renewable electricity
Purple	Electrolysis	Nuclear electricity
Turquoise	Pyrolysis	Natural gas

Source: The Oxford Institute for Energy Studies

Note: areas of focus in this report will be on blue and green hydrogen.

Group	Technology	Maturity	Scale	Carbon capture	Other constraints
Natural gas reformation	SMR with CCS	SMR mature but CCS not	150 - 1000 MW	70-90%	Best placed near CCS T&S
	ATR with CCS	ATR has high TRL but has not been tested at scale; CCS is not mature	300 – 1000 MW	95-98%	Best placed near CCS T&S
BECCS	Biomass Gasification with CCS	Biomass gasification has not been demonstrated at scale; CCS is not mature	50 – 500 MW	Negative emissions	Availability and sustainability of biomass – dependent on waste policies
Electrolysis with dedicated renewables, or with grid connection	Alkaline	Reasonably mature	No minimum scale	N/A	Production may be intermittent
	PEM	Demonstration level but has not been tested at scale	No minimum scale	N/A	

Figure 4: Technology characteristics summary (Source: Frontier Economics)

ii. Hydrogen in the power sector

In the power sector there are a few potential ways in which hydrogen can support the future energy system. As integration of variable renewables in the system increases, so will the need for hydrogen to provide flexibility, and short/long energy balancing services and frequency control. One example here is if generation exceeds demand, the surplus energy can be converted to hydrogen either for re-generation to electricity or use in other sectors.

Electrolysers are already providing system flexibility services to the UK grid. ITM Power's 3 MW electrolyser in Birmingham is able to contract for both frequency response and demand management contracts from National Grid, the UK's electricity system operator. Given that, scale of this surplus is not expected to be significant, and the role for electrolysis in providing some of this system flexibility is not likely to be as competitive as other forms of flexibility such as in demand-side response and batteries. This could however be an option in areas where there is no grid, or where infrastructure limits export to areas of demand such as in Scotland. Here onshore wind can be produced cheaply but upgrades to the electricity transmission system are required in order to send electricity south of the border.

Hydrogen could also be used as a storable fuel to support peak demand. Currently in the UK peak energy demand primarily in the winter is met by fossil fuel power stations like Open Cycle Gas Turbines. The CCC report[38] anticipates that despite other storage methods such as batteries and thermal storage there will likely still be a role for storable fuels in the future which is currently in the form of natural gas. In the future hydrogen could potentially play this role.

Additionally, there is potentially a role in fuel switching in power plants whereby hydrogen and/or ammonia, including ammonia – hydrogen blends can be used as an alternative to natural gas in turbines. This would require retrofitting existing gas turbines to accommodate. If hydrogen and/or ammonia can replace natural gas in existing plants to produce electricity it is possible that it could play a similar role as natural gas plants today in providing capacity, flexible generation and other power system services such as inertia and frequency response.

iii. Hydrogen in the transport sector

Here we will consider the role of hydrogen in various transport modes including passenger cars and vans, heavy duty vehicles including trains, buses and heavy good vehicles (HGVs), as well as in shipping and aviation.

While battery-powered electric vehicles are now well placed to deliver the bulk of decarbonisation for cars and vans, hydrogen could be an option in some cases such as in longer-range journeys in lighter vehicles, where the need to store and carry large amounts of energy is greater or there is a need for quick refills in the case of hydrogen.

It is important to note that hydrogen fuel cell vehicles are electric vehicles that generate electricity on board at relatively high efficiency removing or reducing the need for electricity storage via batteries. Therefore, improvements in electric vehicles will also support hydrogen fuel cell vehicles. It is also possible in the future that hydrogen cars could in the longer-term be hydrogen plug-in hybrids (i.e., combining a battery and a fuel cell).

Hydrogen fuel cell vehicles could also play an important role for heavy-duty vehicles (e.g., buses, trains and lorries). There are already some trials in the UK considering use of hydrogen in ferries, rail and buses (see section 3.2. for more information). An important factor in the future of hydrogen for transport is on the refuelling infrastructure, which might not affect buses and trains as much given the possibility to refuel as base stations. In 2017, the Office for Low Emission Vehicles (OLEV) launched the UK's Hydrogen for Transport programme to support refuelling stations and deployment of fuel cell vehicles.

Long haul- HGVs are also another challenging category within decarbonisation of transport for which there are a number of solutions, including hydrogen. However, given the number of HGVs travelling between the UK and Europe, this needs to be a collaborative effort to ensure that countries transition towards the same low-carbon solutions which would simplify the infrastructure requirements across countries.

In shipping there is also a potentially important role for hydrogen, especially if an international market in low-carbon hydrogen or ammonia (a hydrogen carrier) develops. Hydrogen and ammonia can power ships through fuel cells or internal combustion of hybrid combinations. The decision on use of hydrogen vs. ammonia considers some trade-offs when considering cost as well as storage requirements. More work needs to be done here, and as mentioned in section 2 this will be supported by the Clean Maritime Demonstration Programme. Additionally, the UK are already running hydrogen ferry trials in Orkney and due to launch a hydrogen refuelling port in Teesside.

In relation to aviation, according to the CCC report[39], given the complications with hydrogen use here, there doesn't seem to be a role for hydrogen. However, there is some consideration on use of synthetic fuels in which hydrogen could play a role. Nonetheless, to support the decarbonisation of aviation, as mentioned in the Ten point Plan, the UK government are investing £15 million into FlyZero – a 12-month study, delivered through the Aerospace Technology Institute (ATI), into the strategic, technical and commercial issues in designing and a developing zero-emission aircraft, as well as other mandates and investments as mentioned in section 2.

iv. Hydrogen in the built environment

In the UK hydrogen could play a valuable role in decarbonisation of heating in providing space heating as well as for heating water and cooking. One of the considerations for hydrogen as part of a heating solution for UK buildings is in combination with heat pumps as part of a 'hybrid' system.

A CCC report[40] shows that heat pumps offer the potential to provide heat efficiently for the majority of the time, whereby hydrogen boilers would contribute mainly to meet peak demands on the coldest winter days. Hybrid heat pumps can also be beneficial in acting as a flexible load to the electricity system.

Hybrid systems have been demonstrated in South Wales under the Freedom project[1] which was a joint initiative by Wales and West Utilities, Western Power Distribution and PassivSystems in Bridgend. Under the project 75 hybrid heat pumps were retrofitted and trialled in residential properties to test use alongside existing boilers. The trial allowed investigation of domestic heating systems that have the option of operating either the heat pump, boiler or both and to understand the implications to the consumer, network and energy system. The project demonstrated successfully that the hybrid systems could maintain comfort levels without any wider changes to the heating system (e.g., radiators), across a range of household types.

Decarbonisation of heating includes various options and scenarios. Some of the options for use of hydrogen for heating include:

- hybrid heating systems comprised of an electric heat pump and natural gas boiler, or a heat pump and hydrogen gas boiler
- pure hydrogen solutions such as hydrogen boilers to replace existing natural gas boilers
- fuel cells for heat and electricity

The most viable option will depend on various factors and different options might be best suited to different scenarios, for example retrofits vs. new builds, homes on and off the gas grid, as well as density of heat demand such as in urban settings.

Blending hydrogen into the existing natural gas network is also being considered as a more short-term route in the UK, which keeps the option open for re-purposing of gas networks in the future. The UK has a world-leading gas network and is hugely reliant on it. 85% of homes and businesses use natural gas for heating, cooking and hot water.

Carbon emissions per household from heating need to decrease from almost 3 tonnes a year to 138kg by 2050[41]. Blending up to 20% hydrogen into the gas grid with existing natural gas could provide a shorter-term approach and save around 6 million tonnes of carbon dioxide emissions every year, the equivalent of taking 2.5 million cars off the road[42].

Various initiatives and demonstrations are ongoing to support decarbonisation via multiple routes. The UK is currently delivering the largest innovative heat pump trial (750 homes, over £15 million total investment) under the Electrification of Heat programme to demonstrate the feasibility of a large-scale roll-out of heat pumps. This will support plans by government to see installations of 600,000 heat pumps per year by 2028. However, this still leaves open the choice for pursuing hydrogen heating, full electrification or a mix of both in the future.

Whether existing gas networks will be repurposed for hydrogen is still unclear and there are various advocates for re-purposing those networks, as well as for moving to full electrification via heat pumps. Nonetheless, blending hydrogen enables a more short-term approach and could provide a reliable source of baseload demand to support early low carbon hydrogen producers.

To support use of hydrogen in the built environment and blending there are various projects and demonstrators in the UK to test the safety and role for hydrogen here, see section 3.2. for more details.

v. Hydrogen in industry

Hydrogen will play an important role in decarbonisation of industry and as an option for fuel switching away from fossil-fuels to low carbon alternatives alongside other options like biomass and electricity. In a report commissioned by BEIS on Business Models for Hydrogen Production by Frontier Economics,[43] the focus was on industry as the main end user for low carbon hydrogen. This is because industry is currently seen as where the greatest value may be in the short-term. This is because industrial users are likely to have fewer alternatives than other end users and sectors. Industrial users also tend to be clustered together geographically, providing a large baseload demand. In the UK the six largest industrial clusters have been mapped by the Department for Business, Energy and Industrial Strategy (BEIS) (see Figure 5).

In 2019, BEIS commissioned a 3 phase £20 million Industrial Fuel Switching competition allocating funding to stimulate early investment in fuel switching processes and technologies. Under phase 1 a report commissioned by Element Energy and Jacobs[44] examined the potential for fuel switching away from fossil fuels to hydrogen, electricity and biomass (without CCS) in a range of industry sub-sectors. The analysis from the report indicated that hydrogen has significant technical potential and can be applied in some industrial processes such as in the iron and steel industries, where there are no other alternative low-carbon options. Also, hydrogen will be cost competitive to other fuel switching options given assumptions at the time of the report. The Fuel Switching competition also funded further Phase 2 feasibility studies, and Phase 3 ongoing demonstration projects[45] to help stimulate investment in processes and technologies that support fuel switching.

Not covered in that report, but worth noting that hydrogen can also be used instead of fossil fuels for combined heat and power as well as playing a role in reducing emissions from industrial heat, particularly where applications cannot be electrified such as when there is need for direct contact with heating substances in processes such as in furnaces.

Finally, CCS will be a key enabler of hydrogen in promoting production of blue hydrogen from natural gas via steam methane reforming and bioenergy. However, it is also worth noting that the potential use of CCS in industry is likely to be a key competitor to hydrogen. The CCC report[46] states there is considerable overlap between various decarbonisations routes:

- switching away from fossil fuels to hydrogen (likely with CCS given role for bulk production)
- continuing to use fossil fuels and instead capturing and storing the resultant CO_2 emissions
- potential use of biomass with CCS to achieve negative emissions.

These options can be grouped into:

- **Pre-process CCS** where hydrogen is produced predominantly from CCS to remove the carbon before use in industrial processes. This scenario is likely suited to smaller sources of emissions and those further from CO_2 networks where implementing CCS on-site will be more difficult and expensive.
- **Post-process CCS** where there is direct application of CCS to industrial sites. This is well suited to large point sources of CO_2, especially those located close to CO_2, networks. This also provides an advantage over use of hydrogen for other industrial processes that do not use fuel, such as in the cement sector.

The CCC report mentions that the ideal approach regarding use of hydrogen and direct use of CCS in industry is not clear yet and will depend on a variety of factors such as costs and CO_2 savings.

Furthermore, to support decarbonisation of Industry in the UK, the Industrial Strategy Challenge Fund (ISCF), by the UK Research and Innovation (UKRI), is providing up to £170 million, matched by £261 million from industry, to invest in developing technologies such as carbon capture and storage and hydrogen fuel switching. The technologies will be deployed and scaled up within the UK's largest industrial clusters. This is to support the UK's mission to establish the world's first net-zero carbon industrial cluster by 2040 and 4 low-carbon clusters by 2030.

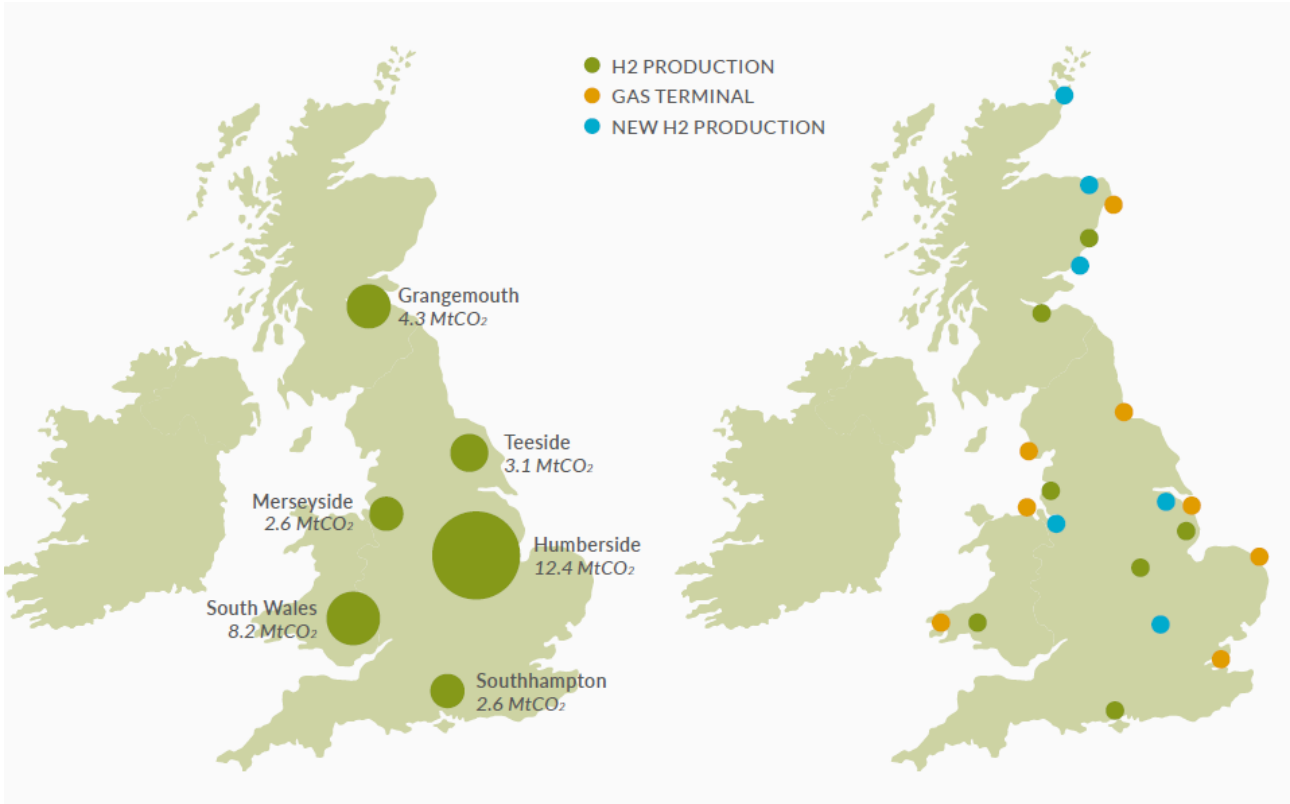

Figure 5: UK's largest industrial clusters by emission and hydrogen production hubs. Source: OREC report[47]

3.2. Research and Innovation

This section provides an overview of some of the key initiatives and programmes enabling research, innovation and demonstration of hydrogen projects in the UK across the four sectors discussed in the previous section.

Some of the previous competitions launched to support these projects include:

- £20m Low Carbon Hydrogen Supply competition
- £20m Industrial Fuel Switching
- £20m Carbon Capture and Utilisation Demonstration programme
- £24m Call for CCUS Innovation programme.

Additionally, new initiatives are being set up to continue to promote research and innovation as well as collaboration amongst government, academia and industry:

- Industrial Decarbonisation Research and Innovation Centre (IDRIC) formed under the ISCF agenda to act as the national focal point and international gateway for UK industrial decarbonisation research and innovation. The goal is to deliver multi-disciplinary research, support knowledge sharing, develop leadership and providing evidence to policy makers and public. Delivery is expected for 2021.
- Scotland's Hydrogen Accelerator recently established to support and enable effective and efficient implementation of hydrogen technologies into Scotland and supports economic growth in this important low carbon sector.
- The Energy Research Accelerator which builds on innovation and research from the Midlands, with partners from the University of Birmingham, Cranefield University, Lancaster, Nottingham, Loughborough and Warwick. The goal is to work with government, industry and research to develop the next generation of energy leaders and demonstrate low carbon technologies.
- The Michelin Scotland Innovation Parc formed as a joint venture between Michelin, Scottish Enterprise and Dundee City Council to drive growth in the Scottish economy and support the climate emergency. Seen as a home for innovation and connecting industry, academia and government. The Innovation Parc also includes a 16-week accelerator targeted at early stage start-ups as well as access to various spaces and hubs for businesses to grow.

Below are some examples of the key projects in the UK supporting test and scale-up of hydrogen across the four end-use applications and production of both blue and green hydrogen. Please note this is not an exhaustive list of all the hydrogen-related projects in the UK.

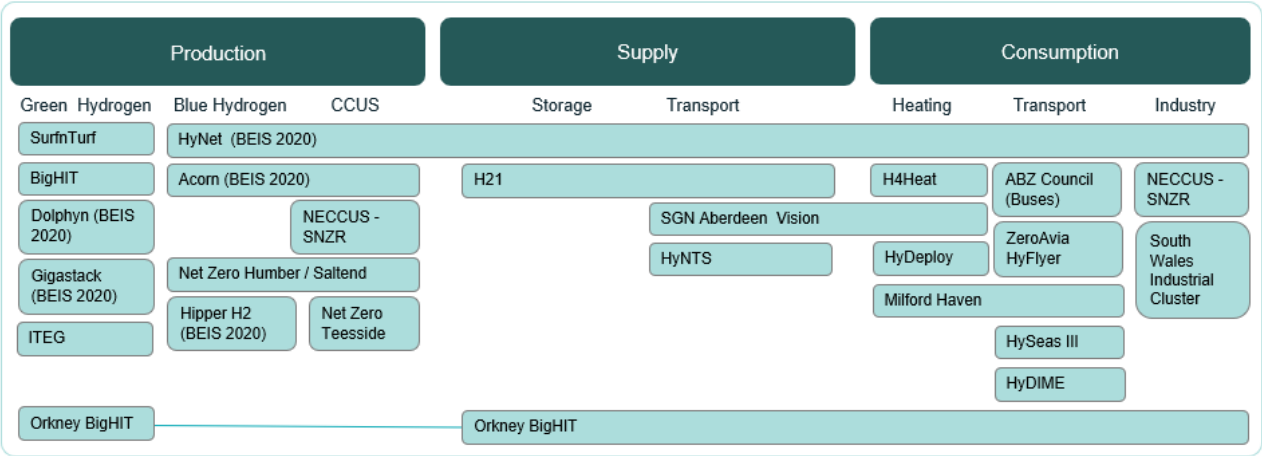

Figure 6: Hydrogen related projects in the UK

i. Hydrogen Production

Gigastack[48] - a demonstration project focussing on production of green hydrogen and decarbonisation of industrial clusters. It is located on the Humber in North Lincolnshire at Phillips 66's Humber refinery. It is being delivered by a consortium led by ITM Power and partners: Orsted, Texas-based oil refining company Phillips 66 and low-carbon energy consultant Element Energy. It will focus on the production of green hydrogen from Orsted's offshore wind, and production of the UK's first industrial scale, 100MW electrolysers, using polymer electrolyte membrane (PEM) technology. It is currently in phase 2 of a 3-phase programme.

Dolphyn[49] - is focussed on the production of green hydrogen at sea by coupling a wind turbine, PEM electrolysis and desalination facilities on a floating platform. The hydrogen produced is transported via existing oil and gas piping infrastructure, which will support an additional supply of hydrogen to the Hydrogen Coast projects*. The project led by a sustainability consulting firm, Environmental Resources Management Ltd., is at the detailed design stage and it will progress into the investment decision on a 2MW prototype this year.

Acorn[50] – a CCS and Hydrogen Project that consists of two elements which are the CO2 capture and storage and hydrogen production from natural gas reformation at St Fergus, Scotland. Using the already existing oil and gas expertise (offshore CO2 storage site) and infrastructure, the blue hydrogen produced from North Sea natural gas will be used for transport and heat. The PCI project (European Project of Common Interest) is led by Pale Blue Dot Energy alongside funding from oil and gas industry partners (Chrysaor, Shell and Total). Pale Blue Dot Energy aims to reach operation by 2024 while the support from governments and industry continues.

HyNet[51] - a CCUS project in North West England, planning to capture CO_2 from industrial sources in the early-to-mid 2020's (phase 1), followed by the production of hydrogen from natural gas (phase 2). The proposals include re-using a range of existing oil and gas infrastructure, including a trunk pipeline that connects the Point of Ayr terminal to a depleted oil and gas field in the Liverpool Bay.

*Hydrogen Coast – is a cluster of projects that are delivering innovative hydrogen solutions along the east coast of Scotland from Orkney to Aberdeen to Fife.

ITEG[52] – The Integrating Tidal Energy Storage into the European Grid (ITEG) project is led by the European Marine Energy Centre in Orkney and is looking to develop and validate an integrated tidal energy and hydrogen production solution for clean energy generation to be demonstrated in Orkney. This is being done alongside partners from the UK, France, Belgium and the Netherlands including the Energy Systems Catapult.

ii. Hydrogen for the built environment

HyDeploy[53] - is the first ever live demonstration of hydrogen in homes and aims to prove that blending up to 20% volume of hydrogen with natural gas is a safe and greener alternative to the gas we use now. The project is run by gas distributors Cadent and Northern Gas Networks alongside partners Progressive Energy Ltd, Keele University, ITM Power and the Health and Safety Executive (HSE). The three-stage programme is currently at phase two, where the 20% hydrogen blend supplies the community of Winlaton in the North East of England. Following that hydrogen will also be tested at another demonstration site in the North West to test the blend across a range of networks and customers so that the evidence is representative of the UK as a whole.

H2 metering[54] - is addressing metering and bills given that hydrogen is a different energy density to natural gas and meters charge based on volume. This means that consumers who have hydrogen flow through their meters would be overcharged for the energy they have used. Therefore, meters will need to change if hydrogen is to be blended into the system. This project addresses updates required for the commercial framework around how gas is billed. The current framework was designed for North Sea gas and can be a barrier for alternative sources of gas, particularly low carbon gases. This is because currently alternative gases must be pre-processed to meet current billing standards. This is costly and can add fossil-based carbon back into the process. This project aims to remove the need for this pre-processing, unlocking the door for more low carbon gases. The project is led by Cadent Gas Ltd, a gas distribution network owner and operator.

Hy4Heat[55] - a feasibility study to establish if it is technically feasible and safe to replace natural gas with hydrogen in residential and commercial buildings and gas appliances. This will enable the government to determine whether to proceed to a community trial. The program is divided into five work packages, addressing Hydrogen Gas Standards, Domestic Hydrogen Gas Appliances, Commercial and Industrial Appliances, Comparative Quantitative Risk Assessment (QRA) of the use of hydrogen compared to natural gas in properties, and finally the demonstration. The project is led by Arup in collaboration with a wide range of technical and industry specialists (Kiwa Gastec, Progressive Energy, Embers and Yo Energy).

H100[56] – the project is designed to be a real-life test of the use of hydrogen for heating homes. The idea is to build a facility in Levenmouth, Fife, that will use offshore wind power to generate hydrogen from electrolysis. The hydrogen produced is stored on site and will be used to feed hydrogen to that local area gas network. At the moment, the project is conducting testing on the use of hydrogen in three terraced houses near the site. In 2022 up to 300 local residents will be invited to connect to the hydrogen network as well as switching to hydrogen appliances (oven boilers and hobs). The project is under the control of Scottish Gas Networks (SGN) who run the gas networks in Scotland and South East of England. The project is also a winner of Ofgem's Network Innovation Competition as it was granted £18 million last year. The Scottish government is also providing support in the form of £6.9m funding for SGN and other industry partners in the project.

Milford Haven: Energy Kingdom[57] - a £4.2 million project exploring the role of hydrogen in a decarbonised energy future. This is a detailed design project that will focus on developing diverse, local markets to support the transition, to hydrogen and renewables, of the cluster of major energy infrastructure along the Milford Haven Waterway in Wales. The project will immediately build hydrogen-ready features and technologies into Milford Haven Port's housing, commercial and renewables projects and will allow local people to test real-world hydrogen vehicles and home heating equipment. Project partners include Pembrokeshire County Council, Riversimple, Milford Haven Port Authority, Wales and West Utilities, and Offshore Renewable Energy Catapult, with assistance and support from different organisation including the Energy Systems Catapult.

iii. Transport

HydroFlex[58] - a partnership between academia and private sector to convert a Class 319 dual-voltage electric train to a hydrogen powered train. The projects received funds from Department for Transport in the form of a £750,00 grant followed by more than £1 million of investment from University of Birmingham and Porterbrook (rolling stock company). Currently, the development is underway to retrofit the train with a hydrogen and battery powered module located underneath the carriage, which will allow for more space for passengers in the train.

Aberdeen Bus Project[59] - a collaboration of funds from European funding projects (High V. LO-City and HyTransit), Innovate UK, the Scottish Government, Aberdeen City Council and other industry and government entities. The project up to this point has delivered the deployment of a fleet of 15 hydrogen buses and a local hydrogen production facility (1MW electrolyser). The next step according to Aberdeen City Council is to increase number of buses being delivered to 25 through an additional funding of £1million.

iv. Hydrogen for Industrial Decarbonisation

NECCUS – SNZR (Scotland's Net Zero Roadmap) [60] **-** the project is led by NECCUS (industrial carbon capture and storage alliance) to analyse industrial emissions in Scotland and find routes to decarbonising the sector. The project secured funds (£1.23 million) from UK government's Industrial Decarbonisation Challenge, which aims to establish net-zero emission industrial zones by 2040. The collaboration groups academia and industry partners to identify Scotland's highest emitting industrial sites as well as exploring routes to decarbonise industrial processes. The routes that will be explored are electrification, fuel switching to clean energy vectors – such as hydrogen – carbon capture from fossil fuels, biofuels and industrial processes, and negative emissions opportunities for recapturing carbon from the air or from biomass combustion.

South Wales Industrial Cluster (SWIC) [61] - a jointly funded project by industry partners and UK Research and Innovation to bring together sectors in South Wales that are crucial for decarbonisation and the development of a hydrogen economy. SWIC covers industries such as energy, oil refining, paper, nickel, chemicals, LNG import, steel and cement. The routes to decarbonisation of the industrial cluster are centred around the production, transport and applications of hydrogen, and the capture and use of CO2.

Note: the two projects mentioned above are funded under the Industrial Decarbonisation challenge fund by UKRI. More information and other funded projects can be found online. Additionally, in March 2021, additional funding of £171 million was announced under this challenge on decarbonisation of industrial clusters phase two: deployment competition[62] to support emission reductions in the UK industrial clusters. More information here.

3.3. Funding

Section 2 provides some of the key investments being commitment by government in the upcoming decade which will continue to support CR&D and demonstration of hydrogen in the UK. In this section (Table 3) we capture some of the existing or annual funding competitions and grants in the UK that support innovation in energy.

Table 3: Funding streams in the UK that provide an opportunity for hydrogen related CR&D

Key Funding Streams	Funder	Short Description
Gas Network Innovation Competition (NIC)63	Ofgem	Annual opportunity for Gas network companies to demonstrate the best innovation projects which help all network operators understand what they need to do to provide environmental benefits, reduce costs, and maintain security of supply as Great Britain moves to a low carbon economy
Gas Network Innovation Allowance (NIA)64	Ofgem	Provides opportunities for innovation programmes to be developed across the gas industry. NIA promotes the encouragement of operational and technological innovation, collaboration & sharing new learning, and focusing on new solutions to old problems that deliver financial value to customers
Innovate UK Smart Grants: November 202165	Innovate UK	Innovate UK, part of UK Research and Innovation, is investing up to £25 million in the best commercially viable innovative or disruptive ideas. Proposal submissions must demonstrate a

Key Funding Streams	Funder	Short Description
		clear game-changing, innovative, disruptive and ambitious idea leading to products, services or processes.
Green Recovery: Low Carbon Energy Project: Capital Funding66	Scottish Government	£50 million support for projects that demonstrate innovative low carbon heat solutions for buildings, as well as proposals for integrated energy systems that support the ambitions for Scotland to achieve net zero emissions
Knowledge Transfer Partnerships67	Innovate UK	The Knowledge Transfer Partnership (KTP) scheme allows a UK registered business to partner with a UK higher education (HE) or further education (FE) institution, RTO or Catapult (which are referred to as the 'knowledge base partner')
Transitioning towards Zero Emission Vehicles: feasibility studies and CR&D68	Office Zero Emission Vehicles (OZEV)	UK registered businesses can apply for a share of up to £7million to develop on-vehicle solutions that address challenges associated with the transition to zero emission vehicles. The project can include partners that do not receive any of this competition's funding, for example non-UK businesses. Their costs will count towards the total eligible project costs.
Infrastructure solutions for zero emission vehicles69	Office Zero Emission Vehicles (OZEV)	UK registered businesses can apply for a share of up to £10million to develop infrastructure solutions that address challenges associated with the transition to zero emission vehicles.

Additionally, Horizon Europe, the EU research and innovation framework programme will be running from 2021-2027 and will be providing funding under Pillar 2 to address global challenges and promote European industrial competitiveness. One of the focus areas will be on Energy, Climate and Mobility and first calls are expected to launch in April 2021. Topics specific to hydrogen and fuel cells will be covered under the Clean Hydrogen Partnership, which is being set up by the European Commission and building on the work of the Fuel Cells and Hydrogen Joint Undertaking, to accelerate the development and deployment of a European value chain for clean hydrogen technologies[70].

3.4. Key Stakeholders

This section highlights the key stakeholders in the hydrogen sector across government, industry, research and academia. Given hydrogen's cross-sector role and applications across various parts of the energy system, there are multiple stakeholder groups across the supply and value chain as shown in Figure 7. Please note the information provided in the tables below are not exhaustive.

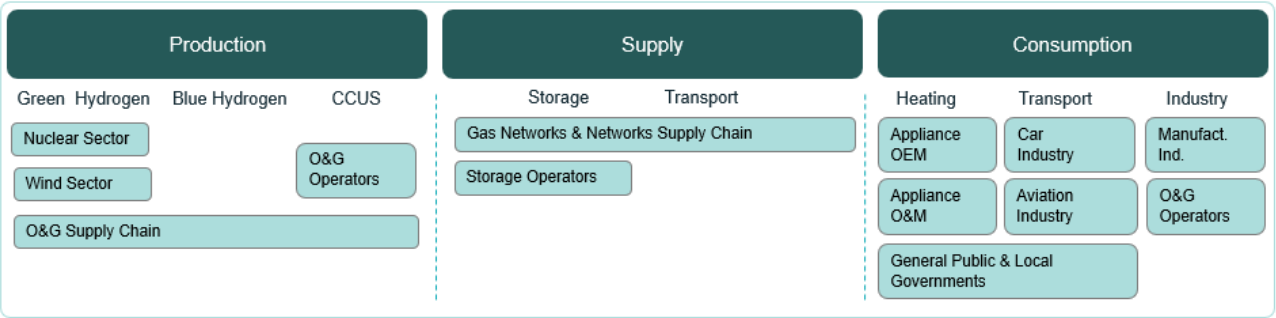

Figure 7: Key hydrogen stakeholder groups

Key UK departments, influential stakeholders and policy makers:

- Department for Business, Energy and Industrial Strategy
- Department for International Trade
- Department for Transport
- UK Research and Innovation
- The Crown Estate
- HM Treasury
- National Grid
- Office of Gas and Electricity Markets (Ofgem)
- Office for Low Emission Vehicles
- Hydrogen Task Force
- Hydrogen Advisory Council
- National Infrastructure Commission
- Committee on Climate Change

3.4.1. Industry, Research and Knowledge Centres

Table 4: Key Associations and Networks

Name	Remit
Scottish Hydrogen and Fuel Cell Association	Production
UK Petroleum Industry Association	Production
Offshore Wind Industry Council	Production
British Ports Association	Transport - Maritime
Airport Operators Association	Transport - Aviation
Rail Industry Association	Transport - Rail
Energy Networks Association	Energy Networks
UKH2 Mobility	Transport – Road
Scottish Hydrogen and Fuel Cell Association	Production & Transport
UK Hydrogen and Fuel Cell Association	Production & Transport
North West Hydrogen Alliance	Whole system
Decarbonised Gas Alliance	Networks
Jet Zero Council	Transport - Maritime
Automotive Council	Transport - Road

Table 5: Research and Knowledge centres incl. Catapult Centres

Centre	Remit
Energy Systems Catapult	Whole System
High Value Manufacturing Catapult	Whole System
Offshore Renewables Catapult	Generation
CASE Centre for Advanced Sustainable Energy	Energy
Advanced Propulsion Centre	Automotive
Aerospace Technology Institute	Aerospace
Centre for sustainable road freight	Transport - Freight/HDV
National Physics Laboratory	Metrology/measurement
European Marine Energy Centre	Transport - Marine
UK Energy Research Institute (UKERC)	Energy

Table 6: Universities & Associated Research Centres

University	Research Centre
University of South Wales	Sustainable Environment Research Centre (SERC)
University of South Wales	Hydrogen R&D Centre
Chester University	Thornton Energy Research Institute
Cranfield University	Hydrogen Research Network
Cardiff University	Centre for Research into Energy, Waste and the Environment
Imperial College London	Sustainable Gas Institute; Grantham Institute
Keele University	Institute for Sustainable Futures
Leeds Beckett University	Sustainability Institute
Leeds University	Centre for Integrated Energy Research

Table 7: Hydrogen Industry Supply Chain and Users

	Electrolysers	Fuel Cells	Production	Storage	Distribution	End use			
						Power (off-grid)	Mobility (air)	Mobility (land)	Heating & appliances
2G						●			
Adelan		●				●			
Almas Technologies									●
Alstom								●	
Arcola								●	
Air Products			●	●	●				
Auriga Energy		●				●		●	
Ballard Fuel Cells		●				●	●	●	
Baxi									●
Bayo Tech			●						
BOC		●	●	●	●	●		●	
BP			●						
Bright Green Hydrogen				●		●			
Cadent				●	●				
Calvera				●					
Ceres Power		●							
Chesterfield Special Cylinders				●					
Clean Power Hydrogen	●		●						
Enocell		●				●			
Equinor				●					
Fuel Cell Systems		●				●	●	●	
Gastec					●				
Intelligent Energy		●	●					●	
Inovyn	●		●						
ITM Power	●		●						
Johnson Matthey		●	●					●	

	Electrolysers	Fuel Cells	Production	Storage	Distribution	End use			
						Power (off-grid)	Mobility (air)	Mobility (land)	Heating & appliances
Logan Energy Group	●	●		●	●				
Luxfer								●	
MicroCab		●					●	●	
NanoSun						●		●	
PowerHouse Energy			●						
Progressive Energy			●						
Pure Energy Centre		●	●	●		●		●	●
Riversimple								●	
Scotia Gas				●					
Shell			●						
SSE Gas Storage				●					
Storengy				●					
Uniper				●					
Vivarail								●	
Wales and West Utilities				●					
Worcester Bosch									●
Wrightbus		●						●	
Zero Avia							●		

Research and knowledge hubs

- Hydrogen & Fuel Cell Research Hub (H2FC SUPERGEN) - http://www.h2fcsupergen.com/

This is an inclusive network encompassing the entire UK hydrogen and fuel cells research community, with more than 400 associate members, including 100 UK-based academics supported by key stakeholders from industry and government. It is funded by Research Councils UK Energy Programme, as part of the government's Sustainable Power Generation and Supply initiative. Research undertaken within the Hub focuses on specific areas that cut across policy and socio-economic systems. These include key technical programmes such as hydrogen production, hydrogen storage, PEM fuel cells, and solid oxide fuel cells/electrolysers, but also safety, education and training.

- Hydrogen knowledge centre - https://www.h2knowledgecentre.com/

This is a digital repository dedicated to the advancement of hydrogen learning globally and supporting the transition to a net-zero carbon emissions future. The repository hosts and signposts to hydrogen resources from across gas network and supply chain organisations, academic institutions, research bodies, industry experts and policy makers. Developed by the Institution of Gas Engineers & Managers (IGEM), a professional engineering institution for gas to support individuals and organisations connected with the gas industry

- Hydrogen Hub - https://www.hydrogenhub.org/

The Hydrogen Hub is an industry-led community of stakeholders from across the hydrogen and fuel cell supply chain, Government, local authorities, businesses and current and potential users.

3.5. Opportunities and barriers to hydrogen in the UK

As discussed in earlier sections, hydrogen can play an important role in delivering the UK's net zero future and in supporting the energy transition in the upcoming decades. The UK is taking what is being referred to as a 'twin-track' approach which is the promotion of both blue and green hydrogen. It is believed that this approach will enable production to be brought forward to the scale required in the 2020s and promote innovation and investment.

There are multiple end uses for hydrogen however the priority for these areas is uncertain and the earliest opportunities will depend on various factors such as process compatibility, duty cycles, demand flexibility and location. As highlighted in the Frontier report, industry is likely to promote adoption of hydrogen in shorter terms and provide an anchor for early projects as current evidence shows industrial end users are likely to have fewer cost-effective alternative decarbonisation options than other end user groups. Table 8 provides a summary of opportunities and barriers in different end uses.

Some highlights and key areas for innovation in overcome existing barriers:

- Innovation to achieving high capture rates are needed from hydrogen production from natural gas by steam methane reforming
- Demonstration of green hydrogen production at scale in the 2020s. Electrolysis (utilising renewables or nuclear) and gasification (with CCS) offer even lower carbon hydrogen production but require further scale-up and cost reduction
- Steam Methane Reforming (SMR) offers nearest term potential for volume production but relies on Carbon Capture and Storage (CCS) to be consistent with Net Zero emissions targets
- Demonstration of safety of hydrogen in fuel switching for industrial processes
- Salt cavern storage is a cost-effective means of storing large quantities of hydrogen and the UK is fortunate with its geology in this regard (as demonstrated by the HySecure project[71])
- Distribution of hydrogen, with the most appropriate distribution method being heavily influenced by volumes and end use application
- Industry currently appears the most secure application for hydrogen; and may de-risk other applications
- Hydrogen for transport has been demonstrated but faces strong competition from other vectors
- There is potential and support for hydrogen in heating, but safety, economics and supply constraints would need to be addressed as well as consumer acceptance

Table 8: End uses for hydrogen: opportunities and current challenges

Industry	Grid Blending	Transport	Power
• Large baseload demand profile could provide an anchor for early projects • Fewer cost-effective alternative • Switching cost and complexity for natural gas • Switching cost & complexity for natural gas users • Risk that plants shut down or move offshore	• Stable & reliable source of demand could support early projects • Regulatory limits to blending are a barrier • Customer acceptability is unproven • Safety testing for blending and end appliances is needed	• Retain cost-gap between blue/green and petrol is smaller than other fuels • Refuelling infrastructure not in place • Switching costs for consumers who must purchase new vehicles • Smaller scale and unpredictable demand near-term	• Could be cost-effective for dispatchable peaking plants, because hydrogen + CCUS will have higher utilisation rate of CCUS than a dispatchable plant with post-combustion capture • Less-cost effective than post-combustion capture for baseload electricity generation

Source: Frontier Economics

A report delivered by the Hydrogen Task Force[72] calls out some barriers and enablers to the implementation of hydrogen at scale, such as:

- the need for regulatory frameworks which do not currently exist that recognise the importance of hydrogen in the energy transition
- cross-sector coordination with government support is important in bringing together relevant players for example relating to mobility and coordination between OEMs, energy companies and infrastructure providers
- industry standards and codes and uniformity nationally to promote technology scaling as well as internationally to promote export and trade
- raising awareness which is increasing however still relatively low across wider government, policy makers and industry

Another report[73], delivered under the HyLaw project, the UK National Policy Paper considers key legislation and regulation relevant to fuel cells and hydrogen applications and the legal barriers affecting commercialisation. It also includes recommendations relating to certification such as Guarantee of Origin which is still an important consideration that needs to be addressed in the UK. A similar National Policy Paper exists on the Netherlands for comparison. HyLaw also provides an interactive database online which provides a comparative tool on different laws and regulations in countries across Europe against the hydrogen supply chain and end uses.

HyLaw, funded from the Fuel Cells and Hydrogen 2 Joint Undertaking, is a project that considers Hydrogen Law and removal of legal barriers to the deployment of fuel cells and hydrogen applications. It is a flagship project aimed at boosting the market uptake of hydrogen and fuel cell technologies providing market developers with a clear view of the applicable regulations whilst calling the attention of policy makers on legal barriers to be removed.

4. Opportunities for collaboration

In a recent IEA report on hydrogen[74], it was recommended that international collaboration, multilateral initiatives and projects are important in supporting knowledge sharing, developing best practices and leveraging spill over benefits. This is beneficial particularly where there are shared interests, for example in developing trade routes which are crucial in creating a market for hydrogen. Additionally, it also references development of coastal hydrogen hubs to scale up low-carbon hydrogen production and use, which can support low-carbon uptake in other sectors. The North Sea provides one strong example which is shared between the UK and Netherlands and provides an opportunity for re-purposing existing oil & gas assets.

Last year, an agreement was signed between National Grid Ventures and the Dutch System operator TenneT to explore the development of a multi-purpose interconnector to simultaneously connect up to four gigawatts of British and Dutch offshore wind between the two countries' electricity systems, providing an additional two gigawatts of interconnection capacity.

There are also strong opportunities for shared learning between the UK and Netherlands on incentives and structures between the UK and the Netherlands, for example in relation to the SDE++ mechanism in the Netherlands, and other mechanisms referred to in this report being adopted by the UK such as CfD and RTO.

Decarbonisation of transport and heating also provides common themes and areas for collaboration, given similar gas network infrastructure between both countries, with gas-boilers currently playing a dominant role in heating in both the UK and Netherlands. The trading routes between the UK and Netherlands and potential for hydrogen use in long-haul HGVs also provides potential for collaboration here. To promote hydrogen in HGVs there will need to be the necessary refuelling infrastructure and therefore coordination amongst various industry and government stakeholders.

4.1. Platforms promoting collaboration

- Clean Energy Ministerial (CEM) is a high-level global forum to promote policies and programs that advance clean energy technology, to share lessons learned and best practices, and to encourage the transition to a global clean energy economy. Under this forum are two key initiatives of relevance:
    - Hydrogen Initiative (CEM H21) launched in 2019 under the leadership of Canada, the United States, Japan, the Netherlands and the European Commission
    - Carbon Capture Utilization and Storage (CEM CCUS), an initiative to strengthen the frameworks for public-private collaboration
- IEA TCP Hydrogen aims to accelerate the deployment and use of hydrogen technologies by carrying out and co-ordinating collaborative analysis, applied research and communications. Five task teams are currently active: Hydrogen Safety; Power-to-Hydrogen and Hydrogen-to-X; Hydrogen in Marine Applications; Energy Storage and Conversion Based on Hydrogen; and Data and Modelling.
- IEA Advanced Fuel Cells Technology Collaboration Programme is designed to examine in depth the opportunities and barriers to fuel cell commercialisation, to foster the international development of technologies and their applications, and to convey key messages to the community, the IEA, policy makers and the general public.

- Mission Innovation is an international initiative which aims to accelerate clean energy investment and innovation, and currently involves 24 countries and the European Commission (on behalf of the European Union). Mission Innovation Ministers have agreed to develop a second phase to be announced at the Sixth Mission Innovation Ministerial in June 2021.

- Hydrogen Economy Innovation Network formed by the KTN, in partnership with Innovate UK, to link industry, innovators and government to enable local, clean hydrogen uptake at scale and cost and to find innovative solutions to current and potential challenges.

4.2. Relevant public-private partnerships

- Fuel Cells and Hydrogen Joint Undertaking[75] - public private partnership supporting research, technological development and demonstration (RTD) activities in fuel cell and hydrogen energy technologies in Europe.
- The European Clean Hydrogen Partnership[76] will be building on the work of the Fuel Cells and Hydrogen Joint Undertaking, to accelerate the development and deployment of a European value chain for clean hydrogen technologies. It will focus on producing, distributing and storing clean hydrogen and, on supplying sectors that are hard to decarbonise, such as heavy industries and heavy-duty transport applications.
- Energy Research partnership[77], announced in 2005 a public-private partnership seeking to guide and accelerate innovation in the energy sector through enhancing dialogue and collaboration.

4.3. Potential commercial opportunities

The market for Hydrogen has a lot of potential and growing interest. Commercial opportunities are still unclear, and growth of the hydrogen industry will be reliant on the government mechanisms, regulation and policy incentives to come as part of the hydrogen strategy and other strategy documents being published. Figure 8 provides a snapshot of the innovation landscape and potential areas for growth as the UK hydrogen sector economy develops.

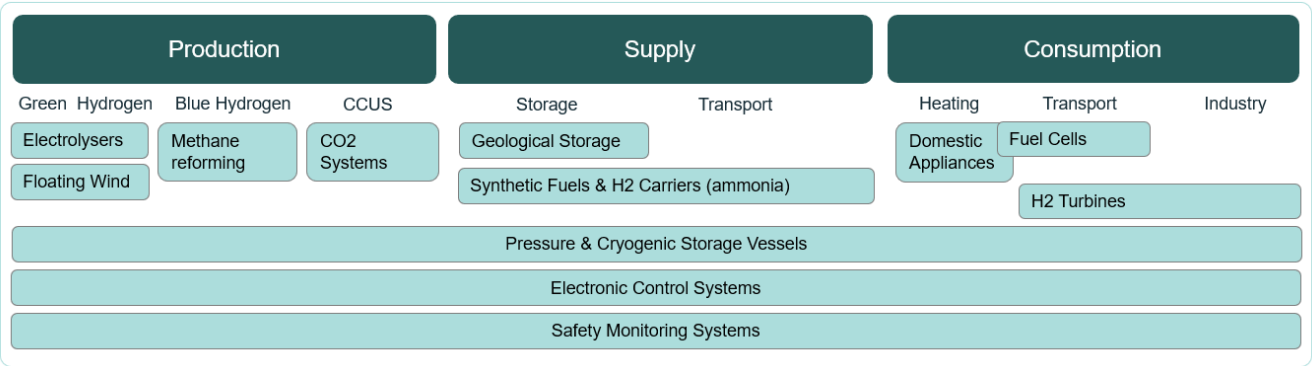

Figure 8: Technology Innovation Landscape

BEIS commissioned the Energy Innovation Needs Assessments (EINA) which were published in 2019 to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation. As part of analyses, reports were produced across 12 sub-themes including the hydrogen and fuel cells sub-theme report. This report provides a good overview of some of the key UK strengths, existing strong market players and business opportunities including the GVA and jobs potential. Further work being delivered by the Catapults has further highlighted the current gaps as well as opportunities in the UK which are captured in Table 9.

Table 9: Technology & Innovation Needs

Sub-sector	Opportunities & needs
Hydrogen Production	• Low cost electrolysers – including subsea, saltwater electrolysers • Low cost and durable materials e.g. catalysers • Biomass gasification-based routes' equipment • SMR related equipment: High-efficient reformers / membranes / CO2 sorbents
CCUS	• Geological studies on behaviour of CO2 • High efficiency CO2 conversion • Compact CO2 processing equipment • Capture materials • Site monitoring
Hydrogen Storage	• Underground storage equipment (salt caverns vs depleted O&G fields) • Small scale H2 Liquefaction • Small scale Ammonia cracking • Ammonia cracking
Hydrogen Distribution	• Refuelling station equipment • New infrastructure/pipelines for T&D • Transmission network compressors • Pipeline re-lining • Liquid organic hydrogen carriers (LOHC)
Transport & fuel cells	• Transport & stationary fuel cells equipment • Fuel cell manufacturing • Cryogenic storage systems / lightweight pressure vessels / fuel cells • Hybrid management systems
Heating	• Safety & monitoring • Appliances • Domestic and commercial supply networks / systems • Hydrogen boiler equipment
Industrial Power	• Retrofits for turbines to support fuel switching
Services	• O&M services • Installation services • EPCm services • Fuel cell design and advisory services

5. Recommendations and suggestions

In this section we have provided a list of some recommendations and suggestions for how Dutch companies and research institutes can engage with the UK energy and hydrogen sector.

1. Use of resources and networks

There are various research institutes, some within academia as well as other centres and hubs some of which are newly being established that provide a wealth of information as well as innovative activities. Depending on specific objectives, different resources and networks are available. Some of these are:

- Scottish Enterprise and Scotland Development International that provide support for setting up businesses in Scotland
- Research hubs, accelerators and industry associations as highlighted in section 3
- Not mentioned in his report but there is large eco-system of support for SMEs such as incubator and accelerator programmes in the UK
- Knowledge hubs mentioned in section 3.4:
    - Hydrogen & Fuel Cell Research Hub
    - Hydrogen knowledge centre
    - Hydrogen Hub

2. To engage with key stakeholders

As highlighted in section three there are various stakeholder groups and working with these stakeholders and partners in the UK could provide an opportunity for knowledge sharing, access to key end customers and involvement in activities and projects in the UK.

Some suggestions include:

- Research, academia and Catapult centres in the UK which provide a route for future collaboration and knowledge sharing
- Engagement with Energy Systems Catapult or other Catapult centres to understand more on the UK energy sector, as well as consider partnership opportunities. ESC has a breadth of capabilities[78] that can support net zero and energy transitions
- Direct engagement with BEIS which may also allow early visibility of new incentives and other activities and initiatives
- Engagement with Embassy of the Netherlands in the UK (including British embassy posts in the Netherlands) who regularly engage with stakeholders and arrange missions and events which promote knowledge sharing and collaboration
- Engagement with the Embassy of the Netherlands in the UK can be done via:
    - The Netherlands Innovation Network UK based at the Embassy stimulates collaboration between Dutch and British companies, research institutes and government bodies in the field of innovation, technology and science. The team can help you identify opportunities for bilateral innovation and R&D collaboration in the hydrogen sector.
    - The Economic Department of the Embassy of the Netherlands in the UK promotes trade between the Netherlands and the UK. The Economic Department at the Embassy can help you identify trade opportunities and find a trade partner or distributor in the UK.

3. Consider funding opportunities and competitions

There are various existing funding schemes, however given the investments and ambitions as highlighted in section 2, there is potential for more opportunities and funding competitions however it is not yet clear how those will materialise and the nature of the schemes. It is recommended that Dutch companies and institutes continue to monitor, whilst being mindful of various eligibility criteria that might require being a UK registered company to participate. Other points to consider:

- The Horizon Europe funding is a good opportunity for partnership and R&D between UK and Netherlands, as well as other European countries.
- It is worth noting that a lot of the grant funding projects detailed require long, often complicated applications and can be quite competitive. After award of the grant there are also often quite onerous reporting requirements. In particular the NIC application process (mention in table 3) takes a long time, with numerous clarifications and iterations. EU funded schemes are also notoriously onerous in terms of the administrative burden during implementation. From our experience, NIC and EU processes are more complicated and difficult than those from BEIS, Innovate UK or the Scottish Government.
- Regional funds (particularly Scotland) might offer a good approach. Local government bodies often have their own funding opportunities. Many of these are not specifically linked to energy, but could be suitable, if for example, jobs are created. Some examples:
    - £10m Cardiff Capital Region (CCR) Challenge Fund which aims to build local wealth through creating commercial opportunities for organisations across the CCR and supports partnerships between the public and private sector.
    - The Scottish Enterprise's Energy Investment Fund provides flexible investment and debt funding for energy projects in Scotland that will facilitate, catalyse and accelerate Scotland's transition to a low carbon economy.
    - The link below provides an example of the kind of websites for regional / local funding that might be worth further exploration under Local Enterprise Partnerships. https://www.northeastlep.co.uk/funding

Some suggested next steps:

- Matching with UK firms in related and complementary sectors – this might be particularly helpful for Dutch SMEs
- Engagement with incubators and accelerators in this space, as well as research hubs and centres
- Consider possible partnerships under Horizon Europe given upcoming calls and clear participation guidelines for both countries
- Engagement in UK pilot and demonstration projects
- Identification of local governments and/or centres that are particularly interested in innovation
- Organisation of events such as roundtables, workshops, webinars between UK and Dutch companies to promote knowledge sharing and collaboration e.g. hackathons or business matchmaking
- Analyses and comparison between UK and Dutch hydrogen sectors and hydrogen supply chains to understand where complimentary expertise lies

Note: Energy Systems Catapult can support with the above given our active role in the UK energy sector and engagement with government, academia and industry (including SMEs) and our role on the UK Hydrogen Advisory Council.

6. References

[1] HM Government (2020), The Ten Point Plan for a Green Industrial Revolution https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

[2] https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs

[3] HM Government (2020), Energy white paper: Powering our net zero future https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

[4] HM Government (2020), The Ten Point Plan for a Green Industrial Revolution https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

[5] HM Government (2020), Energy white paper: Powering our net zero future https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

[6] BEIS (2020), Carbon Capture, Usage and Storage An update on business models for Carbon Capture, Usage and Storage https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-business-models

[7] BEIS (2020), Carbon Capture, Usage and Storage: A Government Response on Re-use of Oil and Gas Assets for Carbon Capture and Storage Projects https://www.gov.uk/government/consultations/carbon-capture-usage-and-storage-ccus-projects-re-use-of-oil-and-gas-assets

[8] https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-guidance-2021

[9] BEIS (2020), Business models for low carbon hydrogen https://www.gov.uk/government/publications/business-models-for-low-carbon-hydrogen-production

[10] BEIS (2020), Carbon Capture, Usage and Storage An update on business models for Carbon Capture, Usage and Storage https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-business-models

[11] Frontier Economics (2020), Hydrogen blending and the gas commercial framework https://www.frontier-economics.com/media/4201/hydrogen-blending-commercial-framework.pdf

[12] ENA (2020), Delivering the pathway to net zero https://www.energynetworks.org/assets/images/ENA%20GGG%202021%20Programme.pdf

[13] Navigant (2019, Pathways to Net-Zero: Decarbonising the Gas Networks in Great Britain https://www.energynetworks.org/assets/images/Resource%20library/ENA%20Gas%20decarbonisation%20Pathways%202050%20FINAL.pdf

[14] Department for Transport (2019), Clean Maritime Plan https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf

[15] National Audit Office (2020), Achieving Net Zero https://www.nao.org.uk/report/achieving-net-zero/

[16] https://www.gov.uk/government/groups/hydrogen-advisory-council

[17] https://www.gov.scot/publications/scottish-government-hydrogen-policy-statement/

[18] https://gov.wales/sites/default/files/consultations/2021-01/baselining-report-hydrogen-development-in-wales.pdf

[19] https://gov.wales/sites/default/files/consultations/2021-01/hydrogen-in-wales-consultation.pdf

[20] https://www.economy-ni.gov.uk/news/minister-highlights-plan-ambitious-new-renewable-electricity-target

[21] https://www.economy-ni.gov.uk/articles/northern-ireland-energy-strategy-2050#toc-0

[22] https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition

[23] 4,000 zero-emission buses plan to start delivery in 2021 (2021): https://www.route-one.net/environment/4000-zero-emission-buses-plan-to-start-delivery-in-2021/

[24] https://www.gov.uk/government/publications/offshore-wind-manufacturing-investment-support-scheme-investment-programme

[25] https://www.instituteforgovernment.org.uk/explainers/net-zero-target

[26] https://es.catapult.org.uk/reports/innovating-to-net-zero/
[27] OREC, Offshore wind and hydrogen, solving the integration challenge, https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf
[28] OEE, 80% of UK public backs wave and tidal, May 2020- https://www.oceanenergy-europe.eu/industry-news/80-of-uk-public-backs-wave-and-tidal/
[29] DTOceanPlus, Deliverable D8.4- in progress (link to update- https://www.dtoceanplus.eu/Project-Structure/WP8-Market-Analysis)
[30] Marine Renewables, POSTnote 625-June 2020- https://post.parliament.uk/research-briefings/post-pn-0625/
[31] ITEG- Integrating Tidal energy into European Grid- https://www.nweurope.eu/projects/project-search/iteg-integrating-tidal-energy-into-the-european-grid/
[32] EMEC first tidal battery,Nov 2020- https://www.theengineer.co.uk/tidal-flow-battery-emec/
[33] https://www.gov.uk/government/statistics/energy-trends-section-6-renewables
[34] Energy Research Partnership (2016) Potential Role of Hydrogen in the UK Energy System.
[35] CCC (2018), Hydrogen in a low-carbon Economy, https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf
[36] ESC (2020), Innovating to Net Zero, https://es.catapult.org.uk/reports/innovating-to-net-zero/
[37] Regen, Building the hydrogen value chain, https://www.regen.co.uk/publications/building-the-hydrogen-value-chain/
[38] CCC (2018), Hydrogen in a low-carbon economy, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/
[39] CCC (2018), Hydrogen in a low-carbon economy, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/
[40] CCC (2018), Hydrogen in a low-carbon economy, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/
[41] https://www.energynetworks.org/newsroom/hydrogen-blending-what-is-it-and-why-does-it-matter
[42] https://www.energynetworks.org/newsroom/hydrogen-blending-what-is-it-and-why-does-it-matter
[43] Frontier Economics (2020), Business Models for Low Carbon Hydrogen Production
[44] Element Energy & Jacobs (2018), Industrial Fuel Switching Market Engagement Study https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/824592/industrial-fuel-switching.pdf
[45]Industrial Fuel Switching competition phase 3: successful projects https://www.gov.uk/government/publications/industrial-fuel-switching-to-low-carbon-alternatives/industrial-fuel-switching-demonstration-successful-projects-phase-3
[46] CCC (2018), Hydrogen in a low-carbon economy, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/
[47] ORE Catapult (2020), Offshore wind and hydrogen: Solving the integration challenge https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf
[48] https://gigastack.co.uk/
[49] National Development Programme: ERM Dolphyn Project (2020): https://www.transformingplanning.scot/media/1500/083-environmental-resources-management-limited.pdf
[50] Acorn CCS & Acorn Hydrogen, (2020): https://pale-blu.com/acorn/
[51] https://hynet.co.uk/
[52] https://es.catapult.org.uk/impact/projects/integrating-tidal-energy-into-the-european-grid/
[53] Hydrogen is vital to tackling climate change (2021): https://hydeploy.co.uk/
[54] Future Billing Methodology: https://futurebillingmethodology.co.uk/faqs/
[55] Hy4Heat (2021) : https://www.hy4heat.info/
[56] H100 NIA (2020): https://www.sgn.co.uk/about-us/future-of-gas/hydrogen/hydrogen-100
[57] https://es.catapult.org.uk/impact/projects/milford-haven-energy-kingdom/
[58] UK's first hydrogen train takes to the mainline marking major step towards decarbonising Britain's railways (2020): https://www.birmingham.ac.uk/research/railway/research/power-systems-and-energy-use/hydrogen-train-mainline.aspx

[59] Aberdeen City Council (2020): https://news.aberdeencity.gov.uk/aberdeen-to-see-further-expansion-of-hydrogen-buses-project/
[60] SCCS (2021): https://www.sccs.org.uk/news-events/recent-news/592-net-zero-pathway-to-be-mapped-by-industries-and-universities-with-123m-award
[61] South Wales Industrial Cluster: https://www.group.rwe/en/our-portfolio/innovation-and-technology/hydrogen/south-wales-industrial-cluster
[62] https://www.ukri.org/news/ukri-awards-171m-in-uk-decarbonisation-to-nine-projects/
[63] Gas Network Innovation Competition: https://www.ofgem.gov.uk/network-regulation-riio-model/current-network-price-controls-riio-1/network-innovation/gas-network-innovation-competition?page=1#block-views-publications-and-updates-block
[64] Gas Network Innovation Allowance: https://www.ofgem.gov.uk/network-regulation-riio-model/network-innovation/gas-network-innovation-allowance
[65] Innovate UK Smart Grants: November 2021: https://apply-for-innovation-funding.service.gov.uk/competition/810/overview
[66] Green Recovery: Low Carbon Energy Project: Capital Funding https://www.gov.scot/publications/green-recovery-low-carbon-energy-project-capital-funding-form-and-guidance-2/
[67] Knowledge Transfer Partnerships https://www.gov.uk/guidance/knowledge-transfer-partnerships-what-they-are-and-how-to-apply
[68]Transitioning towards Zero Emission Vehicles: feasibility studies: https://apply-for-innovation-funding.service.gov.uk/competition/869/overview#eligibility
[69]Infrastructure solutions for zero emission vehicles (2021): https://apply-for-innovation-funding.service.gov.uk/competition/873/overview
[70] https://www.fch.europa.eu/news/eu-proposal-set-clean-hydrogen-partnership-europe-1
[71]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866376/Phase_1_-_Inovyn_-_HySecure.pdf
[72] Hydrogen Taskforce (2020), The Role of Hydrogen in Delivering Net Zero https://www.hydrogentaskforce.co.uk/wp-content/uploads/2020/04/FINAL_Hydrogen-Taskforce-Report-Feb2020_Lores.pdf
[73] HyLAW (2018), UK National Policy Paper, https://www.hylaw.eu/sites/default/files/2019-01/HyLaw%20UK%20Policy%20Paper_Final_December%202018.pdf
[74] IEA (2020), Hydrogen IEA Paris https://www.iea.org/reports/hydrogen
[75] https://www.fch.europa.eu/news
[76] https://www.fch.europa.eu/news/eu-proposal-set-clean-hydrogen-partnership-europe-1
[77] https://erpuk.org/
[78] https://es.catapult.org.uk/capabilities/