Hydrogen Innovation Initiative (HII)

FUNCTIONALITY AND SCOPE OF FUTURE HYDROGEN HUBS: 'BEYOND PRODUCTION: EXAMINING THE DUAL ROLE OF FUTURE HYDROGEN HUBS'

HII partners:

DISCLAIMER

HYDROGEN INNOVATION INITIATIVE

The Hydrogen Innovation Initiative's mission is to accelerate the development of critical technologies and supply chains in the UK for the fast-growing hydrogen economy. The Hydrogen Innovation Initiative's partners include the Catapult Network, the Advanced Propulsion Centre, the Aerospace Technology Institute, the Net Zero Technology Centre and the National Physical Laboratory. The Hydrogen Innovation Initiative is supported by Innovate UK.

THE OFFSHORE RENEWABLE ENERGY CATAPULT

The Offshore Renewable Energy (ORE) Catapult, was established in 2013 by Innovate UK as part of a network of Catapults set up in high growth industries. It is the UK's leading innovation centre for offshore renewable energy. Independent and trusted, with a unique combination of world-leading test and demonstration facilities and engineering and research expertise, ORE Catapult convenes the sector and delivers applied research, accelerating technology development across offshore wind (fixed and floating), wave & tidal energy, reducing risk and cost and enhancing UK-wide economic growth. Active throughout the UK, ORE Catapult has operations in Glasgow, Blyth, Levenmouth, Aberdeen, the Humber, the East of England, the Southwest, and Wales and operates a collaborative research partnership in China.

The UK energy system is facing unprecedented challenges to meet carbon emission reduction targets, including Net Zero by 2050. It will require intensive expansion of low-carbon electricity generation technologies and decarbonising heat and transport sectors using electrification and hydrogen. This transition will provide many opportunities for UK innovators to grow and thrive, and policymakers will face several key decision points that will determine the prospects for UK plc, outcomes for consumers, and the overall impact of the transition on UK Gross Value Added (GVA).

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

CCUS	Carbon Capture, Utilisation and Storage
CO_2	Carbon Dioxide
DESNZ	The Department for Energy Security and Net Zero
DNV	Det Norske Veritas
FEED	Front-end Engineering and Design
HAR1	Hydrogen Allocation Round 1
HHV	Higher heating value
GHG	Greenhouse gas
H_2	Hydrogen
IRENA	International Renewable Energy Agency
kW	kilo-Watt
kWh	kilo-Watt hour
LCHS	Low Carbon Hydrogen Standard
LCOE	Levelised cost of energy
LCOH	Levelised cost of hydrogen

LHV	Lower heating value
$MtCO_2$	Metric Tons of Carbon Dioxide
MW	Mega-Watt
MWh	Mega-Watt hour
NZHF	Net Zero Hydrogen Fund
O&G	Oil and gas
ORE	Offshore Renewable Energy
OSS	Offshore Substation
OSW-H_2	Offshore wind - Hydrogen
OTNR	Offshore Transmission Network Review
PEM	Polymer Electrolyte Membrane Electrolyser
SMR	Steam methane reforming
StIC	Solving the Integration Challenge, a report delivered by ORE Catapult and supported by the Offshore Wind Industry Council
TRL	Technology readiness level
TW	Tera-Watt
TWh	Tera-Watt hour

EXECUTIVE SUMMARY

Hydrogen Strategy Delivery led by the UK Government alongside the British Energy Security Strategy have set the direction of travel to 2035; alongside other technologies, there is a major ramp up of offshore wind and hydrogen production via electrolysis and carbon capture utilisation and storage-enabled hydrogen projects. This will feed into the UK Government’s goal of having 5 GW of green hydrogen electrolysis and 5 GW of carbon capture utilisation and storage-enabled hydrogen projects capacity by 2030. Green and blue hydrogen will have a significant effect on the countries energy system for the future. Although there is some uncertainty around the way these new targets will be reached, they have great potential to deliver positive outcomes for the country. Among the numerous hydrogen production routes, renewable energy powered electrolysis is looking increasingly attractive for the UK decarbonisation route. Due to volatile natural gas prices driving the cost of blue hydrogen to approximately ≈ £5.70/kg; [1] [2] the price of green hydrogen from renewable energy is expected to decrease significantly in comparison. Across the sector research groups, like ORE Catapult, it is expected that the cost of green hydrogen falls below those predicted for blue hydrogen in the range of £1.50 – 3/kg by 2050. [3] [4]

Funding outcomes from Hydrogen Strategy Delivery to Market (updated in December 2023, and February 2024) support investment in hydrogen technology. The current plans as per the Hydrogen Strategy Delivery are for the development of Hydrogen Hubs in the UK. The key areas are carbon capture utilisation and storage in phase 2 negotiations, successful projects from the first electrolytic Hydrogen Allocation Round (HAR1), and the £240 million Net Zero Hydrogen Fund (NZHF) that are all growing the hydrogen economy forward. With first stage/phase all indicative capacities that are subject to change over time, however the update to date is that the initial capacity from the research and data available amounts to ≈ 5.2 GW. This includes all successful projects allocated by the Hydrogen Strategy Update to the Market released by the Government (for green hydrogen electrolysis and carbon capture utilisation and storage-enabled hydrogen projects).

For the UK there is potential to use green hydrogen electrolysis, produced from substantial floating offshore wind projects. The Crown Estates Allocated Leasing Round 5 bidding process opened in February 2024. Where we will see developers bidon three Project Development Areas (PDA-1, PDA-2, PDA-3) in the Celtic Sea. Making up the first round of large scale floating offshore wind projects in the Celtic Sea area between Southwest England and South Wales. Feeding into the UK’s Hydrogen Hub economy through floating offshore wind from the total pipeline to 29 GW (with 84.5% of the total capacity in Scottish waters). There are a range of enabling programs to support green hydrogen and offshore wind, many of which the UK Government has already set in place as discussed. Supporting programs include: Contract for Difference style Allocation Rounds to support production; introducing standards, such as the low carbon hydrogen standard; providing support for green hydrogen electrolysis and new offshore wind grid connections. Therefore, the introduction of

[1] Hydrogen Policy Assumes Natural Gas Prices Are Stable. They’re Not - RMI

[2] High gas prices triple the cost of hydrogen production | Article | ING Think

[3] Green hydrogen economy - predicted development of tomorrow: PwC

[4] Costs challenge the hydrogen transformation | E&T Magazine (theiet.org)

regulatory sandpits would accelerate novel projects, providing targeted funding for demonstration and commercial Hydrogen Hub projects to accelerate the Hydrogen Economy.

1 PURPOSE OF THIS STUDY

The focus of this study answered key questions that relate to hydrogen hubs in the UK, with the associated aim to explore the production of hydrogen. How the concept of hydrogen hubs could be implemented to expedite the hydrogen economy to understand the functionality and scope of future hydrogen hubs: beyond production by examining the dual role of future hydrogen hubs.

1.1 Questions associated to the purpose of this study.

1.1.1 Where are there existing 'Hydrogen Hubs' in the UK?

- Aim: To identify and map the current locations and infrastructure of established hydrogen hubs in the United Kingdom, providing a comprehensive overview of the existing hydrogen ecosystem.

1.1.2 Where are the confirmed 'Hydrogen Hubs' being developed imminently in the UK (is timeline known)?

- Aim: To investigate and document the confirmed plans and timelines for the imminent development of hydrogen hubs in the United Kingdom, offering insights into the upcoming advancements in the hydrogen infrastructure landscape."

1.1.3 Are the 'Hydrogen Hubs' forthcoming, mostly about production of hydrogen for preassigned use cases, or will these also double up as places to come and 'fill up the tank' for commercial sales too?

- Aim: To analyse the anticipated roles and functionalities of future hydrogen hubs in the UK, with a focus on understanding whether their primary purpose is hydrogen production for specific use cases or if they also serve as commercial refuelling stations.

1.1.4 Of forthcoming 'Hydrogen Hubs' what is the expected capacity to be and are they permanent, versus the completed Teesside project able to fuel 20 vehicles for several months?

- Aim: To assess and forecast the expected capacities of upcoming hydrogen hubs in the UK, examining whether these facilities are designed for long-term, permanent operation and comparing them to existing projects like the Teesside initiative, which can fuel a specific number of vehicles over an extended period.

1.1.5 When 'Hydrogen Hubs' appear, would customers use 100% hydrogen vehicles than hybrid-diesel options, over electric hybrid, or bio-fuel alternatives?

- Aim: To explore and understand consumer preferences and behaviours regarding the adoption of hydrogen vehicles in the presence of hydrogen hubs, comparing the likelihood of choosing 100% hydrogen vehicles over hybrid-diesel options, electric hybrids, and bio-fuel alternatives.

2 INTRODUCTION

Hydrogen hubs are emerging as a crucial component of the global transition to clean energy, serving as regional centres for the production, storage, distribution, and utilization of hydrogen. These hubs integrate various hydrogen production methods, including electrolysis powered by renewable energy (green hydrogen) and natural gas reforming with carbon capture (blue hydrogen), to create a sustainable and scalable hydrogen economy. Governments and private sector stakeholders are investing heavily in developing hydrogen hubs, with initiatives focused on infrastructure expansion, policy support, and technological advancements. The goal of these hubs is to accelerate the commercialization of hydrogen, reduce carbon emissions, and support industries in their shift toward cleaner energy solutions.

Due to volatile natural gas prices driving the cost of blue hydrogen to approximately £5.70/kg, the price of green hydrogen from renewable energy is expected to decrease significantly in comparison. This document explores the economic and technological factors shaping hydrogen hub development, comparing different production methods and their cost trajectories. It examines the challenges and opportunities in establishing these hubs, highlighting the potential for green hydrogen to become a cost-competitive and sustainable alternative. By analysing current trends and policy frameworks, this document aims to provide insights into the future of hydrogen hubs and their role in decarbonising key sectors.

The UK energy system is facing unprecedented challenges to meet carbon emission reduction targets, including Net Zero by 2050. It will require intensive expansion of low-carbon electricity generation technologies and decarbonising heat and transport sectors using electrification and hydrogen. The race is on to secure our Net Zero future with hydrogen recognised as a critical energy vector capable of rapid decarbonisation to the most challenging areas of the economy. Current global predictions on climate change are ominous, however humanity still has time to challenge our anthropogenic contributions by developing ingenious strategies that actively support sustainable efforts to sustain global temperature increase to below 1.5°C. The design of those strategies could begin with reinforcing and creating new hydrogen hub economies. These hydrogen economies would be built on enhanced cross sector collaboration & integration within the energy mix of the country, which connects power generation to match consumer demand.

Key technologies considered for scaling the hydrogen hub economy include Carbon Capture, Utilisation, and Storage (CCUS) for blue hydrogen production and cryogenic liquid hydrogen storage for efficient large-scale storage and transport. Noted that hydrogen presents a low ambient temperature density, which results in a low energy per unit volume. This is the reason why hydrogen storage methods must present higher energy density. Liquid hydrogen faces challenges due to the high energy consumption required for the liquefaction process and hydrogen losses during storage. However, in the context of a hydrogen hub, hydrogen can serve as a means to store excess renewable energy, helping to reduce curtailment. This makes hydrogen hubs particularly beneficial for regions with abundant renewable energy resources, where hydrogen can be produced, stored, and later transported to areas with higher industrial-scale hydrogen demand.

However, despite the current acceleration to form hydrogen hubs through national hydrogen plans, roadmap, and announced strategies, hydrogen economies are extremely slow to progress. In 2021, IEA, Global Hydrogen Review announced that only (4%) of hydrogen produced came from green hydrogen (water electrolysis powered by renewable energy sources); most of the hydrogen produced (83%) still comes from fossil fuels, mainly from grey hydrogen (steam methane reforming (SMR) without CCUS technologies).[5]

As the hydrogen economy evolved, it became necessary to classify hydrogen by colour based on its source and production method. Although naturally colourless, hydrogen can be produced through various processes, including electrolysis, steam methane reforming, gasification, thermochemical, photochemical, biochemical, and biological methods.[6]

What is a Hydrogen Hub

A hydrogen hub is a centralised infrastructure that integrates various components of the hydrogen value chain, including hydrogen production, storage, distribution, and utilisation. The goal of a hydrogen hub is to create a local or regional ecosystem that promotes the use of hydrogen as a clean and sustainable energy carrier.

Key features and components of a hydrogen hub may include:

Hydrogen Production Facilities: The hub typically includes facilities for the production of hydrogen. Common methods for hydrogen production include SMR, electrolysis (using renewable electricity to split water into hydrogen and oxygen), and other advanced technologies.

Storage and Distribution Infrastructure: Hydrogen hubs involve the development of storage systems for hydrogen and distribution infrastructure, which may include pipelines, trucks, or other means of transporting hydrogen from production sites to end-users.

End-Use Applications (and Refuelling Stations): Hydrogen produced at the hub can be utilized across various applications, including fuelling hydrogen fuel cell vehicles, supplying feedstock for industrial processes, and generating electricity through fuel cells. To support the expansion of hydrogen-powered transportation, hydrogen hubs often incorporate refuelling stations, promoting the growth of the hydrogen fuel cell vehicle market.

Integration with Renewable Energy: Many hydrogen hubs aim to integrate renewable energy sources into the hydrogen production process, making the overall hydrogen production process more sustainable and environmentally friendly.

Research and Development Facilities: Some hydrogen hubs may include research and development facilities to advance hydrogen technologies and explore new applications for hydrogen.

Hydrogen hubs play a crucial role in the development of a hydrogen economy by addressing challenges related to hydrogen infrastructure and promoting collaboration among industry stakeholders, governments, and research institutions. They are seen as important elements in the transition toward a low-carbon and sustainable energy future. The development of hydrogen hubs is often part of broader government and industry initiatives to decarbonise sectors such as transportation, industry, and energy.

[5] IEA, Global Hydrogen Review, IEA, Paris, 2022.

[6] "Colors" of hydrogen: Definitions and carbon intensity - ScienceDirect

3 HYDROGEN CONCEPT

Hydrogen is designated with the symbol H on the modern periodic table having an atomic number 1, Hydrogen is therefore defined as a chemical element. Molecular form (H_2) is typically how hydrogen exists in nature; it is nontoxic at room temperature and pressure. Although by applying extremely low temperatures (typically -423°F or -253°C) hydrogen can be condensed to form a liquid. In compounds, for example, water (H_2O), ammonia (NH_3), methane (CH_4), and hydrocarbons (that fall in the groups, like natural gas, coal, and oil) are made up of elemental hydrogen. Therefore, according to the International Energy Agency (IEA) hydrogen is currently mainly used for industrial processes, so globally this would include oil refining (≈ 33%), ammonia production (≈ 27%), methanol production (≈ 27%), and steel production (≈ 3%).[7] This is predominantly important for hydrogen hubs as hydrogen production can also be used as a fuel for electricity production, transport, and building heating. This is important because hydrogen must be produced from other energy sources, therefore hydrogen is considered as an energy carrier rather than an energy source. For this reason, once hydrogen is produced, it can then be stored, transported, and later used in various applications.

3.1 Hydrogen colours and processes

Hydrogen is a clean-burning gas that is odourless, and colourless hence when it comes to hydrogen classification, this is based on the carbon emission intensity of the full production cycle. To help differentiate between these different carbon emission processes, and their respective outputs each option has been loosely designated a colour for process identification. Although there is broad agreement on the colours these are hydrogen production process commonly used, listed in Table 3.1.

Caution should be administered when comparing hydrogen colours, for example when comparing blue hydrogen for example. As blue hydrogen uses natural gas as the feedstock and includes CCUS to minimise direct carbon dioxide (CO_2) emissions, often referred to as a low-carbon hydrogen production process. However, blue hydrogen production can produce methane emissions a destructive greenhouse gas (GHG), associated to the production and transportation of natural gas sources.

The CO_2 emissions of each production pathway are affected mostly by the sources of hydrogen and energy. For example, those pathways that require water as their source material (like in green, pink, and yellow), there are practically no associated CO_2 emissions. For hydrogen production where fossil fuels are the source material, for example, like grey, brown and black, high CO_2 emissions are certain unless CCUS has been included in the production process.

Table 3.2 List of specified hydrogen colours by original energy source, process, and outputs.

[7] Hydrogen 101: Frequently Asked Questions About Hydrogen for Decarbonization — Greening the Grid

Specified hydrogen colour	Produced using	Production Process	Outputs	Carbon intensity classification
Brown	Bituminous coal, water, and oxygen	Gasification with water gas shift reaction	Hydrogen and carbon dioxide	***High-carbon hydrogen***
Black	Lignite coal, water, and oxygen	Gasification with water gas shift reaction	Hydrogen and carbon dioxide	
Grey	Natural gas or Methane and water	Steam-methane reforming with water gas shift reaction	Hydrogen and carbon dioxide	
Turquoise	Natural gas	Methane Pyrolysis	Hydrogen and solid carbon	
Green	Renewable energy and water	Electrolysis	Hydrogen and oxygen	***Low-carbon hydrogen***
Blue	Methane and water	Steam-methane reforming with water gas shift reaction with CCUS	Hydrogen and carbon dioxide, some of which is captured and stored	
Pink	Nuclear power and water	Electrolysis	Hydrogen, oxygen, and radioactive waste	
Yellow	Grid electricity and water	Electrolysis	Hydrogen, oxygen and potentially radioactive waste and carbon dioxide, depending on grid mix	

3.2 Environmental impacts

There are associated environmental impacts evident throughout the production of all hydrogen forms, this includes green hydrogen produced from renewable energy resources. These resources are for example, from wind, wave, tidal, solar photovoltaics, and hydro. Therefore, to have an accurate account of the CO_2 emissions and their respective environmental impact, it is necessary to consider the whole supply chains emissions. In Table 3.3 relevant CO_2 emissions have been compared to approximate the associate CO_2 equivalent per kg of H_2 from the production system, with brown and black production eliminated due to association to coal.

Table 3.3 Carbon dioxide emissions associated to hydrogen production per kilogram.

Specified hydrogen colour	Production Process	CO_2 Emissions ≈ $kg_{CO2}eq./kg_{H2}$	Water Consumption ≈ kg_{H2O}/kg_{H2}
High CO_2			
Brown	Bituminous coal	18 to 25 [11]	31 to 31.8 [8]
Black	Lignite coal	18 to 25 [11]	31 to 31.8 [8]
Grey	SMR	7.5 to 13 [9]	6.4 to 32.2 [10]
Turquoise	Methane pyrolysis	1.9 to 4.8 [11]	Indirect
Low CO_2			
Green	Electrolysis	0.7 to 2.8 [11]	25.7 to 30.2
Blue	SMR @(95%) CCUS	0.8 to 4.8	6.4 to 32.2 [10]
Pink	Electrolysis	0.3 to 0.6 [11]	25.7 to 30.2

4 INCREASING HYDROGEN IN THE ENERGY SYSTEM

4.1 Potential hydrogen increase

Integrating renewable energy into the national energy system requires supporting technologies to expand the reach of low-carbon energy, particularly for sectors that are difficult to decarbonise and to address the intermittency of wind and solar resources. Among various solutions, hydrogen stands out as a promising option—not only as a clean fuel but also for large-scale, long-term energy storage within hydrogen hubs. [12]

Significant interest has gained momentum regarding hydrogen is not a form of energy production, currently driven by green and blue hydrogen production options as discussed earlier. Firstly, fuelled and matured in discussions from our commitment and ambitions to reducing global warming. [13] [14] Secondly, the fact that renewable energy costs have fallen dramatically, which could ignite the industry into major steps towards making green hydrogen financially competitive from electrolysis.

[8] U.S. Department of Energy Office of Scientific and Technical Information, Technical Report: Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels

[9] IEA, Global Hydrogen Review, IEA, Paris, 2022.

[10] Altgelt F, Micheli M, Sailer K, Crone K. Water Consumption of Powerfuels. Berlin: Deutsche Energie-Agentur GmbH (dena); 2021.

[11] UNECE. Technology Brief Hydrogen. United Nations Economic Commission for Europe Task Force on Hydrogen, Geneva; 2021.

[12] HyStorPor _ storage_briefing_FINAL.docx (ed.ac.uk)

[13] IPCC — Intergovernmental Panel on Climate Change

[14] Mobilising institutional capital for renewable energy (irena.org)

4.1.1 Producing hydrogen in the UK

From previous analysis conducted by ORE Catapult in 'Solving the Integration Challenge', found that the UK energy system would require 130 – 200 TWh of hydrogen by current 2050 ambitions to integrate ≥75 GW, of offshore renewable energy capacity. [15]

Following the Government's British Energy Security Strategy that set ambitious 2030 targets for the hydrogen market, these outlines can be found here: [16]

- "Doubling our ambition up to 10 GW of low carbon hydrogen production capacity by 2030, subject to affordability and value for money, with at least half of this coming from electrolytic hydrogen, by efficiently using our surplus renewable power to make hydrogen, we will reduce electricity system costs.
- "Aiming to run annual allocation rounds for electrolytic hydrogen, moving to price competitive allocation by 2025 as soon as legislation and market conditions allow, so that up to 1 GW of electrolytic hydrogen is in construction or operational by 2025.
- "Designing, by 2025, new business models for hydrogen transport and storage infrastructure, which will be essential to grow the hydrogen economy.
- "Levelling the playing field by setting up a hydrogen certification scheme by 2025, to demonstrate high-grade British hydrogen for export and ensure any imported hydrogen meets the same high standards that UK companies expect."

4.2 The opportunity for hydrogen through renewable energy

As more offshore renewable energy—primarily wind in the near future—is integrated into the grid, it will interact with the existing energy network. With increasing offshore wind capacity, there will be periods when national energy supply exceeds demand, as seen during the extreme storm events of 2023/2024. Instead of curtailing wind resources, grid-connected electrolysers at centralised hydrogen hubs could act as controllable demand, helping to balance the system while maintaining wind output. The goal is to use off-grid electricity to produce, store, and deploy hydrogen, reducing pressure on the grid. This electrolyser interaction between offshore wind can also be direct through integrated systems having the best of both options dictated by the energy resource available. These resulting synergies can be applicable through a range of robust scenarios likely to see in the UK's energy mix. This approach is to increase the nation's energy security, integrate wind farms with electrolysers, and have the ability through a storage system (hydrogen hub) that would allow for the controllable dispatch of renewable energy.

The National Grid ESO Offshore Coordination project [17], which is linked to a plan for a holistic network design (HND) [18] has connections to The Department for Energy Security and Net Zero (DESNZ) that led the Offshore Transmission Network Review (OTNR) [19]. Together, the work should

[15] Offshore Wind and Hydrogen: Solving the Integration Challenge – ORE (catapult.org.uk)

[16] British energy security strategy - GOV.UK (www.gov.uk)

[17] Offshore Coordination Project | National Grid ESO

[18] Offshore Coordination Project - latest news and staying informed | National Grid ESO

[19] Offshore transmission network review - GOV.UK (www.gov.uk)

help to find the best solution to connect new offshore renewable generation into the wider energy system. Offshore renewables and hydrogen are a promising route to reducing our dependency on imported fossil fuels, offering both greater security and progress towards climate goals. They can help to stabilise the electrical network whilst extending the reach of renewable energy beyond electricity.

5 HYDROGEN PRODUCTION ROUTES AND ASSOCIATED COSTINGS

5.1 Key barriers to the development of a hydrogen economy

In a hydrogen economy, there are key barriers that currently prevent clean hydrogen from making a larger contribution to the energy transformation, and challenges to integrate renewable energy and hydrogen. Some of these key barriers are listed as follows: [20]

- Production, transportation, converting (where necessary), storing hydrogen and historically, the cost of 'green' hydrogen has been very high relative to high-carbon fuels. The European energy crisis has only increased the sudden system/market changes, having long term implications on the cost of fossil fuels compared to cleaner green hydrogen.
- The hydrogen supply chain encompasses a low technology readiness level (TRL) in some parts of the hydrogen economy.
- Hydrogen production incurs significant energy losses at each stage of conversion, including CO_2 emissions, efficiency losses during the production process (such as electrolysis or steam methane reforming), and challenges related to storage. These losses can occur due to the energy required for liquefaction, compression, or other storage methods.
- Projections by The International Renewable Energy Agency (IRENA) indicates that 21 GWh of energy will be consumed by modern electrolyser technology by 2050 from renewable energy; that perhaps this energy might be needed elsewhere instead of the hydrogen economy.
- Our hydrogen economy remains high risk for both hydrogen production and the necessary infrastructure that would reduce costs to become a substantial investment.
- Hydrogen production risk has the difficulty of matching supply with demand effectively.

In summary, to reduce hydrogen production costs the ethos of 'learning by doing' in the next decade is needed to accelerate the hydrogen economy race for technology leadership.

[20] Geopolitics of the Energy Transformation: The Hydrogen Factor (irena.org)

5.2 Renewable energy to hydrogen costs

How to calculate the levelised cost of hydrogen (LCOH) and key summaries to renewable energy hydrogen cost projections from various industrial and research groups, will be discussed in this section.

5.2.1 Calculating levelised cost of hydrogen

In general, levelised costs are the discounted lifetime cost of building and operating an asset, expressed as a cost per unit output (forming a popular financial metric called the levelised cost of hydrogen). [21] The LCOH can be calculated by using the following equation, where n is the time period.

$$Levelised\ Cost\ of\ Hydrogen = \frac{\sum_n \frac{(total\ costs)_n}{(1 + discount\ rate)^n}}{\sum_n \frac{(net\ hydrogen\ generation)_n}{(1 + discount\ rate)^n}}$$

In terms of the LCOH formulae here is the accompanied explanation. Measurement of hydrogen used in the denominator is usually expressed in kilograms, i.e., giving costs in £/kg. Another solution is possible to measure hydrogen used according to the energy content of hydrogen, i.e., £/MWh. Regarding the energy content measurement, there are two options, firstly using the higher heating value (HHV), which is ≈ 39.4 kWh/kg (resulting costs in £/MWh-HHV). [21] Secondly, using the lower heating value (LHV), which is ≈ 33.3 kWh/kg (resulting costs in £/MWh-LHV). [21] Be cautious as various research will not specify whether the higher or lower heating value has been used in the analysis. Therefore, while this generates some difficulty for the reader, the fact is that the two values are relatively close (having a difference of 6.1 kWh/kg) means that it is still possible to have a reasonable idea of what the research has identified. Further to the conversions, some common examples to related costings can be found in Table 5.1, for the three sets of units discussed.

Further explanation is recommended using the following conversions:

- To convert costs from £/kg to £/MWh-HHV, divide by 0.0394 MWh-HHV/kg (equivalent to multiplying by ≈ 25.4).
    - To convert from £/MWh-HHV to £/kg, multiply by 0.0394 or divide by ≈ 25.4
- To convert costs from £/kg to £/MWh-LHV, divide by 0.0333 MWh-LHV/kg (equivalent to multiplying by ≈ 30).
    - To convert from £/MWh-LHV to £/kg, multiply by 0.0333 or divide by ≈ 30

This Table 5.1 is important as it provides a clear comparison of hydrogen production costs across different units, helping to understand the financial implications of each conversion method. By converting costs between £/kg, £/MWh-HHV, and £/MWh-LHV, it allows for easier analysis and comparison of efficiency and cost-effectiveness in various hydrogen production scenarios.

[21] BEIS Electricity Generation Costs (2020) - GOV.UK (www.gov.uk)

Table 5.1 Converting costs between £/kg, £/MWh-HHV, and £/MWh-LHV.

£/kg	£/MWh-HHV to £/MWh-LHV	£/kg	£/MWh-HHV to £/MWh-LHV
1	25 - 30	6	152 - 180
2	51 - 60	7	178 - 210
3	76 - 90	8	203 - 240
4	102 - 120	9	229 - 270
5	127 - 150	10	254 - 300

5.2.2 Levelised cost of hydrogen projections

This section explores a range of options, such as deployment of the electrolyser onshore or offshore, centralised and decentralised electrolysers. One study was the Offshore Renewable Energy Catapult's 2020 'Solving the Integration Challenge' report. [22] This report estimated the cost of offshore wind powered electrolysis in several scenarios, including the type of wind turbine foundation, the type of electrolysis technology, and whether the electrolyser was onshore or offshore. In general, costs were high in 2020, between about £5.00 – 9.00/kg depending on the combination of technologies. However, the report expected costs to drop rapidly, with a 2025 range of £2.70 – 4.40/kg. By 2050, the range was between about £1.60 – 1.95/kg, signifying a convergence of technology costs. These results of this report are affirmed in an updated ORE Catapult analysis which compared the cost of blue and green hydrogen in Section 5.3.

5.2.3 Additional wind industry research conducted

ERM (Sustainability Consultancy, in 2019):

ERM used offshore wind powered electrolysis as a function of distance from shore, between 30 to 400 km, cost estimates focused on wind turbine foundation, offshore centralised, decentralised, and onshore hydrogen production. [23] Using the lowest cost option a floating semi-sub foundation with integrated turbine – electrolyser system in their analysis (found onshore electrolysis from offshore wind the most expensive option).

offshore electrolysis (distance from shore)	£2.00/kg at 100 km	£2.20/kg at 300 km
onshore electrolysis (distance from shore)	£2.80/kg at 100 km	£3.60/kg at 300 km

Xodus (Offshore wind to green hydrogen: opportunity assessment, in 2020): [24]

[22] Offshore Wind and Hydrogen: Solving the Integration Challenge – ORE (catapult.org.uk)

[23] Dolphyn Hydrogen - phase 1 final report (publishing.service.gov.uk)

[24] Offshore wind to green hydrogen: opportunity assessment - gov.scot (www.gov.scot)

Used three scenarios to estimate costs, and in the long term Xodus see projected costs falling to £2/kg over the system.

2025	single offshore integrated turbine-electrolyser pilot project	£6.20/kg
2028	commercial scale (500 MW) offshore wind farm coupled with onshore electrolysis	£2.90/kg
2032	commercial scale (1 GW) offshore wind farm coupled with offshore electrolysis	£2.30/kg

Roland Burger's (Innovate and industrialise: Offshore Wind Energy report, in 2021): [25]

Examined costs from two perspectives. In the second perspective Roland Burger's found that, for 1 GW capacities, the onshore option was favourable. In contrast, for capacities of 2 GW and more, the offshore option was preferable. One of the drivers for the difference was a relatively stable/static pipeline cost with increasing capacity, compared to substantially increasing export cable and converter costs.

2025	green hydrogen around the world when produced from offshore wind energy in Europe (specifically a 250 MW electrolyser)	£3.30 – 3.50/kg (EUR 3.9 – 4.2/kg
2025	difference between a centralised offshore electrolyser and an onshore electrolyser, as a function of electrolyser capacity (1 to 10 GW)	

Bloomberg (New Energy Finance outlined their perspective on offshore wind to hydrogen in a short blog, in 2021): [26]

Estimated costs could be around as follows. These costs are relatively pessimistic in the short-term analysis, coupled with the most optimistic long-term analysis. Bloomberg also mentioned that onshore electrolysers were cheaper until 2030, when offshore electrolysers become favourable.

2025	perspective on offshore wind to hydrogen	£5.80/kg ($7/kg)
2030	perspective on offshore wind to hydrogen	£3.80/kg ($4.6/kg)
2050	perspective on offshore wind to hydrogen	£0.80/kg ($1/kg)

[25] Innovate and industrialize: Offshore wind energy | Roland Berger

[26] Offshore Wind-to-Hydrogen Sounds A Starting Gun | BloombergNEF (bnef.com)

BEIS (DESNZ - explored hydrogen production costs in a range of scenarios in a report, in 2021):

One scenario was electrolysis powered by offshore wind for estimated costs.

2025	electrolysis powered by offshore wind	£4.45/kg (£113/MWh-HHV)
between 2040 & 2050	electrolysis powered by offshore wind (costs falling rapidly over the next 15 years, before plateauing)	£2.87/kg (£73/MWh-HHV)

HYGRO Technology (the National Renewable Energy Laboratory Journal, Plug Power and Giner Incorporated - Techno-economic analysis of offshore wind PEM water electrolysis for H2 production): [27]

Hydro technology looked at a scenario where electrolysis costs have fallen to $100 – 300/kW related to the following scenarios. The factors that reduced costs included lower cost energy export and less electrical losses. There was uncertainty over the change in maintenance burden, with numerous electrical components (normally used to ensure grid compliance) removed from the envisaged system and replaced with hydrogen equipment.

cost of production from decentralised, integrated wind turbine – electrolyser systems	£1.70/kg ($2.09/kg)
hydrogen produced from offshore wind in an onshore electrolyser	£3.20/kg ($3.86/kg)

5.3 Hydrogen costs summarised by reflection on green versus blue hydrogen economy comparison

To summarise this section, and reflection of the selection of a wide range of organisations there is a broad consensus that the possible costs of producing hydrogen from offshore wind are currently high. However, according to ORE Catapult currently hydrogen production costs are expected to fall substantially, to the range of ≈ £1.50 - 3/kg by 2050 (for green electrolysis hydrogen). Therefore, to grow the hydrogen hub development there is a debate about an offshore deployment of electrolysers versus onshore electrolyser deployment in some scenarios. The debate continues about the merits of green versus blue hydrogen economy in terms of their individual environmental impact and project economics. A blue hydrogen economy will look attractive to lower natural gas prices, but gas security and higher gas prices on the other hand, the environmental merits are extremely unclear. Related to the uncertainty of energy security and methane leaks occurring during blue hydrogen production, combined with the fluctuation to the exact percentage of CCUS during the production processes as a negative factor.

Natural gas prices are subject to vast uncertainties and increasing for the foreseeable future to record high levels, the economic argument blue hydrogen no longer carries the same weight. With an

[27] Techno-economic analysis of offshore wind PEM water electrolysis for H2 production - ScienceDirect

anticipated UK gas current near-term forecast of 77.51 GBP/therm (Feb 2024) [28], blue hydrogen is likely to cost around £145/MWh-HHV (£5.70/kg) in the short to medium term. At this cost, the economic difference between blue and green hydrogen almost disappears (indicative to changes constantly due to fluctuating natural gas prices). As shown in Figure 5.1, forecasting the cost of producing green electrolysis hydrogen from floating offshore wind will be around £146/MWh-HHV (£5.75/kg) for early commercial projects, over a period from 2025-2027. Thereafter, the cost falls to £76/MWh-HHV (£2.99/kg) by 2030, reducing below £50/MWh-HHV (£1.97/kg) by 2040 indicative. Anticipation to this cost reduction will more than likely be driven by the major cost reductions in offshore wind as well as swift cost reductions in the cost of electrolysis in the supply chain. These are both driven by a combination of technology innovation and large-scale deployment based on the allocation rounds. From this perspective, green electrolysis hydrogen production looks increasingly attractive from economic and environmental perspectives, when compared to blue hydrogen.

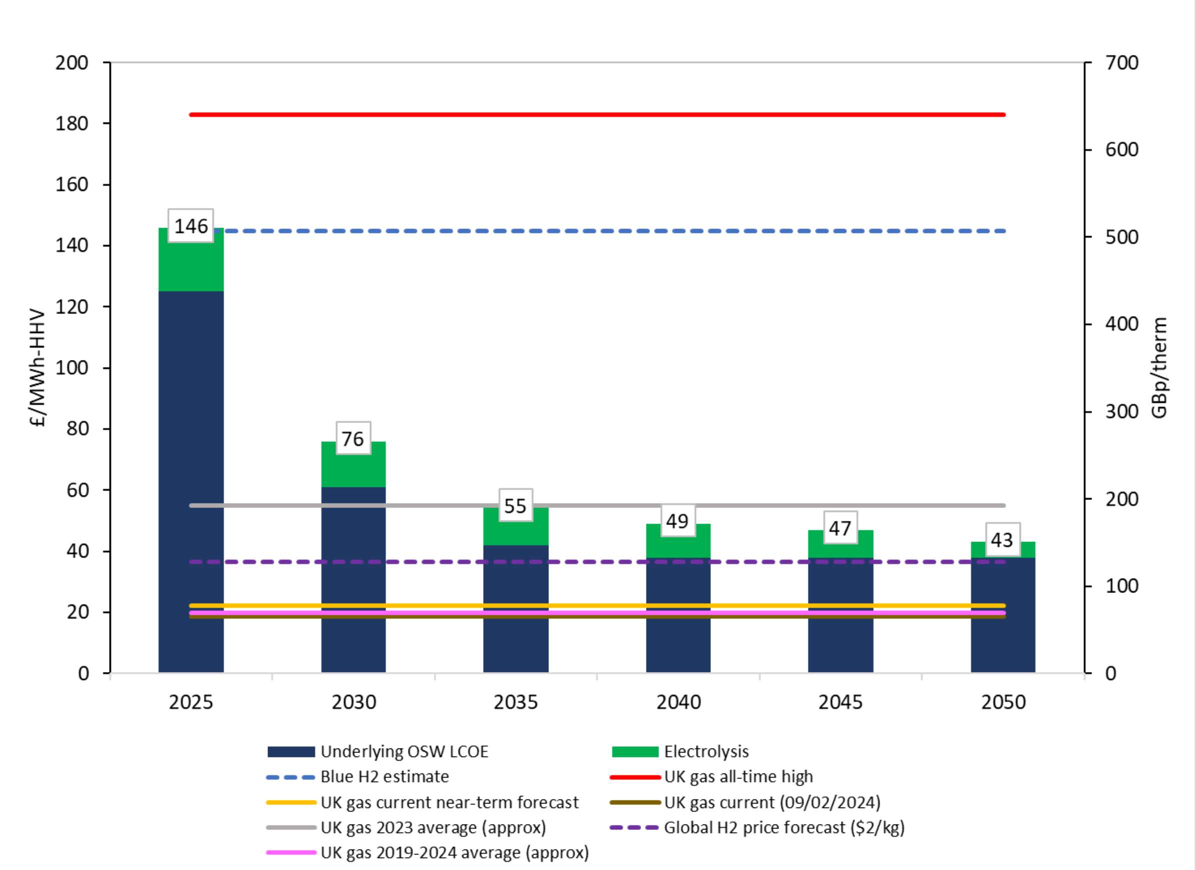

Figure 5.1 Floating offshore wind green and blue hydrogen production UK forecast versus various UK natural gas price benchmarks (ORE Catapult Analysis, 2022 updated).

6 THE NEED FOR HYDROGEN HUBS

Based on the previous definition to a 'Hydrogen Hub', the overarching goal is to create a local and/or regional ecosystem that promotes the use of hydrogen as a clean and sustainable energy carrier. In

[28] Gas prices per therm Great Britain 2023 | Statista

previous sections, the need for switching to green electrolysis hydrogen production enables the hydrogen hub to be a sustainable energy carrier for the future. This centralised infrastructure will integrate several components of the hydrogen value chain, including hydrogen production, storage, distribution, and utilisation. The UK Hydrogen Strategy Delivery sets out the approach to developing a successful low carbon hydrogen sector in the UK. [29] This strategy sets out the increased ambition for 10 GW of low carbon hydrogen production capacity by 2030. As part of the government's whole-system approach to developing a UK hydrogen economy. The strategy considers each part of the hydrogen value chain [29] in more detail to realise their 2030 ambition, and position achieving hydrogen targets (Figure 6.1).

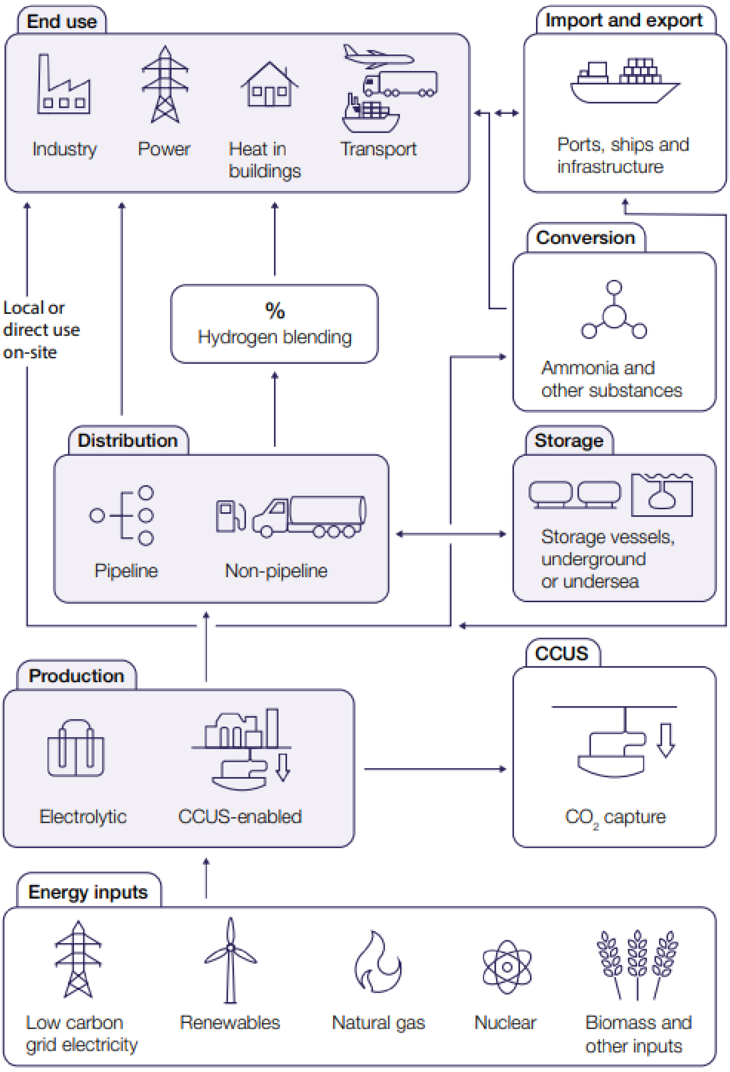

Figure 6.1 The UK hydrogen strategy as part of the hydrogen value chain. [29]

6.1 Industrial size 'Hydrogen Hubs'

The current plans as per the Hydrogen Strategy Delivery Update (December 2023) [29] for the development of hydrogen hubs in the UK, with specifics evolving as an outline in this section, can be seen in

[29] UK hydrogen strategy - GOV.UK (www.gov.uk)

Figure 6.2. The key areas are CCUS in phase 2 negotiations, successful projects from the first electrolytic hydrogen allocation round (HAR1), and the £240 million Net Zero Hydrogen Fund (NZHF), including some of the key areas where hydrogen hubs were being considered or planned, included. This chapter will concentrate on the research questions posed in the beginning of this report as the main purpose of this study. Using the following sections to answer the questions, using the most up-to-date research and government strategy guidelines for consistency and hydrogen economy alignment.

Q1. Where are there existing 'Hydrogen Hubs' in the UK?

It is important to define fundamental terminology used in the hydrogen economy and how this could shape the future hydrogen hub economy in the UK. Outlined in

Figure 6.2, is a full representation in the form of a map and allocated projects, including a summarised description given under each of the following headings as to how they can play a vital role to form strategic hydrogen hubs across the UK.

6.1.1 Electrolytic Hydrogen Allocation Round 1 - (locations 1 to 11) [29] [30]

The term HAR1 refers to an allocation of funding initiative to support electrolytic hydrogen production projects, i.e., using electricity to split water molecules into hydrogen and oxygen. As mentioned previously, this process can be powered by renewable energy sources such as wind or solar power, resulting in "green hydrogen" production with minimal carbon emissions. The hydrogen allocation round is a structured process for distributing funding, grants, or other forms of support to eligible projects to support the hydrogen economy. Interested parties, during HAR1, such as research institutions, companies or government agencies may submit proposals or applications for funding to develop electrolytic hydrogen projects. These projects could include building electrolysers, establishing hydrogen production facilities, developing hydrogen storage and distribution infrastructure, or conducting research and development activities related to electrolytic hydrogen technologies. The HAR1 goal is to accelerate the deployment and commercialisation of electrolytic hydrogen technologies, expedite innovation, and contribute to a low-carbon energy system transition by promoting the use of hydrogen as a clean and sustainable energy carrier.

List of allocated projects under HAR1,

1. Cromarty (town in the Highlands of Scotland) highlighting the geographical context for renewable energy development. Scottish Power represented as a major energy company investing in renewables, and Storegga focusing on CCS solutions to address carbon emissions have been awarded government funding. The project is designed to deliver up to 20 tonnes of green hydrogen per day from 2024, with the potential to scale up to 300 MW in a series of modular expansion phases. [31]

2. Hygen and N-Gen are working together to deliver a state-of-the-art low carbon hydrogen production facility, located in east Bradford (near Leeds). The development will be built on the Northern Gas Network (NGN), namely the Birkshall gas storage site in Bradford working across the upstream and midstream sectors, aiming to produce 75 MW of green hydrogen by

[30] Net Zero Hydrogen Fund strands 1 and 2: summaries of successful applicants round 1 (April 2022) competition - GOV.UK (www.gov.uk)

[31] ScottishPower and Storegga form green hydrogen partnership to 'transform industry in the Highlands' - ScottishPower

2025. The project will deliver one of the UK's largest low carbon hydrogen production facilities with the aim of using renewable energy to produce hydrogen. [32]

3. Tees Green Hydrogen will be a pioneering project. This project will be using green electricity from the nearby Teesside Offshore Wind Farm including a new solar farm, that Electricity of France (EDF) Renewables UK intends to construct near Redcar, to regenerate Tees Valley (Middleborough). The Tees Valley area was identified as a potential location for a hydrogen hub, with projects like the Tees Valley Hydrogen Transport Hub. Adding future phases will seek to deliver up to 300 MW in Teesside before 2030. [33]

4. Carlton Power is an experienced independent developer of low carbon and renewable energy projects in the UK. Langage Green Hydrogen is one of the first of a number of Green Hydrogen schemes in development by Carlton Power in the UK. The project as part of a wider Langage Energy Park/Hub, the development will have an initial capacity of 10 MW. The project is well placed in Plymouth to serve commercial applications in other areas of Plymouth and Devon. [34]

5. The Barrow Green Hydrogen project, run by energy company Carlton Power (involved in power generation across different energy sources, including renewable energy) given government funding. Would supply green hydrogen to the neighbouring Kimberley-Clark manufacturing plant in the Cumbrian town. The development will have an initial capacity of 35 MW, located at Barrow-in-Furness ideally placed because the area has several industrial sites. [35]

6. Trafford Green Hydrogen is the first of a number of Green Hydrogen schemes in development by Carlton Power in the UK. The project has been successful in gaining funding support as part of the DESNZ Hydrogen Business Model and Net Zero Hydrogen Fund. The development will have an ultimate capacity of 200 MW. Planning permission was granted by Trafford Metropolitan Borough Council Greater Manchester that will provide cleaner energy to power industrial facilities in the region. [36]

7. West Wales Hydrogen, H_2 Energy Europe, a developer of large-scale green hydrogen eco-systems, has been awarded government funding for its 20 MW electrolytic hydrogen production facility at the port of Milford Haven, South Wales. The green hydrogen produced at Milford Haven through this West Wales Hydrogen project will fuel a variety of applications across South Wales including shipping and industrial power. Using the site formerly occupied by the decommissioned Milford Haven oil refinery with Trafigura. Trafigura is involved in the trading and logistics of various commodities, including oil, gas, metals, minerals, agricultural products, and more recently the renewable energy sector announced that they would invest in H_2 Energy forming a joint venture. [37]

8. HyMarnham Power, JG Pears and GeoPura is a joint venture in the East Midlands between hydrogen pioneer GeoPura and sustainable waste processing leader JG Pears. The East

[32] Welcome to Hygen & N-Gen Bradford Hydrogen - Hygen (hygenenergy.com)

[33] Tees Green Hydrogen - EDF Renewables (edf-re.uk)

[34] The Project | Langage Green Hydrogen

[35] The Project | Barrow Green Hydrogen

[36] The Project — Trafford Green Hydrogen

[37] H2 Energy Europe plans to develop the first large-scale green hydrogen production facility in South Wales (trafigura.com)

Midlands Hydrogen project aims to develop the production, storage, and transportation of low carbon hydrogen powered by 43 MW of new solar energy and 8 MW of electrolysers. The site is situated at the site of the former High Marnham coal-fired power station. [38]

9. Whitelee Green Hydrogen, Scottish Power project a solar farm and green hydrogen production facility located about 5 km west of Lochgoin Reservoir southwest of Glasgow. To the north of the site the solar farm proposed will provide 20 MW of renewable solar generation to power the green hydrogen production facility through electrolysis. Scottish Power anticipate that this hydrogen will be used to fuel public transport and heavy freight vehicles, incorporating the co-location of the 50 MW battery energy storage scheme to maximise the systems efficiency. [39]

10. Green Hydrogen 3, HYRO, namely RES and Octopus Energy Generation's green hydrogen joint venture HYRO is working with Kimberly-Clark to swap gas for green hydrogen at UK factories (Wales and Kent two projects awarded Government's shortlist for funding). The two green hydrogen electrolyser projects will have a combined capacity of 22.5 MW. [40] [41]

11. HyBont, Marubeni Europower who is a subsidiary of the Marubeni Corporation as part of the HyBont Bridgend green hydrogen project, south Wales. The developing plans for this project are a green hydrogen production and refuelling facility at Brynmenyn Industrial Estate, partially powered by a solar farm at Bryncethin. Consisting of electrolyser modules up to 6 MW, five tonnes of hydrogen storage tanks, compression, refuelling station, and substations within the project. [42] [43]

6.1.2 £240 million Net Zero Hydrogen Fund - (locations 12 to 24) [29] [30]

The £240 million Net Zero Hydrogen Fund (NZHF) is a significant financial commitment aimed at supporting the development and deployment of hydrogen-related projects and net-zero carbon emissions target by 2050, in the United Kingdom. The key efforts of the UK government are to accelerate the transition to a low-carbon hydrogen economy. The primary purpose of the NZHF is to support projects that contribute to the advancement of hydrogen technologies and infrastructure; projects that focus on hydrogen production, distribution, storage, and use across sectors, like transportation, heavy industry, and power generation for the grid. These funds aim to stimulate hydrogen innovation, cost reduction, and to scale up the deployment of hydrogen technologies. All to accelerate the hydrogen economy transition for the UK.

List of allocated projects under NZHF,

12. Trecwn Green Energy Hub, Statkraft are developing proposals for a green energy hub on the former Royal Navy Armaments Depot in Trecwn, Pembrokeshire. The emerging proposals are for the 15 MW hydrogen electrolyser plant. The plant will be powered by renewable energy

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[38] HyMarnham | East Midlands Hydrogen

[39] Whitelee Solar / Hydrogen / BESS - ScottishPower Renewables

[40] HYRO – Green hydrogen for large energy users

[41] Octopus Energy and RES to swap gas for green hydrogen at Andrex & Kleenex factories in the UK | Octopus Energy

[42] HyBont Bridgend – Green Hydrogen Project

[43] Project – HyBont Bridgend

with up to four tonnes of hydrogen storage and facilities to refuel hydrogen buses and heavy goods vehicles. Support the Welsh Government's Net Zero Strategy. [44]

13. Ballymena Hydrogen, Northern Ireland has won funding from the Government's Net Zero Hydrogen Fund for an innovative multi-million-pound green hydrogen production facility at the Ballymena headquarters. The headquarters of globally renowned sustainable bus manufacturer Wrightbus in partnership with Hygen Energy, and Ryze Hydrogen responsible for distributing hydrogen to the region. The project will use the connection from local wind assets using a 5 MW electrolyser. [45] [46]

14. Conrad Energy Hydrogen Lowestoft, Conrad Energy through Hydrogen East has established an overview of how a smart local energy system can be established on land between the Port of Lowestoft and Ness Point into an energy hub. The hydrogen based component is for a 3 MW project comprising of up to three hydrogen electrolysers and associated storage as part of the Lowestoft Power Park. [47]

15. Didcot Green Hydrogen Electrolyser, RWE is pleased to have been awarded UK Government funding for initial investigative for an electrolyser plant to produce green hydrogen at RWE's Didcot site, Oxfordshire. Initially, to investigate Front End Engineering Design (FEED) studies for exact location, plant layout and potential infrastructure needed. RWE is targeting 2 GW of green electrolysers by 2030 across all projects. The core objective of the work is under the FEED study. [48]

16. Green Hydrogen St Helens, Progressive Energy project an Industrial Fuel Switching to Hydrogen initiative. Supplied hydrogen from HyNet Industrial Fuel Switching to undertake a design and practical demonstration programme. Trials have been run at major Northwest-based companies, namely Unilever's Port Sunlight facility and Pilkington Glass's furnace located at St Helens. The core objective of the work is to produce a FEED study. [49]

17. Green Hydrogen Winnington and Middlewich, Progressive Energy a joint venture company formed by the consortium partners Progressive Energy, lead developer and HyNet founding partner; Statkraft (Europe's largest generator of renewable energy); and Foresight Group. The green hydrogen initiative intends to deploy green hydrogen production at TATA Chemical Europe's located in Winnington and Middlewich sites in Cheshire. The core objective of the work is to produce a FEED study. [50]

18. Inverness Green Hydrogen Hub, Getech completed the first step in developing the Inverness green hydrogen hub. Getech is paving the way to convert a legacy natural gas holder site into a future green hydrogen electrolysis storage and distribution facility to decarbonise rail across the Scottish Highlands. The hydrogen facility would scale from 6 MW of alkaline electrolyser capacity to 24 MW over time. There ambitions are to establish green hydrogen and thermal energy assets of 500 MW by 2030. [51]

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[44] Trecwn Green Energy Hub (statkraft.co.uk)

[45] Funding Award For Ballymena Hydrogen Production Facility - Ryze Hydrogen

[46] Hygen Ballymena Green Hydrogen Facility - Hygen (hygenenergy.com)

[47] Hydrogen – Conrad Energy

[48] RWE hydrogen activities in UK

[49] What We Do | Our Projects | Progressive Energy Ltd (progressive-energy.com)

[50] Net Zero Hydrogen Fund strands 1 and 2: summaries of successful applicants round 1 (April 2022) competition - GOV.UK (www.gov.uk)

[51] Milestone Achieved at Green Hydrogen Hub in Inverness | Getech | Unlocking the Earth's Energy Potential

19. Mannok Green Hydrogen Valley, Mannok located in Fermanagh is one of two companies in Northern Ireland to secure funding in the scheme as diverse building products manufacturers. The aim is to generate green hydrogen on onsite from Mannok plans to use local wind assets and a 5 MW electrolyser. [52]

20. Knockshinnoch Green Hydrogen Hub Project, Renantis, the green hydrogen hub situated in East Ayrshire, will be one of the first fully off-grid renewable hydrogen supply systems on the UK mainland. The aim of the project will see wind turbines and battery technology installed directly connected to an electrolyser to produce fuel-cell grade hydrogen and compressed hydrogen storage options as part of the initiative. The project will also contain a battery, connected directly to a 2.5 MW electrolyser for the transport sector. Leading the project is the global renewable energy developer and operator Renantis, alongside project partners Logan Energy. [53]

21. Hynet HPP2, Vertex Hydrogen is designing, developing and building a low carbon hydrogen production plant one of the first in the UK in a joint venture with Essar Oil UK and Progressive Energy. Part of the HyNet cluster, the hydrogen will be produced at the Stanlow complex located in Ellesmere Port, Cheshire. Vertex Hydrogen the leading player in the energy transition. Developing the first large scale, low carbon hydrogen production hub in the UK to produce 1 GW of hydrogen capacity (in its initial phases). [54]

22. Kintore Hydrogen, Statera, Kintore Hydrogen located in Aberdeenshire is developing 3 GW (first phase 500 MW) of hydrogen electrolysis built in phases, to produce green hydrogen from surplus Scottish wind power. [55]

23. H_2NorthEast, Kellas is a major project to build a 1 GW CCUS-enabled low carbon blue hydrogen production facility next to their Central Area Transmission System Terminal (CATS-natural gas pipeline terminal from the Central North Sea) on Teesside. During the initial phase the project will deliver 355 MW of hydrogen to local industry, and therefore upscaling to greater than a 1 GW by 2030 in further phases. Comprising the Humber and Teesside industrial regions. This project is part of the East Coast Cluster, one of the UK's first CCUS clusters. [56]

24. Felixstowe Port Green Hydrogen, Scottish Power explores green hydrogen at the Port of Felixstowe one of UK's busiest ports to help decarbonise the heavy transport sector. The aim is to produce/deliver up to 40 tonnes of green hydrogen per day, from a 100 MW facility. Plans are being developed to use green hydrogen for onshore purposes, with the potential to create liquid forms, such as green ammonia or e-methanol for road, rail and industrial use. [57]

6.1.3 Carbon Capture Utilisation and Storage Phase 2 negotiations - (locations 25 to 26) [29] [30]

The term *CCUS in phase 2 negotiations* refers to a set of technologies and processes designed to capture carbon dioxide emissions from industrial processes or power generation facilities. Make use

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[52] Mannok Set to Generate Renewable Energy with Recent Government Green Hydrogen Fund - Mannok (mannokbuild.com)

[53] Innovative Scottish hydrogen project secures UK Government funding offer - Renantis

[54] Vertex Hydrogen - Building a low carbon future

[55] Kintore Hydrogen | Kintore Hydrogen

[56] Blue Hydrogen | H2NorthEast | Kellas Midstream

[57] ScottishPower vision for green hydrogen fuels hub at port of Felixstowe - ScottishPower

of the captured CO_2 in various applications and then store it underground to prevent its release into the atmosphere. The second phase of negotiations relate to the implementation of CCUS projects; that would involve detailed planning, assessment, and agreement on various aspects of the project. For example, funding, technology selection, site selection, regulatory approvals, and stakeholder engagement. CCUS phase 2 negotiations are crucial for moving CCUS projects from the conceptual stage to actual implementation, through negotiations that focus on resolving key issues and finalizing agreements to advance the projects towards construction and operation.

List of allocated projects under CCUS Phase2,

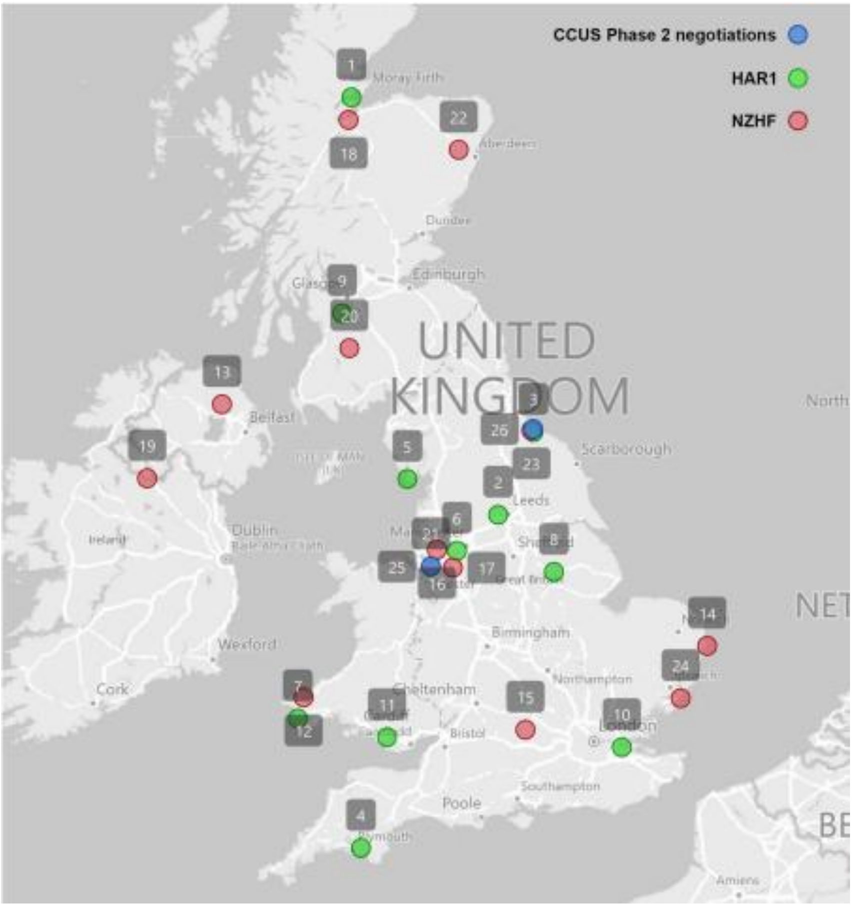
25. Hynet HPP1, Essar Energy Transition (EET) Hydrogen located at the Stanlow site in Ellesmere Port, Cheshire, approved by the Cheshire West & Chester Council. The Council approved groundbreaking plans by EET Hydrogen, [58] for the first large scale blue hydrogen production plant (HPP1) in the UK. Consisting of two plants HPP1 and HPP2, EET will develop the hydrogen hub in phases; HPP1 the first plant at 350 MW capacity, HPP2 the second plant at 1 GW capacity with future plans as an overall target capacity of 4 GWs by 2030. [59]

26. bpH_2Teeside, bp in Teeside as part of their blue hydrogen project select BASF's carbon capture technology (bp and BASF, one of the world's leading chemical companies). bpH_2Teeside targeting 1.2 GW of hydrogen production by 2030, and aims to be one of the UK's largest blue hydrogen production facilities by 2030. [60]

[58] EET Hydrogen | EET Fuels

[59] Plans for UK's largest hydrogen production hub given green light - Essar

[60] bp selects BASF's carbon capture technology for blue hydrogen project in Teesside | News | Home



Hydrogen Allocation Round 1 (**HAR1**)		Net Zero Hydrogen Fund (**NZHF**)	
1	**Cromarty**, Scottish Power and Storegga	12	**Trecwn Green Energy Hub**, Statkraft
2	**Bradford Hydrogen**, Hygen	13	**Ballymena Hydrogen**, Hygen Energy & Ryze Hydrogen
3	**Tees Green**, EDF	14	**Conrad Energy Hydrogen Lowestoft**, Conrad Energy
4	**Langage Green Hydrogen**, Carlton Power	15	**Didcot Green Hydrogen Electrolyser**, RWE
5	**Barrow Green Hydrogen**, Carlton Power	16	**Green Hydrogen St Helens**, Progressive Energy
6	**Trafford Green Hydrogen**, Carlton Power	17	**Green Hydrogen Winnington and Middlewich**, Progressive Energy
7	**West Wales Hydrogen**, H_2 Energy and Trafigura	18	**Inverness Green Hydrogen Hub**, Getech
8	**HyMarnham**, JG Pears and GeoPura	19	**Mannok Green Hydrogen Valley**, Mannok
9	**Whitelee Green Hydrogen**, Scottish Power	20	**Knockshinnoch Green Hydrogen Hub Project**, Renantis
10	**Green Hydrogen 3**, HYRO	21	**Hynet HPP2**, Vertex
11	**HyBont**, Marubeni Europower	22	**Kintore Hydrogen**, Statera
		23	**H_2 NorthEast**, Kellas
		24	**Felixstowe Port Green Hydrogen**, Scottish Power
		Carbon Capture & Utilisation (**CCUS**) Phase 2 Negotiations	
		25	**Hynet HPP1**, Essar Energy Transition Hydrogen
		26	**bpH_2Teeside**, bp

Figure 6.2 Map representation and table of the UK Hydrogen Strategy Delivery plan project updates (December 2023) for CCUS in phase 2 negotiations, successful projects from the first electrolytic hydrogen allocation round (HAR1), and the £240 million Net Zero Hydrogen Fund (NZHF); with first stage/phase indicative capacities that are subject to change over the timelines. [29]

6.1.4 Net Zero Hydrogen Fund strands 1 and 2: (April 2023) Competition Outcomes

The Government has just released the summaries of the successful applicants for round 2 for the NZHF strand 1 and 2 (February 2024). [61]

Strand 1:

1. The Pembroke Phase II project is a 200 MW electrolytic hydrogen production facility located in Pembrokeshire, Wales (RWEs Pembroke Power Station site) and South Wales Industrial Cluster. The project will supply local off takers with low carbon hydrogen and expected to be operational in the late 2020s. Delivered by RWE Generation which is part of RWE has a diverse operational portfolio of ≈ 10 GW. As discussed previously, RWE is developing multiple electrolytic hydrogen projects across the UK aiming to develop up to 2 GW of green hydrogen projects by 2030. In Pembroke Phase I, RWE are developing another project with a 110 MW electrolyser facility also located in Pembroke (anticipated for deployment by 2027). Therefore, RWEs combined Pembroke portfolio across these two projects will have a hydrogen generation capacity of 310 MW. [61]

2. FEED studies included in this strand are 'Grenian Hydrogen Speke' project, Speke in Liverpool City Region.

3. Sullom Voe Terminal Hydrogen Project, located in the Shetland's. Veri Energy intends to establish the Sullom Voe Terminal (SVT) Energy Hub project for advanced electrolysis technology production. The project will have an initial capacity of 50 MW, with potential expansion to 300 MW in subsequent phases. [61]

4. Tees Green Methanol, EDF Renewables and Hynamics, located at Teesport. This is the 3rd phase of the Tees green hydrogen programme with a capacity of 200 MW electrolyser a proposed e-methanol plant at Teesport. [61]

Strand 2:

1. Aberdeen Hydrogen Hub Phase 1, bp Aberdeen Hydrogen Energy Limited (bpAHEL). Joint venture between Aberdeen City Council and bp, the partnership intends to create the Aberdeen Hydrogen Hub to enhance the hydrogen economy in the Aberdeen city and Northeast of Scotland. [61]

2. Tees Valley Hydrogen Vehicle Ecosystem (HYVE), Exolum. At their Riverside storage terminal in the Tees Valley, Exolum will install a 5 MW electrolyser for green hydrogen within the transport sector. Including a hydrogen refuelling station and tube trailer loading facility at the terminal. This facility will supply hydrogen to its customers on site. [61]

3. Suffolk Hydrogen, Ryze, Hynamics & Hygen Energy. Located in Ipswich, the Suffolk Hydrogen Hub project will build a network of hydrogen production and refuelling stations. Starting with

[61] Net Zero Hydrogen Fund strands 1 and 2: summaries of successful applicants round 2 (April 2023) competition - GOV.UK (www.gov.uk)

a 10 MW production facility in Ipswich. The project is led by a consortium of partners: The Bamford Bus Company (Wrightbus), Ryze Hydrogen, Hynamics and Hygen Energy Holdings. [61]

In Figure 6.3, the UK Hydrogen Strategy Delivery plan project updates are represented in a horizontal bar plot. The updates are from both December 2023 and February 2024 showing the initial capacity under these three specified headings, namely hydrogen allocation round 1; net zero hydrogen fund; carbon capture & utilisation - phase 2 negotiations.

Each bar represents the initial capacity in megawatts (MW) of a specific project (1 through to 26, December 2023) and from (1 to 4: strand-1 and 1 to 3: strand-2, February 2024).

The project names are displayed on the y-axis, and the initial capacities are displayed on the x-axis, and the coloured scale bar verifies the level of MWs to each allocated project across the updates.

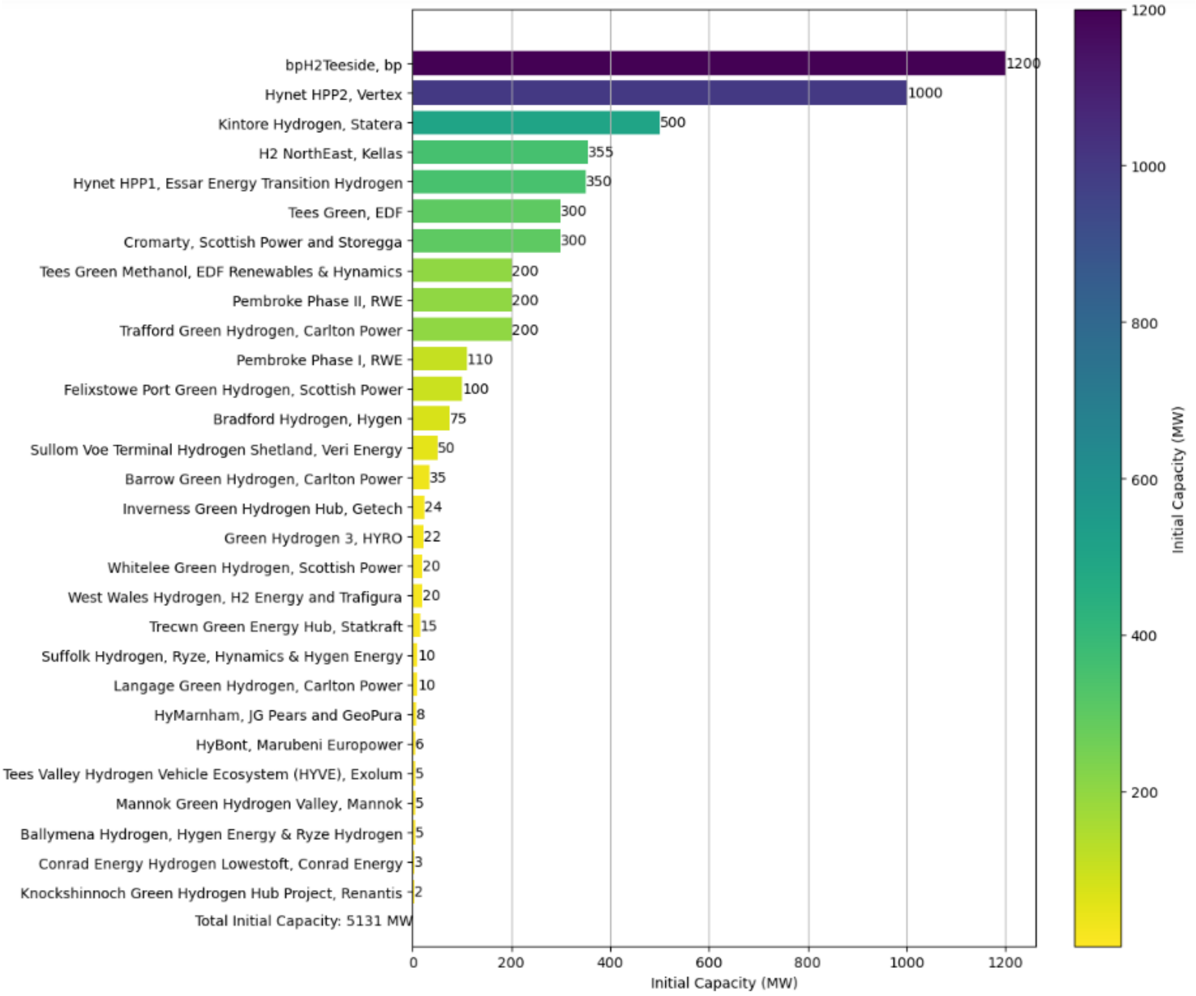


Figure 6.3 Initial hydrogen capacity (MW) in a representation of the UK Hydrogen Strategy Delivery plan project updates (December 2023 & February 2024) for CCUS in phase 2 negotiations, successful projects from the first electrolytic hydrogen allocation round (HAR1), and the £240 million Net Zero Hydrogen Fund (NZHF); with first stage/phase; all indicative capacities that are subject to change over time.

Q2. Where are the confirmed ‘Hydrogen Hubs’ being developed imminently in the UK (is timeline known)?

The UK Hydrogen Strategy sets out the Government’s vision for the role that hydrogen will play to reach their ambitions. The ambitions/targets illustrate the size of the hydrogen challenge to meet the Governments goal. Hydrogen production (from renewable energy) today is extremely low across the country; however, the estimates are that 240 to 500 TWh could be required by 2050 in the UK. [29] As discussed in the previous section large scale initiatives are being developed forming nationwide hydrogen hubs in the UK at various timelines for their completion and production capacities heading towards the mid 2035s. Set out in the British Energy Security Strategy in April 2022, the ambition remains to have up to 10 GW of capacity of hydrogen production by 2030. [62] The Government has also expanded policy mechanisms to bring forward annual allocation rounds that focus on electrolytic hydrogen production including hydrogen transport and storage business models, by 2025.

The Hydrogen Strategy Delivery plan was updated in 2023/2024, along with industry to develop a roadmap to shared vision, through a timeline of expected growth of the hydrogen economy here in

[62] British energy security strategy - GOV.UK (www.gov.uk)

the UK to the mid-2030s (Figure 6.4). The key points and industry challenges from the updated UK hydrogen production delivery roadmap are discussed as follows, [29]

- Through the first electrolytic HAR1 the capacity of 125 MW was announced.
- Two CCUS-enabled hydrogen projects in negotiations through Track-1 of the cluster sequencing process.
- Under the £240 million Net Zero Hydrogen Fund announcements have been made to the first successful applicants.
- From the early funding rounds, and engagement with project developers, whereby sustainable progress must be achieved whilst aiming to provide certainty for investors.

Under the Hydrogen Strategy Update to the Market, found in Figure 6.4 the intention is:

- to allocate up to 4 GW of their 2030 ambition to CCUS-enabled hydrogen through CCUS allocation rounds for Track-1,
- to add an additional, Track-1 expansion and Track-2, subject to cluster and project assessment, and successful negotiations with projects,
- to allocate up to 6 GW of the 2030 ambition to electrolytic production, and contributing towards this total with be alternative technologies,
- to run annual allocation rounds for electrolytic projects, and the period between 2025-2030 dedicated to potentially alternative technologies,
- to allocate up to 875 MW of capacity during the electrolytic HAR2,
- to allocate up to 1.5 GW across both electrolytic HAR3 and HAR4 (expected to be launched in 2025 and 2026 respectively).

The overall expectation across the UK is to see larger-scale electrolytic projects breaking through into the industry increasing deployment of low-cost renewable energy.

The novel siting of large-scale electrolytic projects to meet the current ambitions would be beneficial from a systems perspective.

This means to support and manage grid constraints and/or to use excess electricity produced, for example from renewable energy generation, that would have otherwise been curtailed or constrained.

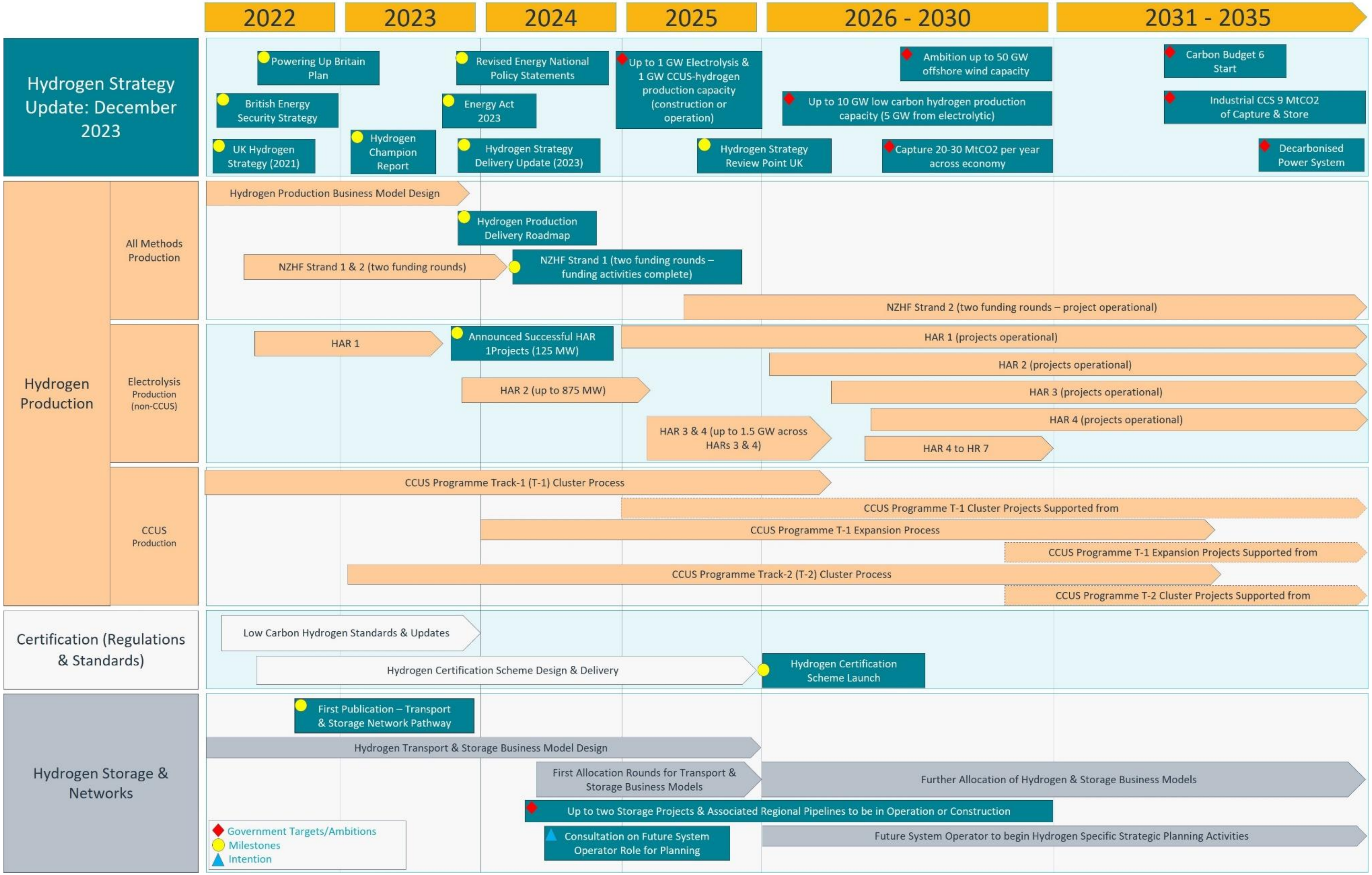


Figure 6.4 Hydrogen strategy delivery roadmap across the hydrogen production, storage and networks sector. [29] This figure should be mentioned in the text .

6.2 Mobility 'Hydrogen Hubs'

Practically all modes of transportation could be run on hydrogen or hydrogen-based fuels, including light and heavy-duty road vehicles, maritime vessels, trains and planes. Some sectors are going to be easier to transition than others. [63] Bloomberg New Energy Finance in 2022, called 'Electric Vehicle Outlook',[64] presented an Economic Transition Scenario. The finding was that less than 1% of all global passenger vehicles would incorporate a fuel cell drive train, by 2040. The expectation from Bloomberg is that battery electric vehicles would be the main route to lowering emissions until hydrogen matures, making up 43% of the 2040. However, the counterargument has been that demand in the industry will push the manufacturers too fast, resulting in battery material shortages and/or recycling issues.

Another argument is that extended range and shorter refuelling times for the hydrogen economy are more important than predicted. There may also be a case for fuel cell vehicles from an energy systems perspective; hydrogen refuelling stations may put less strain on electrical infrastructure networks than fast electric charging stations. Therefore, as discussed in the previous section hydrogen hubs may be more attractive for long-haul and heavy-duty applications from the forthcoming projects already allocated with funding. For example, buses and long haulage transport are good examples of challenging sectors where hydrogen could make inroads in the transport sector.

It must be mentioned in terms of hydrogen quantities for road vehicles regarding the forward-thinking study by 'Riversimple' in the Milford Haven Energy Kingdom (MH:EK) project. They explored the potential demand in Milford Haven on a range of vehicles; findings estimated that in the short term the demand could be 335 kg/day, mid-term demand could be 670 kg/day, and a mature hydrogen hub market could present a long-term demand of up to 1,740 – 1,920 kg/day. [65] Therefore, supporting the mobility industry through the testing of the 'Riversimple' hydrogen fuel cell electric car to great success. [66]

Q3. Are the 'Hydrogen Hubs' forthcoming, mostly about production of hydrogen for preassigned use cases, or will these also double up as places to come and 'fill up the tank' for commercial sales too?

The concept of hydrogen hubs often involves not only the production of hydrogen but also its distribution and utilisation in various sectors. Hydrogen hubs are envisioned as comprehensive ecosystems that facilitate the production, storage, and distribution of hydrogen, as well as its use in different applications.

Key aspects of hydrogen hubs may include:

1. **Hydrogen Production**: Hydrogen hubs typically include facilities for hydrogen production, often using methods such as electrolysis or steam methane reforming. This hydrogen can be

[63] IEA. (2019). "The Future of Hydrogen, Report Prepared by the IEA for the G20, Japan." Seizing Today's Opportunities

[64] Electric Vehicle Outlook 2021. Retrieved from https://about.bnef.com/electric-vehicle-outlook/

[65] Summary Report: Developing the business case for a publicly accessible hydrogen refueller, Riversimple

[66] Green hydrogen electrolyser and car refueler arrive at Milford Haven Waterfront - Pembrokeshire County Council

produced from renewable energy to support the transition of transportation, heavy fossil fuel reliant industries, and power generation to maximise the grid demand when needed.

2. **Storage and Distribution**: Hydrogen hubs incorporate robust and reliable infrastructure for storing and distributing hydrogen at central locations. This may involve pipelines, storage tanks, and the means for large-scale transportation to move hydrogen from production sites, namely the hydrogen hubs to end-users or other hubs as demand is needed.

3. **End-Use Applications**: Hydrogen hub production can be used for several applications across the ecosystem, for example, fuelling hydrogen fuel cell vehicles on demand on site, providing feedstock for industrial processes, or for generating electricity through fuel cells to balance the grid in the region of the hydrogen hub.

4. **Refuelling Stations**: Hydrogen hubs may include refuelling stations for quick and efficient top-ups for hydrogen-powered vehicles. This could include the end-user to be commercial and/or the general public refuelling station. Therefore, a hydrogen hub infrastructure would support the growth of the hydrogen fuel cell vehicle market.

The mobility goal is to create a comprehensive hydrogen ecosystem that addresses these aspects of the hydrogen value chain. This approach can contribute to the development of a hydrogen economy by advancing the implementation of hydrogen across different sectors.

6.3 Hydrogen Hubs expected capacity

Q4. Of forthcoming ‘Hydrogen Hubs’ what is the expected capacity to be and are they permanent, versus the completed Teesside project able to fuel 20 vehicles for several months?

The capacity of forthcoming hydrogen hubs can vary widely based on the scale of the project, intended applications, and regional energy demands. Hydrogen hub projects are designed to meet the needs of multiple sectors, including transportation, industry, and power generation. Therefore, the expected capacity of these hubs depends on factors such as the size of the production facilities, the infrastructure for storage and distribution, and the specific goals of the project.

Therefore, from the full analysis to this chapter it has been identified in Figure 6.3 across the initial hydrogen capacities, in MW as a representation of the UK hydrogen project updates (both for December 2023, and February 2024). Focused on CCUS in phase 2 negotiations, the successful projects from the first electrolytic hydrogen allocation round (HAR1), and the £240 million Net Zero Hydrogen Fund (NZHF); with first stage/phase all indicative capacities that are subject to change over time.

The initial capacity from the research and data that is available has amounted to ≈ 5.2 GW, this includes all successful projects allocated by the Hydrogen Strategy Update to the Market released by the Government.

Q5. When ‘Hydrogen Hubs’ appear, would customers use 100% hydrogen vehicles than hybrid-diesel options, over electric hybrid, or bio-fuel alternatives?

The choice between 100% hydrogen vehicles, hybrid-diesel options, electric hybrids, or bio-fuel alternatives depends on various factors, including the specific use case, technology advancements, infrastructure availability, and environmental considerations. Each technology has its own set of advantages and challenges. Here are some key points to consider:

Hydrogen Vehicles:

- Advantages: Hydrogen fuel cell vehicles produce zero emissions at the exhaust outlet, offering a clean and efficient alternative to traditional internal combustion engines.
- Challenges: Challenges include the current high cost of fuel cells, limited infrastructure for hydrogen refuelling, and the energy-intensive process of producing hydrogen.

Hybrid-Diesel Vehicles:

- Advantages: Hybrid-diesel vehicles combine the efficiency of diesel engines with the benefits of electric drive systems. They can improve fuel efficiency and reduce emissions.
- Challenges: Diesel engines still emit pollutants, and the overall environmental impact depends on factors like the source of electricity for the electric components.

Electric Hybrids:

- Advantages: Electric hybrid vehicles combine an internal combustion engine with an electric motor. They can operate on electric power at low speeds, reducing emissions and fuel consumption.
- Challenges: The range and efficiency of electric hybrids depend on the size of the battery and charging infrastructure. They may still rely on fossil fuels for certain driving conditions.

Bio-Fuel Alternatives:

- Advantages: Biofuels can be produced from renewable sources, reducing reliance on fossil fuels. They can be used in existing internal combustion engines.
- Challenges: The sustainability of biofuels depends on factors such as land use, feedstock sources, and production methods. Some biofuels may still emit pollutants.

The choice of a particular technology will depend on factors like infrastructure availability, cost, energy efficiency, and the specific requirements of the user. Hydrogen hubs can play a crucial role in promoting the adoption of hydrogen vehicles by addressing infrastructure challenges. As technology advances and becomes more economically viable, the landscape of alternative fuels and propulsion systems is likely to evolve. Additionally, regional policies and environmental considerations will also influence the adoption of different vehicle technologies.

7 UNLOCK THE GREEN HYDROGEN ECONOMY CONCLUSION

7.1 Reaching 10 GW of hydrogen production capacity

To drive costs of hydrogen production down long-term, renewable energy commitments will be required, including an accelerated deployment pace. This will feed into the UK Government's goal of having 5 GW of electrolysis and 5 GW of CCUS capacity by 2030. [67] Robust planning is needed to displace fossil fuels, e.g., moving the electrical grid to zero-carbon by 2035 and 95% renewable energy by 2030. [68] Supporting the production and use of hydrogen will help to drive down costs and help to create a business case.

The advances for green hydrogen and blue hydrogen production and further development will contribute significantly to the UK economy. The energy vector is a potential new business opportunity for sectors like Oil & Gas (O&G) and renewable companies. There are so many sectors that will benefit from hydrogen hubs; like electrical networks, airports, automotive industry, heavy-industry, and grid demand. Renewable energy sources will be used to drive the electrolysers of the future to create a green hydrogen economy.

7.2 Grid connected electrolysers

Grid-connected battery storage is a promising approach for linking electrolysers to the grid, allowing them to provide balancing services to system operators. By updating grid connection standards to support this, electrolysers can play a key role in early hydrogen hub development, reducing costs and improving efficiency when paired with storage and fuel cells. This would allow hydrogen to act as an energy storage solution, supporting the grid and strengthening the business case for green hydrogen production.

However, similar to challenges faced with grid-scale batteries, there is the potential issue of double charging. In this scenario, an energy storage system could be charged for both importing energy from the grid (like conventional consumers) and exporting energy back onto the grid (like conventional generators). This could have significant implications for the economics of green hydrogen production.

7.3 Stimulating green hydrogen production challenges

The green hydrogen economy challenge is around allocating risk in an acceptable way. Hydrogen production projects will need to source a suitable demand to offload the hydrogen as part of a hydrogen hub solution. There may also be challenges around projects looking to buy hydrogen, or even hydrogen equipment. These can be resolved to some extent through understanding the hydrogen activities in the local area as discussed earlier in the Hydrogen Strategy Delivery to Market and Roadmap across the hydrogen production. Regulatory issues are another broad theme of challenges, with innovative projects looking to push on with activities that are not covered by current

[67] British energy security strategy - GOV.UK (www.gov.uk)

[68] Green Hydrogen: Optimising Net Zero - RenewableUK

regulations. Putting pressure on the regulators to safely enable and regulate project activities would help. Government steering and influence can also support to increase the rate of change.

Further solutions to stimulating green electrolysis hydrogen production include:

- developing strategic locations for hydrogen refuelling infrastructure for example, Hydrogen Hubs and fuel cell technology cross-over.
- developing demonstration projects to boost sector confidence.
- normalising the use of hydrogen for example, through "purpose-built" regulations.
- electrolyser projects across the UK require clear guidance to accelerate their deployment through an easier and faster national permitting procedure and using grid power in electrolysers.

7.4 Green hydrogen is part of a much larger energy transition

Green hydrogen is becoming increasingly attractive due to falling costs. When produced from renewable energy, current projections see potential for costs to fall to £1.50 – 3/kg over the coming decades. [69] [70] Natural gas prices will influence blue hydrogen costs and seem more volatile to economic changes in comparison to renewable energy driven green hydrogen. The rate of hydrogen cost reduction depends on how fast the electrolyser market grows, this may be accelerated by the 2030 ambitions and allocated hydrogen projects discussed. Regions with good renewable energy resources have an opportunity to use electrolysis to make green hydrogen cost competitive.

Urgent action will be required by the UK to secure an independent energy future. Although challenges exist in delivering the transition, the expected positive outcomes outweigh the initial risk. The rate of hydrogen deployment may be affected by international cooperation to feed into local content. As the offshore renewable energy sector grows significantly, their support in electrolyser production can only benefit a large-scale renewable energy generation transition. One such area is low-cost electricity, expected in the future when there is plenty of generation and low demand. Therefore, relevant to regions across the UK which have large scale offshore wind potential but limited electrical networks/demand.

7.5 ORE Catapult Recommendations

The key recommendation is to initiate a Hydrogen Hub economy future. ORE Catapult can champion offshore wind to hydrogen activity across the wider UK.

In particular, ORE Catapult can make contributions in several areas including:

- Detailed technical studies, such as:
  - How best to integrate wind turbines with electrolysers from an engineering system perspective?

[69] Green hydrogen economy - predicted development of tomorrow: PwC

[70] Costs challenge the hydrogen transformation | E&T Magazine (theiet.org)

    - The characteristics of pipelines compared to cables
    - Testing and demonstration at Blyth and Levenmouth Demonstration Turbine facilities
- Project economics and techno-economics
    - When does it make sense to include hydrogen in an offshore renewable energy project?
    - How does the choice of technology and electrolyser location affect the levelised cost of hydrogen?
- Integrating offshore wind power, either in the form of electricity or hydrogen, into the wider energy system
    - With lots of new wind farms coming online, which should be dedicated to hydrogen production?
    - How does the influence of local energy infrastructure/demand affect this? Examples include disused substation sites from nuclear sites, sites of chemical energy demand, such as ports and airports, and potential sites for geological storage of hydrogen.
- Policy, informing decision makers, and championing green hydrogen.

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