Cornwall FLOW Accelerator

EXPLORING THE POTENTIAL INTERACTIONS BETWEEN FLOATING OFFSHORE WIND AND HYDROGEN

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CORNWALL FLOW ACCELERATOR PROJECT

INNOVATION IN LOW CARBON DESIGN AND MANUFACTURABILITY

EXPLORING THE POTENTIAL INTERACTIONS BETWEEN FLOATING OFFSHORE WIND AND HYDROGEN

REPORT

Electrical infrastructure and grid connections

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ORE Catapult is a not-for-profit research organisation, established in 2013 by the UK Government as one of a network of Catapults in high growth industries. It is the UK’s leading innovation centre for offshore renewable energy and helps to create UK economic benefit in the sector by helping to reduce the cost of offshore renewable energy, and support the growth of the industry.

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DISCLAIMER

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PREFACE

The Offshore Renewable Energy Catapult is a partner in the Cornwall FLOW Accelerator project and is leading work on Low Carbon Manufacturability (Work Package 4)and has commissioned this report as part of the Celtic Sea floating offshore wind (FOW) initiative. This report examines the challenges and future opportunities for FOW and green hydrogen for the integration to the electrical grid infrastructure. The potential combination of both floating offshore wind and hydrogen have received significant interest from the UK Government and this report examines that potential.

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NOMENCLATURE

AEL	Alkaline electrolyser
AEM	Anion Exchange Membrane electrolysis
ATR	Autothermal reforming
BEIS	The Department for Business, Energy and Industrial Strategy
B-F	Bottom fixed
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CfD	Contracts for Difference
CLSA Ltd.	Official name of a capital markets and investment group
COP 26	26th Conference of Parties
CSC	Celtic Sea Cluster
CPS	Celtic Sea Power
CTV	Crew Transfer Vessel
DNV	Det Norske Veritas
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FOSS	Floating Offshore Substation
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
GHG	Greenhouse gas
GVA	Gross value added
H&S	Health & safety
H_2	Hydrogen

HV	High Voltage
HVAC	High voltage alternating current
HVDC	High voltage direct current
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
LF	Load Factor
LRVC	Long Run Variable Cost
MOSS	Multi-Purpose Offshore Substation
MPI	Multi-Purpose Interconnector
$MtCO_2$	Metric Tons of Carbon Dioxide
MW	Mega-Watt
MWh	Mega-Watt hour
NG ESO	National Grid Electricity System Operator
O&G	Oil and gas
O&M	Operation and maintenance
OEM	Original equipment manufacturer
Ofgem	Office for Gas and Electricity Markets
ORE	Offshore Renewable Energy
OSS	Offshore Substation
OSW	Offshore wind
OSW-H_2	Offshore wind - Hydrogen
OTNR	Offshore Transmission Network Review
OWIC	Offshore Wind Industry Council
PEM	Proton Exchange Membrane
pH	potential Hydrogen
PV	Photovoltaics
R&D	Research and development
SMR	Steam methane reforming
SOE	Solid oxide electrolyser
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

The UK Government's Ten Point Plan and British Energy Security Strategy have set the direction of travel to 2030; alongside other technologies, there is to be a major ramp up of offshore wind and hydrogen production via electrolysis. Together, these will have a significant effect on the energy system. Although there is some uncertainty around the manner in which these new targets will be reached, they have great potential to deliver positive outcomes for the country.

Among the numerous hydrogen production routes, offshore wind powered electrolysis is looking increasingly attractive for the UK and Europe. High gas prices are pushing the cost of blue hydrogen to around £5.70/kg[1] [2]. Against this backdrop, the costs of green hydrogen from offshore wind are projected to fall substantially; numerous research groups expect it to be competitive with, or even fall below this blue hydrogen cost by around 2025, then fall further to between £1.50 – 3/kg by 2050[3] [4].

Results from numerous energy system modelling studies support investment in hydrogen technology. Investment group CLSA Limited have reviewed findings from five organisations: Bloomberg New Energy Finance, the International Renewable Energy Agency, the International Energy Agency, the Hydrogen Council and the Energy Transitions Commission. These five organisations have estimated that the world needs at least 500 million tonnes of hydrogen per year by 2050. CLSA, writing after the ongoing crisis in Ukraine, have estimated that this quantity is now required by 2040.

CLSA have observed that the five studies expect hydrogen will provide between 12 to 22% of final energy demand by 2050, with another study from DNV estimating that 15% is required to meet the Paris Agreement goals. CLSA thinks this could be 15 – 20% by 2040. On average, the five studies predict that only about a quarter of this supply comes from blue hydrogen, which emphasises the importance of green hydrogen.

For the UK, and the Celtic Sea region, there is potential to use hydrogen, produced from offshore wind, in sectors which are or could be supplied by British companies. Examples include using hydrogen: for light duty transport, as is the aim of Riversimple and Microcab; for heating, as targeted by Worcester Bosch and Baxi Heating; in refineries, which could help reduce emissions from Welsh and other UK refineries; and as a means of decarbonizing manufacturing in South Wales, which in turn could provide low carbon wind turbine components for Celtic Sea deployment.

There are a range of enabling actions to support green hydrogen and offshore wind, many of which the UK Government has already set in place. Supporting actions include: Contract for Difference style allocation rounds to support production; introducing standards, such as the low carbon hydrogen standard; providing support for electrolyser and new offshore wind grid connections; the introduction of regulatory sandpits to accelerate novel projects; and providing targeted funding for R&D and demonstration projects.

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[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)

1 INTRODUCTION

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).

In the transition towards a low carbon energy system, there will be a substantial investment in a range of low-carbon technologies, including offshore wind and electrolysis. As well as their stand-alone contribution, there is likely to be opportunities to integrate these technologies. These three topics (offshore wind, electrolysis, and their integration) are introduced in more detail in the rest of this section.

1.1 Increased offshore wind in the energy system

Offshore wind (OSW) is likely to play a key role in a UK net zero energy system, with projected capacities of 75 – 150 GW by 2050[5]. Within this, the role of FOW shall also be key, contributing 25 – 50% of this capacity (i.e., 20 – 75 GW). If these sites achieve an average capacity factor of 55%, they will produce about 361 – 723 TWh annually.

To give a sense of the importance of this, we can look at likely future electricity demand. The Climate Change Committee, in a 2020 report[6], explored a range of scenarios in which UK electricity demand was between about 600 – 900 TWh by 2050. Thus, on an annual basis, the contribution from offshore wind could supply between 40% to 100% of electricity demand, potentially with excess to help decarbonise other sectors.

The UK government, in its British Energy Security Strategy, has set an ambitious goal of 50 GW of offshore wind by 2030[7]. There is a lot of activity that will contribute towards this goal. This includes the ScotWind leasing round and, more recently, the fourth round of Contracts for Difference (CfDs). This renewables auction scheme secured almost 11 GW of clean energy, including about 7 GW for offshore wind[8].

The cost of offshore wind continues to fall, even as wholesale energy prices rise. Ofgem has reported weekly average wholesale forward delivery contract electricity prices rose to over £250/MWh in June 2022, compared to about £75/MWh 12 months earlier[9]. In contrast, the fourth round of CfDs saw the strike price of offshore wind power drop to a record £37.35/MWh[10], down from £39.65 – 41.61/MWh in the third allocation round[11].

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[5] FOW-PR19-Strategic-Infrastructure-Dev-Summary-May-22-AW3.pdf (catapult.org.uk)
[6] The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf (theccc.org.uk)
[7] British energy security strategy - GOV.UK (www.gov.uk)
[8] Biggest renewables auction accelerates move away from fossil fuels - GOV.UK (www.gov.uk)
[9] Wholesale market indicators | Ofgem
[10] CfD Allocation Round 4 results (publishing.service.gov.uk)
[11] Contracts for Difference (CfD) Allocation Round 3: results - published 20 September 2019, revised 11 October 2019 - GOV.UK (www.gov.uk)

There are a number of driving forces behind the falling cost of offshore wind. One example is that larger turbines, further from shore, are expected to reach higher wind speeds, which will help to reduce unit costs.

Floating offshore wind becomes attractive compared to fixed bottom offshore wind for water depths over 60 metres. For OSW, capacity factors around 55% are achievable, such that every 1 GW of capacity will generate about 4.8 TWh of electricity annually. Therefore, deploying 4 GW in the Celtic Sea could generate around 19.2 TWh/year for the South West region. Although Celtic Sea development is in very early stages, estimates[12] suggest that up to 50 GW of floating wind capacity could realistically be developed, which would generate about 240 TWh annually. More estimates are likely to follow.

FOW projects are anticipated to grow in scale around the UK from 2022 to 2035 – from small demonstrator projects to full scale commercial projects. This ties into the future developments of FOW in the Celtic Sea, with the potential for the South West to be a world leader in this technology; there is potential to lay down the primary foundations for a new long term sustainable FOW industry.

Due to the excellent renewable energy resource, the Celtic Sea can provide energy stability and security, including through potential to be exposed to different weather systems compared to the North Sea, which currently hosts most of the UK's offshore wind.

1.2 Increased hydrogen in the energy system

Renewable energy generators will require supporting technologies to extend the reach of low-carbon energy to hard-to-abate sectors, and to overcome the intermittency of wind and solar resources. Alongside others, hydrogen is a promising option, with potential for large scale, long term energy storage[13] (i.e., hundreds of GWh, or even TWh, over months). It can also be used to decarbonise a range of industrial processes, such as steel, ammonia and synthetic fuel production.

Hydrogen energy has spurred significant waves of interest in the past – what makes the current wave different? The answer to this question has two parts.

The first part is the commitment to reducing global warming, as evidenced by the 26th Conference of Parties meeting in Paris, where 197 governments agreed to keep global warming below 2°C, and ideally to 1.5°C. Additionally, governments around the world are now establishing net zero targets[14] [15].

The second part is that the cost of renewable energy has fallen dramatically. This is a major step towards making green hydrogen financially competitive.

There is a growing consensus around the quantities of hydrogen required to reach climate goals. Numerous studies expect the world to require at least 500 million tonnes of hydrogen by 2050, and that it will provide between 12 – 22% of final energy demand. Section 3.1.1 goes into more detail on these studies.

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[12] Floating wind in Wales substructure and port review (gov.wales)

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

[14] IPCC — Intergovernmental Panel on Climate Change

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

1.2.1 Hydrogen in the UK context

Previous analysis from ORE Catapult found that the UK energy system requires 130 – 200 TWh of hydrogen by 2050 to integrate 75 GW, or more, of offshore wind capacity[16].

In the UK, the Government's British Energy Security Strategy set ambitious 2030 targets for the hydrogen market as below[17],

- "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."

1.3 The opportunity for hydrogen with floating offshore wind

Given the importance of offshore wind and electrolysis, especially in the UK, it seems likely that they will interact to some extent in the future energy system.

The interaction could be through the existing network, as in the following example: with more offshore wind coming onto the grid, there could be times when supply is greater than demand. In these cases, grid connected electrolysers could act as controllable demand, thus balancing the system while maintaining wind output.

The interaction between offshore wind and electrolysers could also be direct, through integrated systems. The resulting synergies may be applicable in a range of scenarios we are likely to see in the UK's energy future. One scenario is where plans for large, new offshore wind farms are stifled by a relatively low capacity electrical network. In this case, the wind farm's power could be sent directly to an electrolyser, thus by-passing the electrical network. Another example is where we would like to increase energy security. In this case, an integrated wind farm – electrolyser – storage system would allow for controllable dispatch of renewable energy.

The Climate Change Committee have also identified that variable renewable energy sources need to be considered for integration, hence the importance of OSW-H_2. This topic was explored further in the

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

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

Solving the Integration Challenge (StIC) report by the ORE Catapult in partnership with the Offshore Wind Industry Council (OWIC). This report examined the potential for hydrogen to play a key role to the UK's energy-balance, including increasing flexibility[18]. The study found that, (1) driving deployment of electrolysers is essential for reducing their cost – the UK has done this before, with offshore wind - and (2) there are signs in the marketplace that green hydrogen will take off faster than we assumed, cutting costs by 2030 by more than estimated.

Another relevant piece of work is the National Grid ESO Offshore Coordination project[19]. This is linked to a plan for a holistic network design (HND)[20], which has connections to the BEIS-led Offshore Transmission Network Review (OTNR)[21]. Together, these pieces of work should help to find the best way to connect lots of new offshore renewable generation into the wider energy system.

In summary, offshore renewables and hydrogen are a promising route to reducing 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. Additionally, this will help to create new, highly skilled jobs as well as new innovative research pathways which will help to diversify the local economy.

1.4 Objectives of the research

This research will address the following topics.

- Section 2: hydrogen production routes, with a focus on electrolysis; cost projections for hydrogen produced from offshore wind; a comparison of blue and green hydrogen costs; and green hydrogen production in the UK in the context of global markets
- Section 3: forecasts on the size of the global hydrogen markets and the contribution of green hydrogen; and key markets for hydrogen in Cornwall and South Wales
- Section 4: supply chain opportunities, with a focus on UK companies which are developing new hydrogen technologies, the demand from which could be satisfied by Celtic Sea projects
- Section 5: enabling actions to unlock the green hydrogen future

In addition to this report, the Cornwall FLOW Accelerator project, led by Celtic Sea Power, supported by partners University of Exeter, University of Plymouth and ORE Catapult, has conducted research into cable connection interfaces, the potential role of multi-purpose connectors, and the South Wales transmission network for FOW in the Celtic Sea. This has helped to provide insights into the potential scale of FOW and the scale and role of hydrogen in system balancing.

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[18] Offshore Wind and Hydrogen: Solving the Integration Challenge – ORE (catapult.org.uk)
[19] Offshore Coordination Project | National Grid ESO
[20] Offshore Coordination Project - latest news and staying informed | National Grid ESO
[21] Offshore transmission network review - GOV.UK (www.gov.uk)

2 HYDROGEN PRODUCTION ROUTES AND COSTS

This section covers the various hydrogen production routes, before giving a more detailed introduction to electrolysis and various types of electrolysers. It highlights some of the challenges of integrating hydrogen into the energy system, including from offshore wind, and outlines some options for exporting energy from offshore wind farms. Finally, it introduces a commonly used financial metric, the levelised cost of hydrogen (LCOH), and outlines some studies which have projected hydrogen costs when produced using offshore wind power. It then compares the cost of green hydrogen and blue hydrogen, and considers local and global hydrogen production costs.

2.1 Types/colours of hydrogen

Atomic hydrogen is present in lots of chemicals, including water and hydrocarbons. Various processes, each with its own outputs, allow us to extract gaseous hydrogen from those chemicals. To help differentiate between the different feedstocks, processes, and outputs, each option has been loosely designated a colour. (Although there is broad agreement on the colours, there are some points on which organisations will take different approaches e.g., whether biogas steam reforming results in green hydrogen. This is explored further in Section 5.2) Common definitions are outlined in Table 2.1.

Table 2.1 List of specified hydrogen colours by original energy source, process, and outputs.

Specified hydrogen colour	Produced using	Process	Outputs
Green	Renewable energy and water	Electrolysis	Hydrogen and oxygen
Blue	Methane and water	Steam-methane reforming with water gas shift reaction with CCS	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
Grey	Methane and water	Steam-methane reforming with water gas shift reaction	Hydrogen and carbon dioxide
Turquoise	Natural gas	Pyrolysis	Hydrogen and solid carbon
Brown	Brown coal, water, and oxygen	Gasification with water gas shift reaction	Hydrogen and carbon dioxide
Black	Black coal, water, and oxygen	Gasification with water gas shift reaction	Hydrogen and carbon dioxide

2.2 Introduction to electrolysis

This section focuses on the electrolysis process, and some electrolysis technologies.

2.2.1 The electrolysis process

Water electrolysis is an electrochemical reaction in which an electrical current is used to drive a chemical reaction, namely the decomposition of water (H_2O) into its basic components, hydrogen (H_2) and oxygen (O_2). This is a carbon-free process.

The electrolysis process transforms electrical energy into chemical energy. This chemical energy can then be used as a fuel in a similar way to other fuels that we use today (including fossil fuels), and as an industrial feedstock.

The electrolysis reaction takes place in a cell. This is composed of two electrodes, namely a negatively charged cathode and a positively charged anode, plus an electrolyte and, usually, a membrane. An external power source can be connected to the electrodes, completing an electrical circuit through which current passes.

Although the reactions that take place at the anode and cathode are different between the various technologies (depending on pH and temperature), the overall reaction is the same:

$$2H_2O \rightarrow 2H_2 + O_2$$

2.2.2 Electrolyser technology

In the future there are plans to expand electrolysers, from MW through to GW scale. The plants are expected to be composed of a series of smaller modules or stacks. Currently, stacks are reaching multi-MW capacity e.g., up to 5 MW.

The rest of this section outlines four broad types of electrolysers.

2.2.2.1 Alkaline electrolysis

AEL is the most mature form of electrolysis. It is an established technology and has been used on an industrial scale for over 100 years. This reaction separates the water into hydrogen and oxygen in an electrolyte comprised of water and a strong caustic base such as potassium hydroxide (KOH) or sodium hydroxide (NAOH). Today, the technology has an electricity requirement of 50 – 78 kWh per kg of hydrogen, although there is a 2050 target to reduce this to less than 45 kWh/kg. They normally operate in the temperature region of 70 – 90°C[22].

One drawback of AEL compared to other electrolysis technologies, such as PEM, is the response time to power supply fluctuation. Another is the challenge of operating these systems at pressure without leakage of corrosive electrolyte, or damaging the cells.

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[22] Green hydrogen cost reduction (irena.org)

2.2.2.2 *Proton Exchange Membrane electrolysis*

In PEM electrolysis, an ionically conductive solid polymer plays the role of both the membrane and the electrolyte. The energy requirement today is about 50 – 83 kWh/kg, with a 2050 target of less than 45 kWh/kg. The operating temperature is usually between 50 - 80°C[23].

The benefit of using the PEM is rapid dispatchability that is capable of matching fluctuations in renewable power output, for example OSW farms. It is also relevant for grid ancillary services. PEM have several advantages over AEL, such as high product gas purity in partial load operation, the ability to operate at low turn down ratios, operating at higher current densities, and eliminating the hazard from corrosive liquid electrolyte. On the other hand, their harsh operating conditions require expensive materials, such as platinum group metals, and it is arguably a less mature technology than alkaline systems.

2.2.2.3 *Anion Exchange Membrane electrolysis*

AEM structure is similar to PEM, in that the membrane also plays the role of electrolyte. However, AEM electrochemistry is the same as conventional alkaline systems. One of the main advantages of AEM technology is retaining high performance characteristics whilst using lower cost materials.

The energy requirement today is about 57 – 69 kWh/kg, with a 2050 target of below 45 kWh/kg. Operating temperatures today are usually 40 – 60°C[24].

2.2.2.4 *Solid Oxide Electrolysis*

SOEs carry out the water splitting reaction at high-temperatures, circa 700 – 800°C. The SOE electrolyte is made from a ceramic yttria-stabilized zirconia (YSZ) type solid material that becomes ion conducting at temperatures above 700°C. At present SOE is very limited commercially, however the future potential of this technology at large scale is significant.

The main advantage for SOE is its electrical efficiency at such high temperatures; due to the thermodynamics of the water electrolysis reaction, at these high temperatures (700 – 800°C), a greater proportion of the energy required for the reaction can be supplied as heat, and so only the remaining energy requirement needs to come from electricity. In contrast, in low temperature systems, nearly all the energy requirement is met by electricity. Overall, this means the electrical requirement is usually in the range of 40 – 50 kWh/kg[25].

Due to the high temperature requirement, there may be limited applicability for SOE in the context of offshore wind. There may be synergy with coupling SOE electrolysis with nuclear plants, as these can supply both high-temperature heat and electricity.

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[23] Green hydrogen cost reduction (irena.org)

[24] Green hydrogen cost reduction (irena.org)

[25] Green hydrogen cost reduction (irena.org)

2.3 Barriers to the development of a hydrogen economy

Hydrogen is part of a much bigger energy transition, and setting the priorities correctly in the initial stages is essential. There are barriers that currently prevent clean hydrogen from making a larger contribution to the energy transformation, including integration with offshore wind and hydrogen. Some of these are listed below[26]:

- Historically, the cost of 'green' hydrogen has been very high relative to high-carbon fuels. This has included production, transportation, converting (where necessary) and storing hydrogen. However, the recent European energy crisis has caused sudden system/market changes, and may have long term implications on the cost of fossil fuels compared to green hydrogen.
- A low technology readiness level (TRL) in some parts of the hydrogen value chain.
- There are significant energy losses incurred through hydrogen production and conversion at each stage, through to the end user.
- Understanding the best use of renewable energy; there are projections that up to 21,000 TWh of energy will be consumed by modern electrolyser technology by 2050, which might be needed elsewhere as we aim for Net Zero.
- Substantial investment, which remains high risk for both hydrogen production and the necessary infrastructure that would reduce costs.
- The difficulty of matching supply with demand is effectively a risk for hydrogen production.

Learning by doing in the 2020s will bring costs down and accelerate the race for technology leadership.

2.4 Options for offshore wind energy export

The main options for exporting offshore wind power to the wider energy system are to export as electricity, as with current wind farms, or to send it to electrolysers for the production of green hydrogen.

There is a possibility to combine these approaches. For example, it would be possible to use high voltage alternating current (HVAC) to transmit wind power to a multi-purpose offshore substation (MOSS), deployed far offshore. This could receive power from multiple wind farms, which could potentially reduce costs and reduce landing-points. From there, the power could be sent through a high voltage direct current (HVDC) export cable to a nearshore MOSS with a DC/AC converter to feed the grid via a HVAC cable. Alternatively, the nearshore MOSS could host electrolysers, and export hydrogen.

Following production at the nearshore substation, the hydrogen could be compressed and transferred, through a pipe, to shore for distribution through a network or directly to end users. Alternatively, it could be collected by ships for regional distribution. This eliminates the need for some electrical

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

infrastructure, like onshore substations, export cables and grid connections. Further R&D could also include backup battery provision as a buffer where a surplus of electricity is produced due to excess wind.

Large-scale production of hydrogen from electrolysers will present new challenges in the future. This could include optimising operations for efficiency and assessing technical requirements to pair electrolysis with the electricity grid and offshore wind farms.

2.5 Offshore wind to hydrogen costs

This section explores how to calculate the levelised cost of hydrogen, and summarises some offshore wind to hydrogen cost projections from various industrial and research groups.

2.5.1 Calculating levelised cost

A popular financial metric is the 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[27]. This can be calculated using the following equation, where n is the time period.

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

The measure of hydrogen used in the denominator is usually kilograms (giving costs in £/kg). However, it is also possible to measure it according to the energy content of hydrogen (£/MWh). There are two main ways to measure energy content. One is the higher heating value (HHV), which is about 39.4 kWh/kg. Using this gives costs in £/MWh-HHV. The other is the lower heating value (LHV), which is about 33.3 kWh/kg. Using this gives costs in £/MWh-LHV.

(Some reports do not specify whether the higher or lower heating value has been used. While this generates some difficulty for the reader, the fact that the two values are relatively close means that it is still possible to have a reasonable idea of what the report is saying.)

Some conversions below:

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

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

Some common examples of costs in the three sets of units are shown in Table 2.2.

Table 2.2 Converting costs between £/kg, £/MWh-HHV, and £/MWh-LHV, without decimal places.

£/kg	£/MWh-HHV	£/MWh-LHV
1	25	30
2	51	60
3	76	90
4	102	120
5	127	150

2.5.2 Levelised cost projections

Although there has been limited physical connection of offshore wind turbines to electrolysers to date, several organisations/groups have carried out high-level explorations of the likely costs. Some of these have explored a range of options, such as deployment of the electrolyser onshore or offshore, including centralised and decentralised electrolysers, and different types of wind turbine foundations. This section introduces some of these studies.

One study was the Offshore Renewable Energy Catapult’s 2020 Solving the Integration Challenge report[28]. This 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. The results of this report are affirmed in an updated ORE Catapult analysis which compared the cost of blue and green hydrogen (Section 2.6).

In 2019, sustainability consultancy ERM estimated costs for offshore wind powered electrolysis as a function of distance from shore (between 30 – 400 km), wind turbine foundation, and for offshore centralised, decentralised, and onshore hydrogen production[29]. In this analysis, a floating semi-sub foundation with integrated turbine – electrolyser system was always the lowest cost option, with undiscounted costs of about £2.00/kg at 100 km from shore and £2.20/kg at 300 km from shore, with costs plateauing with increased distance from shore. They found onshore electrolysis was always the most expensive option, with undiscounted costs of about £2.80/kg at 100 km from shore and £3.60/kg at 300 km from shore, with costs continuing to rise with increased distance from shore.

Another study was performed by Xodus[30], in 2020. They estimated costs in three scenarios. First, a 2025 single offshore integrated turbine-electrolyser pilot project had a projected cost of about

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[28] Offshore Wind and Hydrogen: Solving the Integration Challenge – ORE (catapult.org.uk)
[29] Dolphyn Hydrogen - phase 1 final report (publishing.service.gov.uk)
[30] Offshore wind to green hydrogen: opportunity assessment - gov.scot (www.gov.scot)

£6.20/kg. Second, a 2028 commercial scale (500 MW) offshore wind farm coupled with onshore electrolysis had an estimated cost of about £2.90/kg. Third, a 2032 commercial scale (1 GW) offshore wind farm coupled with offshore electrolysis had an estimated cost of about £2.30/kg. Long term, they see costs falling to £2/kg.

Roland Burger's 2021 Innovate and industrialize: Offshore Wind Energy report[31] examined costs from two perspectives. One perspective was the cost of green hydrogen around the world in 2025, including when produced from offshore wind energy in Europe (specifically a 250 MW electrolyser); this had an estimated cost of about £3.30 – 3.50/kg (EUR 3.9 – 4.2/kg). The other perspective was the cost difference between a centralised offshore electrolyser and an onshore electrolyser, as a function of electrolyser capacity (1 to 10 GW). They found that, for 1 GW capacities, the onshore option was favourable. However, for capacities of 2 GW and more, the offshore option was preferable. One of the drivers for this was a relatively stable/static pipeline cost with increasing capacity, compared to substantially increasing export cable and converter costs.

Bloomberg New Energy Finance outlined their perspective on offshore wind to hydrogen in a short 2021 blog piece[32]. They have estimated costs could be around £5.80/kg ($7/kg) in 2025, but this could drop to about £3.80/kg ($4.6/kg) by 2030 and about £0.80/kg ($1/kg) by 2050. This is a relatively pessimistic short term analysis, coupled with the most optimistic long term analysis. They also mentioned that onshore electrolysers were cheaper until 2030, when offshore electrolysers become favourable, although the reasons for this were not described.

BEIS explored hydrogen production costs in a range of scenarios in a 2021 report. One scenario was electrolysis powered by offshore wind. They estimated 2025 costs of around £4.45/kg (£113/MWh-HHV), with costs then falling rapidly over the next 15 years, before plateauing at about £2.87/kg (£73/MWh-HHV) between 2040 and 2050.

Journal papers have also explored the costs of offshore wind to hydrogen. One such paper was written by a team comprising of HYGRO Technology, the National Renewable Energy Laboratory, Plug Power and Giner Inc.[33]. They looked at a scenario where electrolysis costs have fallen to $100 – 300/kW. They found that the cost of production from decentralised, integrated wind turbine – electrolyser systems could be about £1.70/kg ($2.09/kg), whereas hydrogen produced from offshore wind in an onshore electrolyser was about £3.20/kg ($3.86/kg). 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.

To summarise the above paragraphs, amongst this wide range of organisations and teams there is a broad consensus that the costs of hydrogen produced from offshore wind are currently high but are expected to fall substantially, probably to the range of £1.50 - 3/kg. Additionally, offshore deployment of electrolysers seems to be favourable in some scenarios.

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

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

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

What can we take from this? On one hand, the offshore wind to hydrogen field is only now in development, and, based on the contents of the documents, most of these studies seem to have been relatively high-level. Still, if we are satisfied that the analysis of these teams is sound, we can take these initial findings as a reasonable indication of what the future of the sector will look like: costs falling to between £1.50 – 3 /kg, with offshore electrolysis being advantageous in some scenarios.

2.6 Comparing the costs of green and blue hydrogen

There is ongoing debate about the merits of green vs blue hydrogen in terms of environmental impact and project economics. Over the last decade, record low gas prices have made the economics of blue hydrogen look attractive. On the other hand, the environmental merits are not clear, with uncertainty over methane leaks and the percentage of carbon captured in CCS processes.

For the foreseeable future, with gas prices subject to huge uncertainty and climbing to record high levels, the economic argument no longer carries the same weight. With an anticipated gas price of £3.53/therm, 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, as shown in Figure 2.1.

In Figure 2.1, we forecast that the cost of producing green hydrogen from floating offshore wind will be around £146/MWh-HHV (£5.75/kg) for early commercial projects, taking place in 2025-2027. This falls to £76/MWh-HHV (£2.99/kg) by 2030, and reducing below £50/MWh-HHV (£1.97/kg) by 2040.

This cost reduction is driven by the major cost reductions in FOW as well as swift cost reductions in the cost of electrolysis. These are both driven by a combination of technology innovation and large-scale deployment.

In this context, green hydrogen looks increasingly attractive, from economic and environmental perspectives, when compared to blue hydrogen.

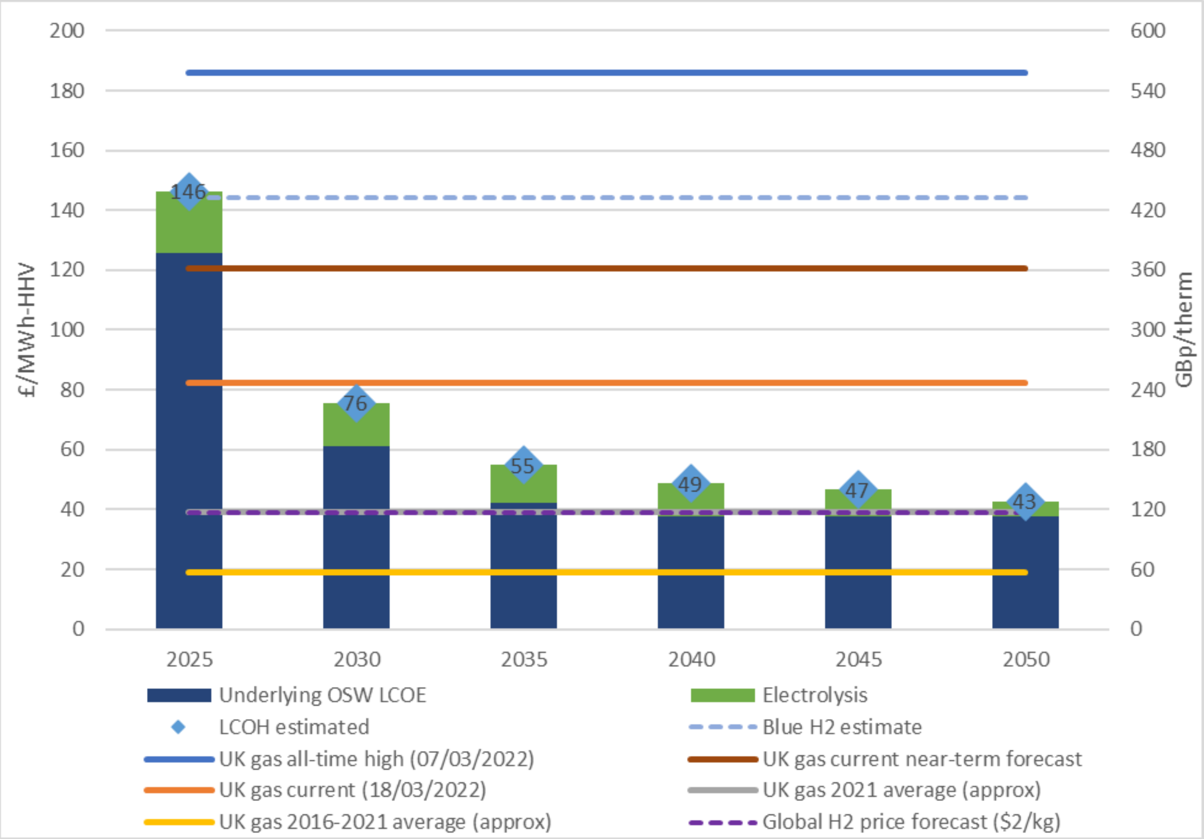

Figure 2.1 Forecast UK FOW green hydrogen vs various UK gas price benchmarks (ORE Catapult, 2022)

2.7 UK, European and global supply

ORE Catapult have predicted the cost of UK FOW-produced green hydrogen with the cost of green hydrogen imported from overseas. By 2050, UK FOW-produced hydrogen should be at cost parity with the global forecast price for green hydrogen, around the $2/kg mark (which, using the March 2022 exchange rate of $1.31/£1, is about £39/MWh-HHV, or £1.53/kg). This is shown in Figure 2.2. If used regionally, UK hydrogen will have the advantage of low transport costs, compared to overseas supplies.

In the long-term, as markets and infrastructure matures, global hydrogen prices may become a valid comparison to expected UK prices. However, in the near-term, the comparison with hydrogen imported from Europe is more relevant. ORE Catapult forecasts that UK FOW-produced hydrogen should reduce below the cost of green hydrogen imported from Europe around 2030 and continue to track below European prices for the foreseeable future.

In addition to the benefits of using UK-produced green hydrogen domestically, the scale of the UK's offshore wind resource and ambition mean that there is huge potential to export UK green hydrogen to Europe and beyond. This opportunity was valued at £48bn per year in ORE Catapult's Solving the Integration Challenge (StIC) study[34], with hydrogen forming 25% of Europe's energy needs by 2050. This opportunity will only accelerate and increase as demand grows even faster than previous

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

predictions, given the imperative faced by an increasing number of countries to reduce reliance on Russian gas.

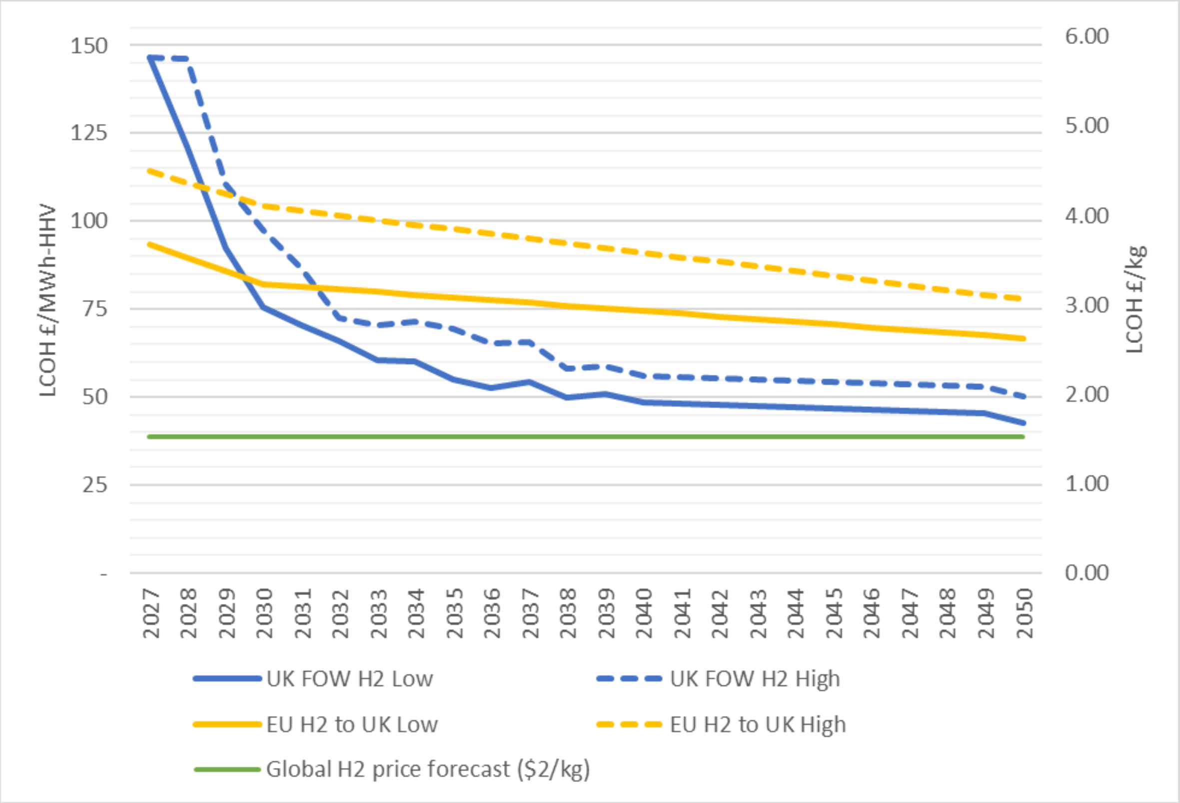

Figure 2.2: costs of UK FOW H2 vs European and global H2 imported into the UK (ORE Catapult, 2022). This forecast for the European hydrogen price came from the International Council on Clean Transportation (ICCT)[35].

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[35] Cost of renewable hydrogen produced onsite at hydrogen refueling stations in Europe - International Council on Clean Transportation (theicct.org)

3 UK AND GLOBAL MARKET POTENTIAL FOR GREEN HYDROGEN IN THE CELTIC SEA REGION

This section explores the global picture for hydrogen, drawing insights from a range of studies. It then considers how much hydrogen could be produced in the Celtic Sea region, before outlining some of the key markets for hydrogen in Cornwall and South Wales.

3.1 Global Market Forecasts for Hydrogen

This section gives an overview of the market forecasts for hydrogen in both the UK and globally. This includes a description of the current status of green hydrogen production and its trajectory globally (3.1.1), followed by information on the range of ongoing or planned hydrogen projects across the globe (3.1.2).

3.1.1 The Current Status and Global Trajectory of Green Hydrogen

The International Energy Agency[36] has estimated that hydrogen demand in 2020 was about 90 million tonnes, with 80% produced through emissions intensive natural gas reforming and coal gasification, and almost all of the remainder as a by-product of other processes e.g., at refineries. Hydrogen dedicated electrolysis accounted for about 0.03% of total production. However, for the reasons discussed in Sections 1 and 2, both the annual hydrogen production rate, and the proportion produced through electrolysis, are set to change.

As mentioned in Section 1.2, there is a growing consensus about the role that hydrogen will play in a net zero world. Investment group CLSA Limited[37] have reviewed findings from Bloomberg New Energy Finance[38], the International Renewable Energy Agency[39], the International Energy Agency[40], the Hydrogen Council[41] and the Energy Transitions Commission[42]. Studies from these five organisations have estimated that the world will need at least 500 million tonnes of hydrogen annually by 2050. CLSA, writing after the Russian invasion of Ukraine, estimate this quantity is required by 2040.

CLSA have observed that the five studies expect hydrogen will provide between 12 to 22% of final energy demand by 2050, with another study from DNV[43] estimating that 15% is required to meet the Paris Agreement goals. CLSA thinks this could be 15 – 20% by 2040.

On average, the five studies predict that only about a quarter of this supply comes from blue hydrogen, which signifies the importance of green hydrogen.

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[36] Hydrogen – Analysis - IEA
[37] Crushing it 2: Hydrogen to be the net-zero hero, Chris Goodall, Ken Shin, CLSA U Blue Books, 4 July 2022
[38] NEO 2021 Executive Summary (bbhub.io)
[39] Geopolitics of the Energy Transformation: The Hydrogen Factor (irena.org)
[40] Net Zero by 2050 - A Roadmap for the Global Energy Sector (windows.net)
[41] Hydrogen for Net Zero - Hydrogen Council
[42] Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy (energy-transitions.org)
[43] Hydrogen Forecast to 2050 (dnv.com)

3.1.2 Hydrogen Projects Across the Globe

The Hydrogen Council's February 2021 Hydrogen Insights report[44] found that there were 228 announced hydrogen projects globally. These covered a vast range of purposes, such as giga-scale production, large-scale industrial usage, transport, hydrogen integration and hydrogen infrastructure. Over half of these projects were located in Europe, with many having a strong emphasis on wider hydrogen integration.

3.2 The contribution of floating wind to Celtic Sea hydrogen production

One of the central targets of the Celtic Sea FOW initiative is to have 4 GW of FOW installed in the region by 2035. How much of a contribution this will have towards the UK's total green hydrogen production (including the 2030 - 5 GW target) is unclear at present.

By 2030, there are ambitions to have up to 1 GW of green hydrogen capacity at RWE's Pembroke Net Zero Centre (PNZC), which includes the Pembroke Demonstration Zone. This in itself would have a sizable contribution to the UK's hydrogen ambitions over the next decade[45].

With 1 GW of green hydrogen production capacity set as a target for the PNZC alone, it is possible that the total green hydrogen production capacity of the Celtic Sea by 2035 will be multiple times greater.

3.3 The key markets for hydrogen in Cornwall and South Wales

There are many different aspects to the hydrogen supply chain, as shown in Figure 3.1.

In this section the key markets for hydrogen in Cornwall and South Wales are explored. These markets are broken down into categories that cover mobility (3.3.1), heating in buildings (3.3.2), heat and power for industry (3.3.3), and industry feedstock (3.3.4). For each covered area, examples of current or potential end uses of hydrogen that is produced from CFA FOW projects will be presented.

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[44] https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf

[45] Milford Haven: Energy Kingdom - Non-Funded Collaborator & Supporter Update Session

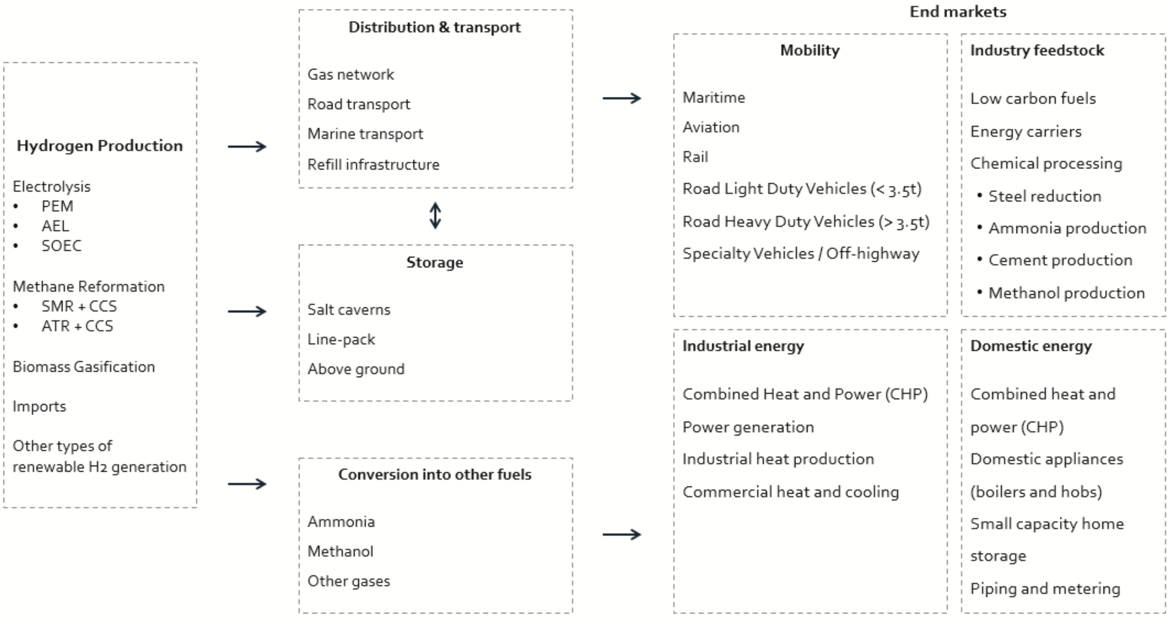

Figure 3.1: Hydrogen supply chain, ORE Catapult

3.3.1 Mobility

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. Having said that, it would be easier to transition some of these machines than others[46].

In their 2022 Electric Vehicle Outlook, Bloomberg New Energy Finance[47] presented an Economic Transition Scenario in which 1% or less of global passenger vehicles have a fuel cell drive train by 2040. This is fairly representative of the conversation around decarbonising road transport, with many commentators/analysts expecting battery electric vehicles to be the main route to lowering emissions. These made up 43% of the 2040 fleet in the Bloomberg analysis.

Although there is a general consensus that battery electric vehicles will be more important than hydrogen fuel cell alternatives, it is early days, with currently over 1.2 billion passenger vehicles in the global fleet today, and only around 1% of these have battery electric drive trains[48]. As the transition progresses, fuel cell drive trains may present a favourable alternative to battery options in a few scenarios. One is where there are battery materials shortages or recycling issues. Another is that extended range and shorter refuelling times 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 infrastructure/electrical networks than fast electric charging stations.

Hydrogen may be more attractive for long-haul and heavy-duty applications. Buses and long haulage transport are good examples of sectors where hydrogen could make inroads in the transport sector.

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[46] IEA. (2019). "The Future of Hydrogen, Report Prepared by the IEA for the G20, Japan." Seizing Today's Opportunities
[47] Electric Vehicle Outlook 2021. Retrieved from https://about.bnef.com/electric-vehicle-outlook/
[48] Electric Vehicle Outlook 2021. Retrieved from https://about.bnef.com/electric-vehicle-outlook/

In terms of hydrogen quantities for road vehicles, a study by Riversimple in the Milford Haven Energy Kingdom (MH:EK) project explored potential demand in Milford Haven. Including a range of vehicles, they estimate that short term demand could be 335 kg/day, mid-term demand could be 670 kg/day, and a mature market could present a long-term demand of up to 1,740 – 1,920 kg/day[49]. This work also investigated what a hydrogen based smart local energy system could look like for the local area, including the testing of Riversimple's hydrogen fuel cell electric car[50].

In Cornwall, there is an opportunity for specialist vehicles. Mining is an area of the economy that is expected to grow, with the region being a traditional base for China clay extraction alongside the more recent interest in the local lithium deposits. With the UK government planning on removing red diesel subsidies, this will open an opportunity for hydrogen-fuelled mining vehicles to become more competitive in the long-term. However, this is dependent on the rate at which hydrogen-fuelled mining vehicles are made available by manufacturers[51].

The maritime sector consumes around 5% of global oil demand, 80% of which is used in international shipping. Of this, 90% is used for maritime freight[46]. Hydrogen-based fuels, such as ammonia or methanol, could be used to tackle the carbon emissions from the international shipping industry and also some of the associated port activities.

As FOW projects are developed and eventually commissioned off the coasts of Cornwall and South Wales, maritime fleets will be required to carry out O&M activities. With decarbonisation of the wider offshore wind supply chain in mind, zero-emissions vessels could become a greater priority for the industry, with hydrogen powered vessels being one potential solution. With this comes the opportunity to develop onshore hydrogen fuelling systems that are able to decarbonise the wider maritime sector as well as port operations.

The aviation sector could use synthetic hydrogen-based liquid fuels without much changes to the design of aircrafts and the airport infrastructure[46]. This move towards hydrogen could begin with blending of hydrogen based liquid fuels with conventional jet fuel.

3.3.2 Heating in Buildings

Although the use of hydrogen fuelled boilers and combined heat and power (CHP) plants will be adopted far beyond Cornwall and Pembrokeshire, these technologies serve as a means to decarbonise heating in buildings, one of the hardest to tackle areas in reaching net zero. The proximity of Cornwall and Pembrokeshire to FOW sites in the Celtic Sea can make these optimal regions for deployment of hydrogen boilers and CHP.

Cost reductions will be heavily dependent on a combination of wider energy prices, infrastructure investment and regional/national policy[52]. Leading up to 2030, it is unlikely that significant deployment of hydrogen boilers will be achieved. However, Wales and West Utilities plan for Cornwall's gas

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

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

[51] https://www.regen.co.uk/wp-content/uploads/Cornwall-Council_Hydrogen-Opportunities-Study_Executive-Summary_Regen-1.pdf

[52] https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

infrastructure to be hydrogen ready by 2035 and for a consistent stream of hydrogen to be available by 2040[53].

3.3.3 Heat and Power for Industry

The following points are examples of heat and power requirements of industry.

- Medium Temperature Heating – Sectors which require medium temperature heat input include the production of fast moving consumer goods. Examples of these include food processing, brewing, distilling, and production of over-the-counter drugs such as aspirin. Green hydrogen may be applicable in decarbonising these processes in the future.

- High Temperature Heating – Decarbonising steel and cement production in South Wales is a key focus of the South Wales Industrial Cluster (SWIC). One of the most prominent SWIC project partners is Tata Steel, of whom have a steel production plant in Port Talbot which has a production capacity of around 5 million tonnes per annum[54]. With such a large production plant in South Wales, this serves as a primary use case for hydrogen-fuelled high temperature heating. This may play a role in decarbonising offshore wind supply chains, including steel production for wind turbine components.

- Flexible Power Generation – As renewable generation sources continue to provide a larger portion of our energy, fast responding generators and energy storage solutions will be required to combat the intermittent nature of solar and wind assets.

    - To ensure grid stability during times of fast fluctuating renewable generation, transmission system operators (TSO) such as National Grid will offer large-scale generators additional revenue streams for the provision of ancillary services such as frequency control, voltage control, reactive power supply and black-start capability. The deployment of large-scale hydrogen storage has the potential to provide such ancillary services to support transmission system stability in regions across Cornwall and South Wales.

    - Changes to UK grid regulations could support grid stability on distribution networks in Cornwall and South Wales. These changes could enhance the range of services that grid participants can provide to distribution networks. Overall, this could help with enabling relevant technologies, such as hydrogen energy storage, to maximise potential revenue streams while easing the transition to a more decentralised energy system with increasing amounts of embedded generation and storage[55].

- Backup and Remote Power Generation – The Smart Islands project on the Isles of Scilly is investigating the potential of smart grid enablement and the ways in which hydrogen can be integrated with wave, tidal and floating wind in the future. The main project partners, Waves4Power and Marine-i, aim to establish a new databank which will determine key

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[53] https://www.regen.co.uk/wp-content/uploads/Cornwall-Council_Hydrogen-Opportunities-Study_Executive-Summary_Regen-1.pdf

[54] https://www.tatasteeleurope.com/construction/sustainability/performance-at-our-sites/port-talbot

[55] Ancillary Services Market Design in Distribution Networks: Review and Identification of Barriers

decisions about marine renewable energy development on the islands[56]. Although this project is focused on island energy systems, findings regarding hydrogen integration should be built upon where applicable to energy systems in Cornwall and South Wales.

- Seasonal and Large-Scale Energy Storage – Once large enough streams of green hydrogen are developed there will be interest in using this for purposes of energy storage to balance the electrical network. Hydrogen storage in salt caverns has the potential to contain hundreds of GWhs[57], and porous rock media could store TWhs[58].

3.3.4 Industry Feedstock

This section gives some examples of where hydrogen can be used as an industrial feedstock.

- Oil Refining – Pembroke Refinery is a key area of focus in the drive to reduce emissions in oil refining operations. At present oil refining takes up a significant portion of global hydrogen consumption, with almost all hydrogen supply generated on site from fossil fuels with unabated emissions. Through significant FOW and electrolyser deployment, a consistent stream of green hydrogen can be established to reduce emissions in the production of products such as diesel and kerosene at the UK's refineries[59].

- Ammonia Production – Ammonia is prominently used in the production of fertilisers. At present, ammonia production accounts for around 2% of total global energy consumption and 1.3% of CO_2 emissions from energy systems[60]. The use of green hydrogen can play a role in decarbonising fertilisers used within the agricultural sectors in Cornwall and South Wales. Additionally, ammonia produced via green hydrogen can play a role in decarbonising maritime transport if ammonia combustion engines become a mainstream commercial product for vessels in the coming years. However, adequate bunkering infrastructure at ports will need to be in place before this becomes a feasible route towards maritime decarbonisation[61].

- Methanol Production – Methanol is most commonly used to synthesise chemicals such as formaldehyde, acetic acid, methyl methacrylate, ethylene and propylene. These chemicals can then be processed further to be used in paints, plastics and building materials[62]. Over time methanol has typically been produced using coal and natural gas. However, methanol production via green hydrogen has received significant attention in recent years. Methanol to hydrogen is achieved via dehydrogenation, with particular attention being required on the sourcing and management of CO_2 used during this process to remain carbon neutral. Like ammonia, methanol can be used to fuel low-carbon combustion engines on maritime vessels. Again, adequate bunkering infrastructure will need to be in place to make methanol a feasible low-carbon fuel for vessels.

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[56] https://www.regen.co.uk/wp-content/uploads/Cornwall-Council_Hydrogen-Opportunities-Study_Executive-Summary_Regen-1.pdf
[57] FileNewTemplate (energnet.eu)
[58] Microsoft Word - HyStorPor _ storage_briefing_FINAL.docx (ed.ac.uk)
[59] https://www.argusmedia.com/en/news/2304469-lowcarbon-hydrogen-gathers-pace-in-uk-refineries
[60] https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf
[61] Decarbonising Maritime Operations in North Sea Offshore Wind O&M
[62] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

- Iron and Steel Production: Hydrogen can be used to decarbonise iron (and steel) production by acting as a chemical agent that enables the direct reduction of iron ore (DRI). Today, 7% of steel is produced using this approach[46], with natural gas or coal as the original source of energy. There is potential for switch to using green hydrogen in this process.

4 SUPPLY CHAINS AND ECONOMIC OPPORTUNITY

4.1 The new UK economic opportunity from OSW-H_2

In the long-term, the transition to a green hydrogen economy offers significant economic opportunity for the UK, particularly in regions near substantial amounts of OSW. By 2050, this transition has the potential to create thousands of skilled jobs, billions in gross value added, and substantial UK-based intellectual property creation.

When focusing on shorter-term timescales, to 2030, maximising gross value added and export potential will not be as high a priority. Instead, the main focus will be on cost reduction which can be achieved through a combination of policy and market reforms which create clear investment signals.

Referring back to the British Energy Security Strategy[63], cost reduction of green hydrogen will be achieved via annual allocation rounds which aim to become price competitive by 2025 when legislation and market conditions allow. By 2025, it is planned to have business models in place that enable the expansion of hydrogen transport and storage infrastructure while finalising a hydrogen certification scheme that proves British hydrogen high-grade and fit for export. Such certification will also ensure that any hydrogen imports meet the same standards seen in domestic production.

When considering the years 2030 – 2040, export potential comes into greater focus, with the potential for the UK to be a net energy exporter. This will help to generate value and create jobs while improving European energy security.

4.2 Existing supply chain capabilities and long-term opportunities in the UK

The UK has numerous companies working in the development of the hydrogen economy. Areas of focus include the manufacture of fuel cells, electrolysis, and the distribution of hydrogen. Several of these companies are O&G multinationals branching out into hydrogen and providing industrial knowledge transfer. However, many small and medium companies based in the UK are playing a starring role in providing technological solutions to this industry set for rapid growth in the coming years. This section will cover UK companies involved in mobility, heating in buildings, industry feedstock, and production, transport and storage of hydrogen.

4.2.1 Mobility

For light-duty road transport, Riversimple and Microcab are the UK’s most prominent players in the manufacture of cars powered by hydrogen fuel cells, with both companies aiming to gain a foothold in the wider UK automotive market.

Riversimple are in the process of raising funds to build a new manufacturing plant in the UK[64]. With this comes the creation of around 220 jobs which will produce approximately 5,000 vehicles per annum. Furthermore, Riversimple have had a recent collaboration with the California Mobility Centre

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[63] https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy#hydrogen

[64] https://www.riversimple.com/wp-content/uploads/2022/05/CMC-Press-Release-220505-1.pdf

which aims to accelerate the commercialisation of the products and services of innovative transportation companies, and to help these companies gain a foothold in the California market. Riversimple sell their cars as a service and not a product, offering customers a monthly subscription that includes all motoring costs such as fuel, maintenance and insurance.

When focusing on heavy-duty road transport, Ballymena based hydrogen bus manufacturer Wrightbus have delivered hydrogen buses for use in London and Belfast. More recently, Wrightbus have agreed to build 60 buses for Cologne based operator Regionalverkehr Köln. This deal represents the first large-scale production of left-hand drives that Wrightbus will export to the European market[65].

For advancing the development of hydrogen trucks, DAF are currently developing a hydrogen combustion engine and won the 2022 European Truck Innovation Award for their DAF XF H2 model[66].

4.2.2 Heating in Buildings

As mentioned in 3.3.2, there is the potential for heating in buildings to be decarbonised using green hydrogen, but this will be dependent on wider energy prices, investment in infrastructure, and policy at a regional and national level.

Focusing on UK companies looking to achieved decarbonised heating in buildings via hydrogen, Worcester Bosch[67] and Baxi Heating[68] both showcased 100% hydrogen boilers at their respective demonstrations.

Despite demonstrations indicating progress towards more widespread use of hydrogen for domestic heating in the UK, it is hard to gauge the future export potential for UK companies involved in the manufacture of 100% hydrogen boilers. Much of this is down to the uncertainty of how many other European nation’s gas grids will be hydrogen ready by 2035 and beyond. According to the report *Ready4H2: Europe’s local hydrogen networks*, published in December 2021, only 24% of members said they would be “fully ready” for 100% hydrogen by 2035, and only 67% said they would be ready by 2040[69]. For greater context, Ready4H2 is a group of 90 European gas distributors campaigning for 100% hydrogen in their networks.

4.2.3 Industry Feedstock

As well as the Pembroke Refinery mentioned in Section 3.3.4, there are five other oil refineries in the UK, all of which are developing projects to reduce emissions in their refining processes. One of these refineries, Phillips 66's Humber refinery, plans to use green hydrogen via its wind-powered 100 MW Gigastack project in collaboration with Orsted[70]. Opportunities remain for all refineries to be supplied with green hydrogen in the future. Despite UK refinery output having decreased by around a third since 2003 (from 1.81 to 1.25 million barrels per day)[71], the portion of current hydrogen demand that

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[65] https://wrightbus.com/en-gb/Wrightbus-secures-first-major-European-order-in-Bamford-era

[66] https://www.daf.co.uk/en-gb/trucks/alternative-fuels-and-drivelines/hydrogen

[67] https://www.worcester-bosch.co.uk/about/news/worcester-bosch-provide-hydrogen-boilers-for-uks-first-100-hydrogen-public-showcase

[68] https://www.baxiheating.co.uk/news/baxi-demonstrates-its-hydrogen-boiler-in-uks-first-hydrogen-house

[69] https://www.rechargenews.com/energy-transition/revealed-what-18-independent-studies-all-concluded-about-the-use-of-hydrogen-for-heating/2-1-1240962

[70] https://www.argusmedia.com/en/news/2304469-lowcarbon-hydrogen-gathers-pace-in-uk-refineries

[71] https://www.statista.com/statistics/332158/refinery-capacities-in-the-united-kingdom-uk/#:~:text=Refinery%20capacity%20of%20oil%20in,1.25%20million%20barrels%20per%20day.

is consumed by oil refineries justifies interest in using green hydrogen from both a decarbonisation and GVA perspective.

The conversion of hydrogen to ammonia and methanol also has great GVA potential, as outlined in the UK Hydrogen Strategy[72]. By 2050, it is estimated that demand for hydrogen based fuels (mostly in the form of ammonia) could reach 75 – 95 TWh for UK domestic and international shipping. This is a market which could reach £8 – £11 billion per annum by 2050. If the UK maintained its current market share of around 5%, this would result in GVA of £360 – £510 million per annum by the middle of the century, indicating a huge opportunity for relevant companies to invest further in decarbonising maritime operations.

4.2.4 Production, Transport and Storage

The UK has approximately 284,000 km of gas network infrastructure, with five of Britain's gas grid companies aiming to be ready to switch to a 20% hydrogen blend in their networks by the end of 2023 as part of the Gas Goes Green initiative. At present, the network is capable of this transition, with no requirement for households or businesses to replace their cookers, boilers, or heating systems[73]. This alone would create a huge increase of hydrogen demand in the UK, with annual UK natural gas demand sitting at 811 TWh in 2020[74].

It should be noted that 2020 gas demand was lower than usual due to the impact of the COVID-19 pandemic. Regardless, if 20% of gas demand is to be met by hydrogen, it presents an opportunity for UK companies involved in the production of electrolysers and fuel cells such as ITM Power, Ceres Power, and Johnson Matthey[75]. However, much of the initial hydrogen blended into the UK gas network would be a combination of grey and blue hydrogen, meaning this opportunity would be one to be taken in the long-term as greater quantities of hydrogen are blended into the network, end appliances become better suited to the consumption of hydrogen, and green hydrogen becomes the lowest cost fuel option.

4.2.5 Offshore wind infrastructure

There is a wide range of manufacturing expertise in South Wales, some of which is applicable for various wind turbine technologies. Thus, there is an opportunity for project developers to choose technologies that can be made locally, rather than systems that would need to be imported from overseas. This can be achieved through early conversations between South Wales manufacturers and project developers.

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[72] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf
[73] https://www.energynetworks.org/newsroom/britains-gas-grid-ready-to-deliver-hydrogen-across-the-country-from-2023-energy-networks-announce
[74] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1006628/DUKES_2021_Chapter_4_Natural_gas.pdf
[75] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

5 ENABLING ACTIONS TO UNLOCK THE GREEN HYDROGEN FUTURE

5.1 Reaching 10 GW of hydrogen production capacity

To drive costs of OSW-H_2 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 capacity by 2030[76]. The question is, how will this target be met? Robust planning will be needed to displace fossil fuels, e.g., moving the electrical grid to zero-carbon by 2035 and 95% renewable energy by 2030[77]. Supporting the production and use of hydrogen will help to drive down costs, and help to create business cases.

The advances for green hydrogen production and further development will contribute significantly to the UK economy. The energy vector is a potential new business opportunity for sectors like O&G and renewable companies. Additionally, other sectors will benefit from green hydrogen, including, electrical networks, airports, automotive industry, industrial hubs for hydrogen demand, and the renewable energy sources that will be used to drive the electrolysers to create green hydrogen as seen in Figure 5.1[78].

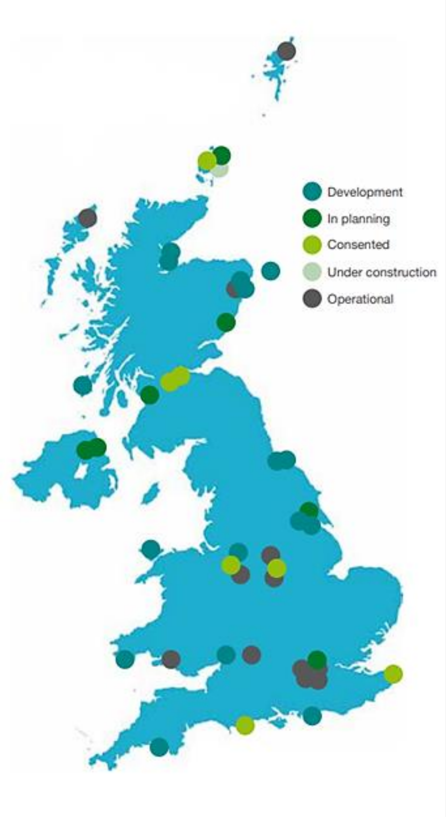

Figure 5.1 Map representing the green hydrogen project pipeline in the UK through projects.

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[76] British energy security strategy - GOV.UK (www.gov.uk)
[77] Green Hydrogen: Optimising Net Zero - RenewableUK
[78] Green Hydrogen: Optimising Net Zero - RenewableUK

5.2 Green hydrogen standards and progress to date

In the UK, the Government has established a Low Carbon Hydrogen Standard (LCHS). This defines the conditions by which hydrogen will be considered low carbon, namely that associated emissions are less than 20 g-CO_2 / mega-Joule by lower heating value (MJ-LHV)[79]. Although this removes ambiguity in some senses (such as the difference between the colours of hydrogen), the down side of this approach is that it doesn't recognise the difference between hydrogen which has associated emissions below this threshold e.g., 0 g-CO_2 and 20 g-CO_2 per MJ-LHV are seen as equally low carbon.

Other national and international standards are being developed by a range of organisations. To give just two more examples:

- Certifhy[80], the first EU-wide Guarantee of Origin scheme for green and low carbon hydrogen. This considers both the original energy source/production route of the hydrogen and its greenhouse gas intensity in reference to a benchmark, namely the greenhouse gas intensity of producing hydrogen from natural gas. Specifically, they require a 60% reduction from 91 g-CO_2 equivalent per MJ i.e., 36.4 g-CO_2 equivalent per MJ. They appear to use the lower heating value of hydrogen[81]. They consider biomass/biogas a potential source of green hydrogen, provided the emissions requirement is met.

- The Green Hydrogen Organisation[82]. Their standard covers the production route and emissions as well as other factors.

  - In terms of production route and emissions, they define green hydrogen as that produced through electrolysis of water with 100% renewable or near 100% renewable energy with close to zero greenhouse gas emissions, specifically less than 1 kg of CO_2 equivalent per kg-H_2 annually. (This gives flexibility for backup systems.) This equates to 8.3 g-CO_2 equivalent per MJ-LHV and 7.0 g-CO_2 equivalent per MJ-HHV.

  - The standard also requires environmental, social and governance consequences of green hydrogen production to be addressed and that development opportunities and impacts of green hydrogen production are considered. This includes complying with/promoting international human rights standards and engaging with stakeholders and communities.

Even within the three standards mentioned here, there is significant differences in approach e.g., which categories to consider (green, low carbon, or both), and how to define these – in terms of emissions alone (in which case, what should the threshold be?), or to also consider production routes and additional factors (e.g., social, environmental)?

For national projects, it may be easiest to work within the national framework. For international projects, early discussion on which standard to adopt will help to establish expectations for all parties.

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[79] Green Hydrogen: Optimising Net Zero - RenewableUK
[80] CertifHy_Leaflet_final-compressed.pdf (waterstofnet.eu)
[81] 280120_Final_Report_CertifHy_publishing approved_publishing (ID 7924419) (ID 7929219).pdf (europa.eu)
[82] The GH2 Green Hydrogen Standard | Green Hydrogen Organisation

5.3 Connecting electrolysers to the grid

One promising approach for connecting electrolysers to the grid is to take a similar strategy to that used by grid-connected scale battery storage. This could involve updating current and future grid connection requirements and standards to reflect arrangements that enable electrolysers to provide balancing services to the system operator. This could help to support early hydrogen growth, reduce costs and, if coupled with storage and a fuel cell (or similar), will allow hydrogen to act as an energy store which can support the grid. This may help to improve the business case of green hydrogen production.

Another possibility with a grid connected electrolyser is to take advantage of low electricity prices (e.g., on a windy night).

Similar to past issues with grid-scale batteries, there might be an issue of double charging, where an energy storage system is charged for both importing energy from the grid (like conventional consumers) and exporting energy onto the grid (like conventional generators). This has implications for the economics of green hydrogen.

5.4 Challenges and solutions for stimulating green hydrogen production

One of the challenges with developing the green hydrogen sector is around allocating risks in an acceptable way. Upfront discussions about the types and allocation of risk can help.

Another challenge, for production projects, is to find a suitable demand to offload to. 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/country. However, some problems like long lead times may point to broader challenges faced by manufacturing as a whole.

Regulatory issues are another broad theme of challenges, with innovative projects looking to push on with activities that aren’t covered by current regulations. This puts pressure on the regulators to safely enable/regulate these activities. Government steer/influence can help to increase the rate of change.

Other solutions to stimulating green hydrogen production include: developing strategic locations for hydrogen refuelling infrastructure and fuel cell technology cross-over; developing maritime demonstration projects to boost sector confidence; and normalising the use of hydrogen e.g., through “purpose-built” regulations. Electrolysis projects across the UK require clear guidance to accelerate their deployment through an easier and faster national permitting procedure, including for using grid power in electrolysers.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Green hydrogen is part of a much larger energy transition using offshore wind

OSW and H_2 are a central focus of the UK Government's decarbonisation strategies. They have the potential to be pillars of the UK's energy future; together, they offer the foundations of a renewable and dispatchable "forever" (sustainable) energy system that can decarbonise even hard-to-abate sectors. Publications from the UK Government, including the Ten Point Plan and the British Energy Security Strategy, are helping to advance these technologies and deliver on this vision.

OSW powered green hydrogen production is possible from electrolysers in either offshore or strategic onshore locations. As hydrogen markets develop, they are likely to affect socioeconomics, environmental considerations, and geopolitics.

Green hydrogen is becoming increasingly attractive due to falling costs. When produced from offshore wind, current projections see potential for costs to fall to £1.50 – 3/kg over the coming decades[83] [84]. In contrast, today's high gas prices are pushing up the cost of blue hydrogen. The rate of OSW-H_2 cost reduction depends on how fast the electrolyser market grows, and this may be accelerated by the 2030 ambitions. Regions with good renewable energy resources, like the Celtic Sea, 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. This action should include R&D programmes, and a OSW-H_2 roadmap. This could lead to acceleration of the electrolysis market thus leading to a cost reduction for green hydrogen.

Although challenges exist in delivering the transition, the expected positive outcomes outweigh the initial risk. The UK's industrial, chemical and electrical engineering heritage can assist in achieving the transition. The UK electrolyser companies ITM Power[85], Clean Power Hydrogen[86] and Supercritical Solutions[87] are part of a broader sector which is advancing innovative technology and reduce risks.

The rate of hydrogen deployment may be affected by international cooperation. Other countries have their own research organisations and companies, and so there may be benefits from such cooperation.

As the offshore renewable energy sector grows significantly, additional research needs to be undertaken on the less discussed benefits of large-scale renewable energy generation. One such area is low-cost electricity, which we may expect to see when there is lots of generation and low demand. This kind of problem is relevant to regions across the UK, including the Celtic Sea, which have large offshore wind potential but limited electrical networks/demand.

As integrating offshore wind with hydrogen is a new field, one recommended piece of work is to monitor the actual cost of offshore wind to hydrogen projects against projections. More generally, we

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[83] Green hydrogen economy - predicted development of tomorrow: PwC
[84] Costs challenge the hydrogen transformation | E&T Magazine (theiet.org)
[85] ITM Power | Energy Storage | Clean Fuel (itm-power.com)
[86] Home | CPH2
[87] Supercritical | Developing the world's most efficient electrolyser | England

recommend supporting the development of hydrogen standards and projects, including around the Celtic Sea.

The key recommendation is to initiate a Celtic Sea FOW-H_2 future. ORE Catapult can champion offshore wind to hydrogen activity in both the Celtic Sea and the wider of the 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 a engineering system perspective?
    - The characteristics of pipelines compared to cables
    - Testing and demonstration at out 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 effect 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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