

Enabling the UK to become the Saudi Arabia of Wind?

The cost of green hydrogen from offshore wind



An Energy Futures Lab Briefing Paper

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Executive Summary

The United Kingdom has made rapid progress in decarbonising its power sector. However, decarbonising the entire UK economy poses far greater challenges and demands beyond just the production of clean electricity. Progress in reducing emissions from heating, transport and industry has been slower, and these sectors will pose significant challenges to meeting the UK's legally binding target of net zero by 2050.

A major pillar of the UK's energy transition pathway is to invest substantially in offshore wind. The rhetoric of the UK aiming to become *"the Saudi Arabia of wind"* is backed up by ambitious targets for offshore wind deployment over the coming decades, but managing the system implications of the variability of wind energy could pose a major roadblock.

Hydrogen offers a potential solution to balancing variable wind energy production with electricity demand, allowing low-carbon electricity to decarbonise other sectors of the economy. Flexible green hydrogen production could provide an efficient and effective solution to the challenges of wind generation exceeding national electricity demand. Hydrogen could be used to store surplus electricity generation and be converted back to electricity later when wind is in short supply. It can be used as both a feedstock and energy source in industry and provides potential low-carbon solutions for domestic heating and heavy-duty transport.

This briefing paper explores the potential for producing green hydrogen from wind energy in the UK. It uses geospatial modelling to map the potential production cost of green hydrogen across the UK and its territorial waters. The key conclusions underscore the potential benefits of pairing offshore wind with hydrogen production.

The UK's ample wind resources have the potential to produce hundreds of millions of tonnes of hydrogen per year – sufficient to more than meet the current global demand for hydrogen. The cost of production is below £3 per kg, which is only marginally higher than the cost of production from natural gas before the 2022 energy price crisis.

Pairing the UK's offshore wind resources with green hydrogen production is a promising strategy, which offers a flexible path that could contribute towards achieving decarbonisation goals, and could potentially establish the UK as a key supplier in the global energy market. The UK benefits from some of the world's best wind resources, so wind-powered hydrogen provides an opportunity for the UK to once again become an energy exporter, as the North Sea oil and gas reserves reach their end of life.

Introduction

The UK Government showed its commitment to the low-carbon energy transition when it led the world in passing the Climate Change Act into law in 2008. This was the world's first legally binding target to reduce greenhouse gas (GHG) levels, targeting a reduction of at least 80% on 1990 levels by 2050, and in 2019 the Act was amended to a 100% reduction by 2050 (Carver & Walker, 2023). This included committing to a series of five-year carbon budgets, which replaced the older and less ambitious Kyoto Protocol targets (Rahil et al., 2018) and act as stepping stones to the 2050 target. These carbon budgets are supported by independent, science-based advice from the UK's Climate Change Committee (CCC), and they become increasingly stringent over time. The Fifth Carbon Budget committed the UK to a 57% reduction in carbon dioxide emissions by 2035 (compared to a 1990 baseline), with the electricity sector taking on a stronger 72% target (Committee on Climate Change, 2015).

These targets have focused initial decarbonisation efforts on electricity supply. This approach has been highly successful, with the UK's carbon emissions falling by 28% from 482 million tonnes in 2010 to 331.5 million tonnes in 2022 (Department of Energy Security and Net Zero, 2023). The power sector has made strong progress so far, as it was among the easiest sectors to decarbonise. The 'quick wins' of coal phase-out and growing the share of renewables have largely been achieved already (Green & Staffell, 2021). Offshore wind has been a particular strength, with the UK taking an early lead in the industry and developing the world's second-highest installed capacity (behind only China), see Figure 1.

In December 2020, the then Prime Minister outlined the government's ten-point plan for a green industrial revolution, expressing an ambition *"to turn the UK into the Saudi Arabia of wind power generation, enough wind power by 2030 to supply every single one of our homes with electricity"* (Rao & Whiteside, 2021). The reference to Saudi Arabia, one of the world's largest oil producers for many decades, hints at the significant role the UK's energy ambitions hoped to play in the global economy.

Considering the UK's wind energy development plan and net zero targets, it is evident that wind energy will play a significant role in the decarbonisation of the power system and other energy sectors. Noting the enormous offshore wind potential across the UK's waters, it is important to discuss how to effectively maximise this renewable energy potential. The direct replacement of gas consumption in buildings, industries, and other sectors with hydrogen has become a hotly contested, even controversial, subject. A key factor which influences the relevancy of hydrogen as a decarbonisation technology to these sectors will be its cost and safety relative to other decarbonisation options. Rather than pick sides in this polarised debate, this briefing paper explores the cost of green hydrogen production from offshore wind energy. It aims to contribute to the debate on the future role of green hydrogen in the UK by presenting more robust evidence on the cost of its production from offshore wind.

The Context of Net Zero

“Net zero emissions” refers to the target of achieving a balance between the amount of greenhouse gases emitted into the atmosphere and the amount removed from it, with no net increase in the atmosphere. Net zero can be achieved by reducing greenhouse gas emissions to as close to zero as possible and offsetting any remaining emissions through measures such as direct air capture, planting trees, or burning biomass with carbon capture and storage (BECCS) (BBC News, 2023; The Royal Society, 2018). Achieving net zero does not necessarily mean eliminating all emissions of greenhouse gases completely; some emissions (such as from hard-to-decarbonise sectors like heavy industry) may still occur. However, these must be balanced out by the active removal of greenhouse gases from the atmosphere.

To achieve net zero in the UK by 2050, the significant progress in power system decarbonisation must be replicated in other sectors. Two of the most important and debated sectors for decarbonisation are the heat and transport sectors. Heat is difficult to decarbonise for several reasons: the dominance of natural gas in home heating, the highly variable demand at daily and seasonal scales, the highly distributed nature of demand (spread across tens of millions of buildings), and the sheer scale of heat demand in temperate regions compared with other energy demands (Staffell & Pfenniger, 2018). Similarly, transport is difficult to decarbonise because demand is closely linked to population and economic growth, the sector is largely dependent on fossil fuels, the high cost of electric vehicles, the limited range of EVs, and inadequate infrastructural investment in EV charging stations (Brand, 2021; Office of National Statistics, 2023). These sectors are expected to decarbonise at a third of the rate of power generation and represent more than half of the UK’s total CO₂ emissions in 2022 (Department of Energy Security and Net Zero, 2023).

While wind energy and solar PV have played a significant role in power system decarbonisation in the UK, this impact cannot be replicated in the heating and transportation sectors for three reasons.

One of the main issues is the intermittency of solar and wind electricity generation, which means it cannot be relied upon without some form of backup or sufficient storage. Solar PV production varies strongly along both the day-night and seasonal cycles. While output is higher during the daytime (when demand is higher than overnight), it is close to zero when it is needed most, during the times of peak electricity demand (winter evenings from 5-6 PM). At present, when wind output is low, the UK can fall back to fossil fuels to make up for the shortfall in electricity supply. Homes stay warm, and cars keep moving. If all sectors were to run on variable renewables, either the country needs to curb energy usage during shortfalls (unlikely to be popular with consumers), accept continued use of fossil fuels across all sectors (incompatible with climate targets), or develop a large source of flexibility such as energy storage (likely to be prohibitively expensive at present).

Second, there are issues around the high peaks in heating demand during winter, with all-electric heating very expensive to serve (as the generators built to serve that load are only needed for a few days a year). Converting all the UK’s vehicles to EVs would increase total electricity demand from 279 TWh to 395 TWh (Whalen, 2022). Switching all homes across the country to heat pumps would increase demand by a further 30% to 506 TWh. This implies that the full electrification of the heating and transport sectors would increase the annual power needs in the country by 81% (Whalen, 2022). This will require the expansion of the electricity system (transmission capacity, distribution grids, transformers, substations, etc.), which would pose serious

The Context of Net Zero

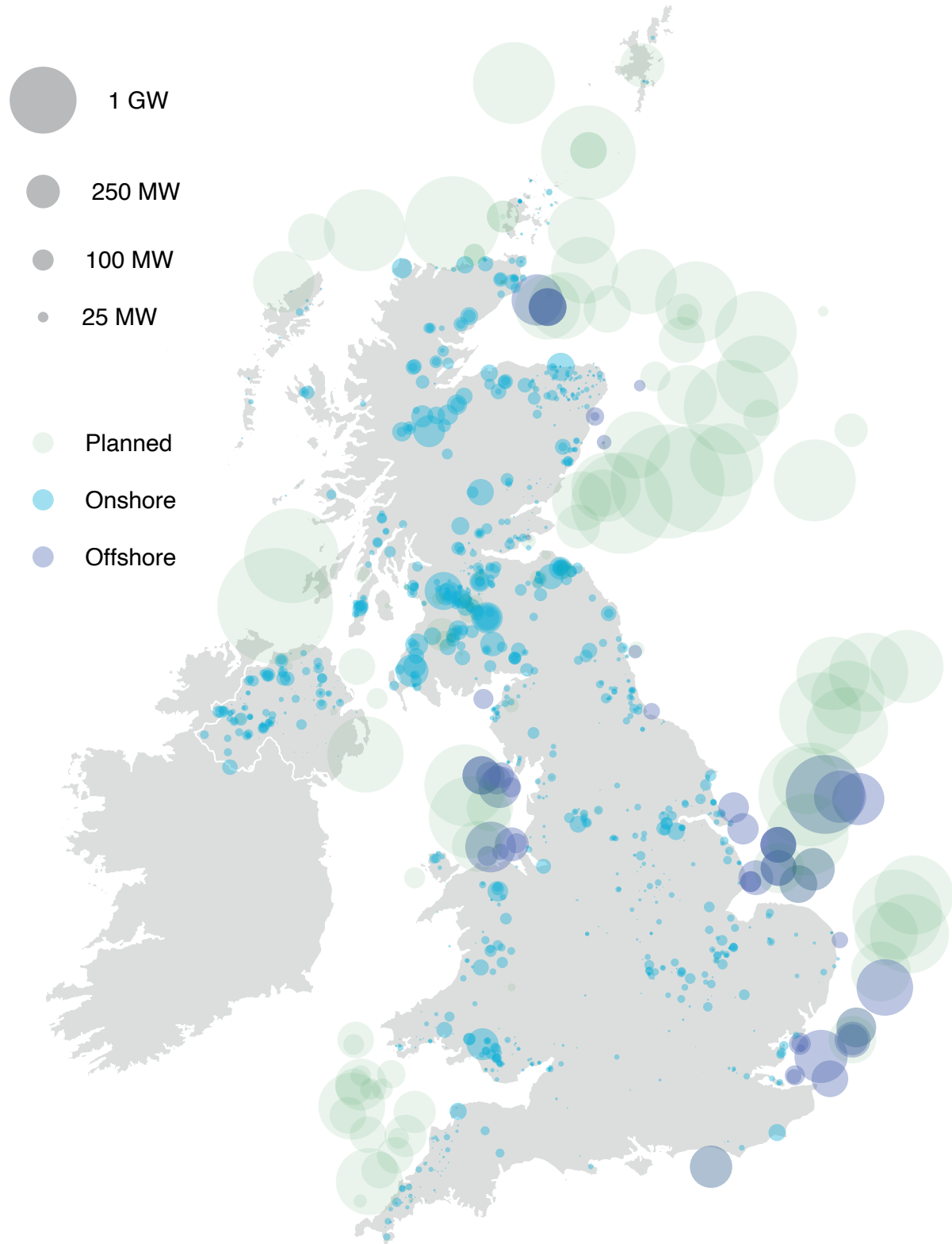


Figure 1 Map of the UK’s wind farms as of July 2023. Data from (Pierrot, 2023).

social, economic and technical challenges. Various paths, policies and technologies for the decarbonisation of heating, transport, and industrial emissions must be considered in order for the UK to meet its zero-emission targets (Staffell & Pfenninger, 2018).

Third, electrifying all forms of transport might prove difficult (e.g., long-distance heavy goods) or nigh impossible (e.g., aviation) due to the high energy density requirements, which current batteries cannot meet. Hydrogen has therefore been widely suggested as a low-carbon energy source for these sectors, benefiting from high energy density (by weight), ease of storage (relative to electricity) and its versatility to be used in many ways. Hydrogen is also one of the few technologies capable of providing very long-duration energy storage (e.g., moving energy between seasons), which is critical to supporting the decarbonisation of the whole energy system with high shares of renewables because it allows times of supply and demand mismatch to be managed over both short and long timescales. It is a clean alternative to fossil fuels (Staffell et al., 2019) as its use (e.g., combustion) does not emit any CO₂. The growth of green hydrogen technology has been held back by the high cost, lack of existing infrastructure, and its lower efficiency of conversion. Providing services with hydrogen requires two to three times more primary energy than direct use of electricity (Rosenow, 2022).

Offshore Wind

Offshore wind is one of the fastest-growing forms of renewable energy, with the UK taking a strong lead on the global stage (Costanzo et al., 2023; Taylor, 2023). Deploying wind turbines offshore typically leads to a higher electricity output per turbine, as there are typically higher wind speeds and fewer obstacles to obstruct wind flow (such as trees and buildings). The productivity of the UK's offshore wind farms is nearly 50% higher than that of onshore wind farms, as illustrated in Figure 2. Offshore wind generation also typically has higher social acceptability as it avoids land usage conflicts and has a lower visual impact (Iberdrola, 2023). To get the most out of this resource, very large structures (more than twice the height of Big Ben) must be connected to the ocean floor and operate in the harshest conditions for decades. Offshore wind turbines are taller and have larger rotor diameters than onshore wind turbines, which produces a more consistent and higher output (Green & Vasilakos, 2011).

The speed of deploying offshore wind energy has increased rapidly. New annual capacity additions have increased by almost 20% year-on-year between 2018 and 2022 (GWEC, 2023). China showed a particularly strong performance in 2021, adding 17 GW (IRENA, 2023b), hence newly installed offshore wind capacity slowed down in 2022 to just 9 GW. Offshore wind formed more than 10% of newly added wind capacity in 2022. This brings the cumulative installed wind capacity to 64 GW by the end of 2022, while overall wind farm capacity broke the 1 TW barrier globally in mid-2023 (Wood Mackenzie, 2023). Globally, offshore wind capacity is projected to grow fivefold between 2022 and 2030 to meet the net zero emission targets (Lee & Zhao, 2021) (Figure 3). Capacity is projected to grow to over 250 GW by 2030 (Abdelilah et al., 2022; DNV, 2022) and continue beyond, tapping into a vast potential of 120 TW (IEA, 2019a). The UK and its neighbours must therefore accelerate investment into more wind energy to mitigate climate change.

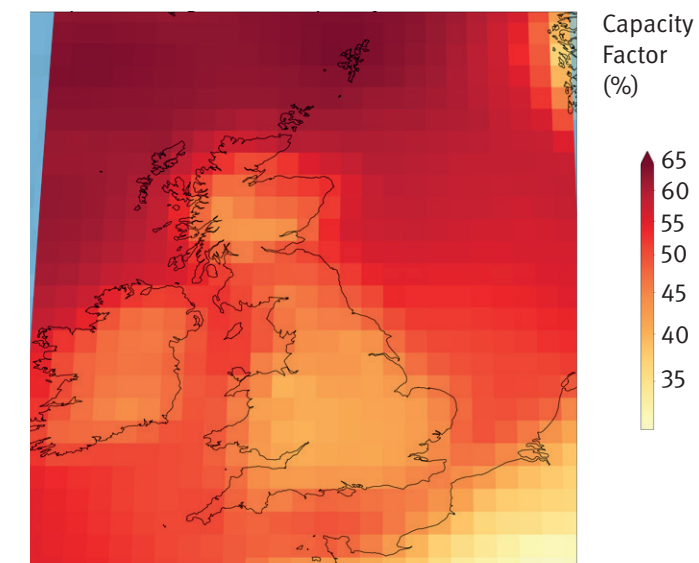


Figure 2 A heatmap presenting the average wind capacity factor across the UK in 2022, with data taken from NASA's MERRA-2 Dataset. Capacity factor measures the annual electricity output relative to the output that would be produced if the wind turbine ran at its full capacity all through the year.

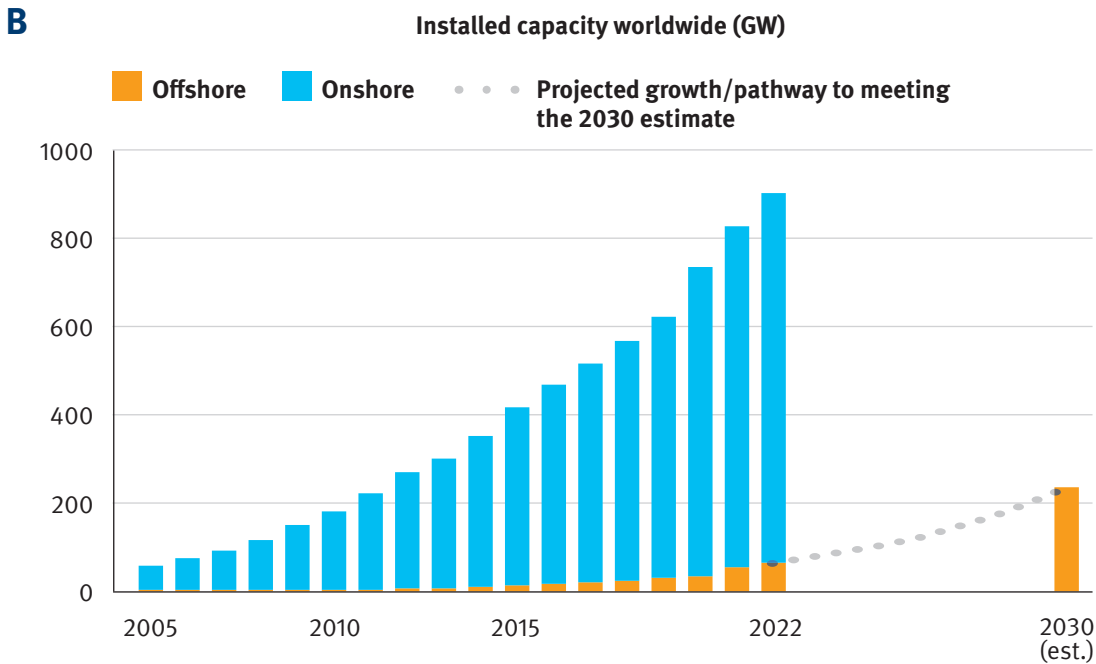
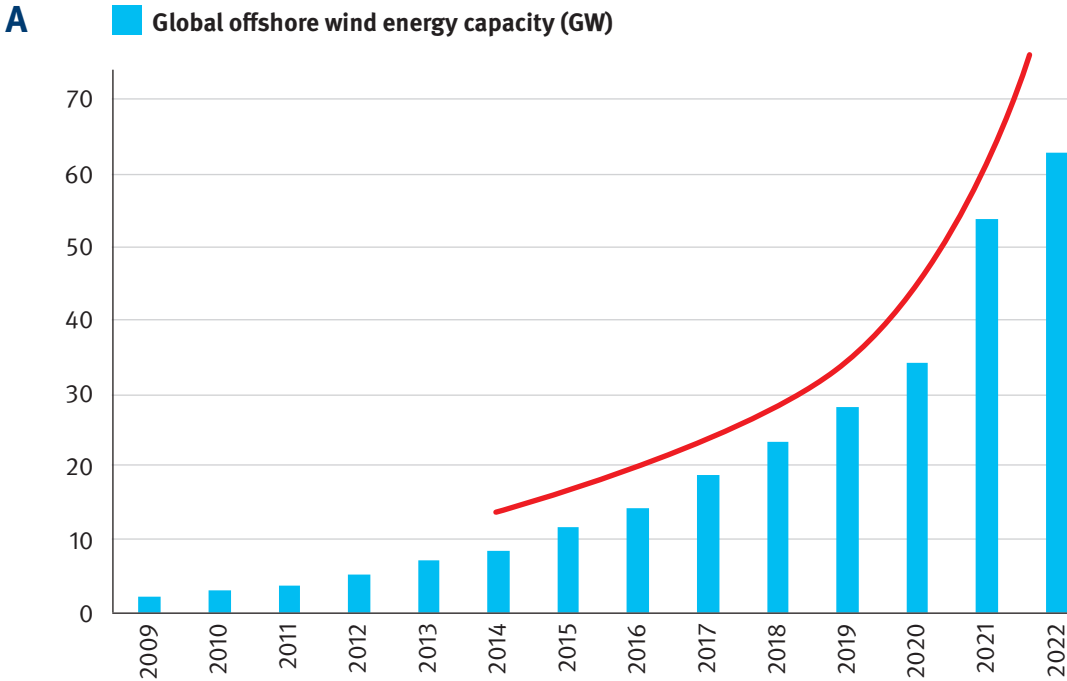


Figure 3 (a) global offshore wind energy capacity from 2009 to 2022 (IRENA, 2023b), (b) global offshore and onshore installed capacity from 2005 to 2022 and the 2030 target (GWEC, 2023; IRENA, 2023b).

Scale and Cost of Offshore Wind

The geographical distribution of offshore wind is heavily skewed towards Europe, which hosts over 80% of the total global offshore wind capacity (Wilson, 2020). This can be attributed to the good wind conditions and the shallow water depths of the North Sea. The UK is ideally located to take advantage of offshore wind due to its extensive resource. The UK could produce over 6000 TWh of electricity if the offshore wind resources in all the feasible area of the exclusive economic zone (EEZ) is exploited (Bosch et al., 2018).

The growth in the global market, policy support and bigger turbines allowed for UK cost reductions via learning-by-doing and economies of scale (Kota et al., 2015; Lecca et al., 2017; Thomas, 2017). ‘Learning-by-doing’ was coined by Arrow in 1962 (Arrow, 1962), who described the increase of cumulative economic output and production without

investment through experience gained by doing the process repeatedly. This effect has been observed across numerous products and industries (Deng et al., 2021; Niiranen, 2021; Sweerts et al., 2020).

The cost of UK offshore wind has fallen because of the reductions in capital expenditure (CapEx), operational expenditure (OpEx), and financing costs. This has been supported by the global roll-out of bigger offshore wind turbines, hence, causing an increase in offshore wind energy capacity. This increase in installed capacity has been fuelled by several low-carbon support schemes from the UK government (UK Government, 2021). The effect of these schemes can be seen in the UK 2017 Contracts for Difference (CfD) auctions where offshore wind reached strike prices as low as 57.50 £/MWh (BEIS, 2017) and an even lower strike price of 37.35 £/MWh in 2022 (Edwardes-Evans, 2023).

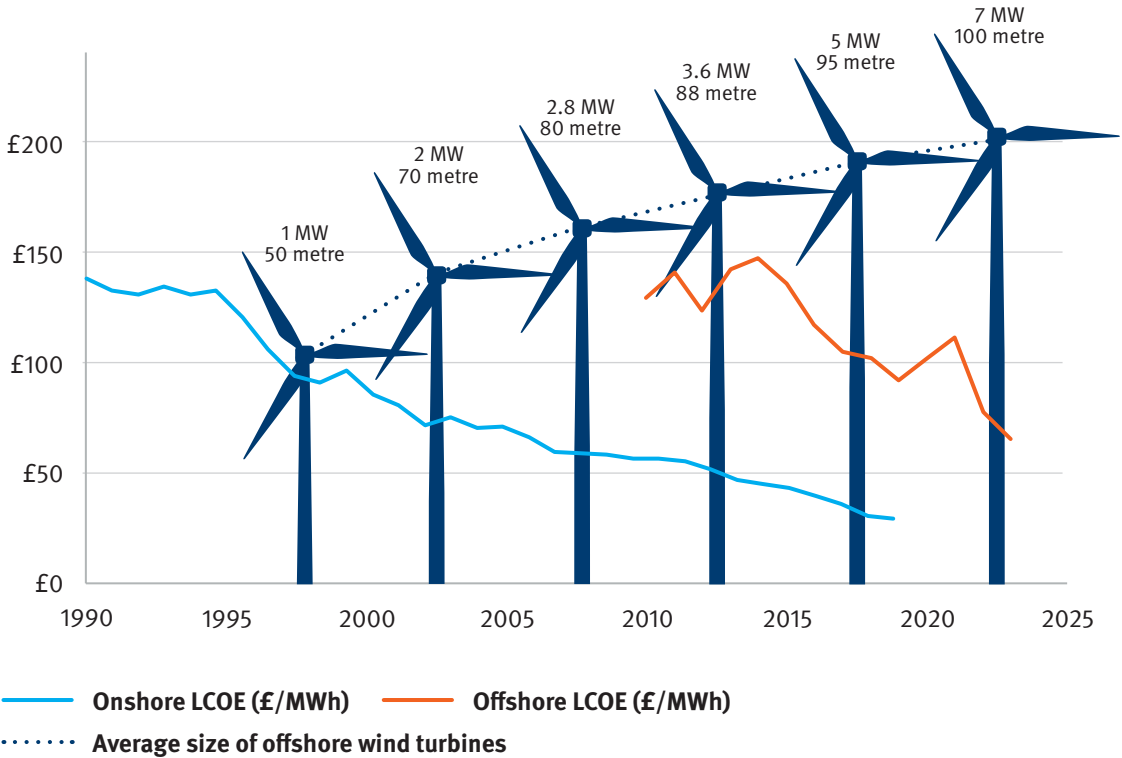


Figure 4 Reductions in the Levelised Cost of Electricity (LCOE) for onshore and offshore wind over the last three decades, set against the increasing turbine size used for UK wind farms. Data from (IRENA, 2023a; Pierrot, 2023).

The current cost of UK offshore wind is very low (with a CfD strike price as low as 45.37 £/MWh in 2023 (Electricity Settlements Company, 2023)). However, this has not always been the case. The cost of offshore wind has gone up in the last two years due to commodity prices and supply chains with the CapEx of offshore wind projects rising to almost £3.39m in 2022 (NREL, 2023). The market moved to increased turbine size, which combined with the supportive policy environment led to a dramatic drop in the Levelised Cost of Energy (Shields et al., 2021) (LCOE) seen in Figure 4. LCOE is the lifetime project costs split across the lifetime of energy production. The current cost of offshore wind is already relatively low, and the future can be cheaper, with offshore wind paying back to the consumers (Jansen et al., 2020).

The UK's Offshore Wind Targets

The offshore wind capacity in the UK has grown over the past decade. Currently, the UK has a total offshore wind capacity of 13.8GW (Department for Energy Security and Net Zero, 2022) (Figure 5), which is sufficient to power more than 10 million homes. This represents a more than fourfold increase compared to the capacity installed in 2012. The UK government has set ambitious targets for offshore wind development. In 2019, the target was to install a total of 40 GW of offshore wind capacity by 2030, and this was later raised to 50 GW (Jansen et al., 2022), with up to 5 GW of floating offshore wind. This will play a pivotal role in decarbonising the UK's power system by the government's deadline of 2035 (Davies, 2021).

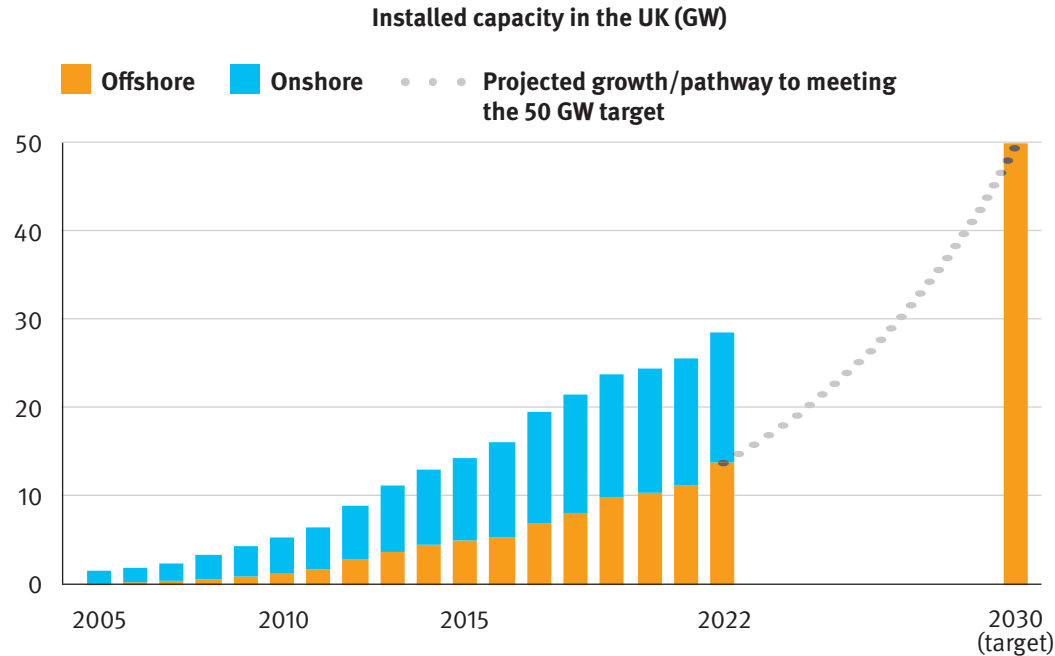


Figure 5 The growth of UK offshore and onshore installed capacity from 2005 to 2022, in comparison to the 2030 target. Data from (GWEC, 2023; IRENA, 2023b).

With the largest deployment of offshore wind in Europe, the UK has successfully demonstrated the feasibility of delivering offshore wind projects at an expanding scale, all while reducing costs. The UK plans to develop and deploy floating offshore wind technology. Currently, there are two operational floating offshore wind projects in the UK: Kincardine and Hywind Scotland with a capacity of 48 MW and 30 MW respectively. Hywind Scotland is the world's first floating offshore wind farm, and has achieved a capacity factor of 54% over its five years of operation, making it also the world's best performing offshore wind farm (Equinor, 2022). Crown Estate Scotland selected 17 offshore wind projects in its ScotWind seabed leasing round. These projects have proposals with a total capacity of 25 GW, and it aims to procure at least 10 GW (Buljan, 2022). It is noteworthy that 10 out of the 17 offshore projects are using floating wind technology. These projects and proposals have contributed to the overall offshore wind capacity, and they showcase continuity in the UK's commitment to advancing innovative offshore wind solutions. By fostering more innovation and supporting the development and deployment of advanced technologies, the UK can position itself as a global leader in offshore wind.

Challenges with Offshore Wind

Although offshore wind energy has become an important component of the global energy transition, the intermittent nature of the weather poses challenges to the consistent and reliable supply of power. The variability of wind speed and difficulty in forecasting it days ahead poses challenges to reliability, grid integration, and balancing of electricity supply and demand. This means that offshore wind systems do not always generate when electricity is most needed. To put into context, a period of low wind was recorded in the UK between the 26th of February and the 8th of March 2020. The national wind fleet capacity factor during this period did not exceed 20% and the average capacity factor was reported as 11% for this period (Drax, 2022). Specifically, the total wind farm output in the UK, on the 3rd of March 2021, was as low as 0.6 GW, and this is in sharp contrast to the 18.1 GW recorded later in the same month (Drax, 2022).

The major weather patterns that affect wind speeds are much larger than individual countries in Europe. If there are low wind speeds in the UK, it is likely they will be low in all neighbouring countries in northwest Europe (Grams et al., 2017). Hence, relying on neighbouring countries for electricity imports to make up for the shortfall when wind output drops is not a safe bet. Electricity production from wind energy and other intermittent renewable energy sources must therefore be complemented by some form of flexibility. The four main options for this are dispatchable power stations, energy storage, interconnection, and demand-side response (Yasuda et al., 2023). Fossil fuels currently provide the majority of the UK's flexibility, with more than twice as much gas power station capacity installed as interconnection and storage combined. However, the global decarbonisation drive means that countries cannot continue using this source of energy forever. Hence, there is a need for feasible and low-carbon alternatives to complement wind electricity.

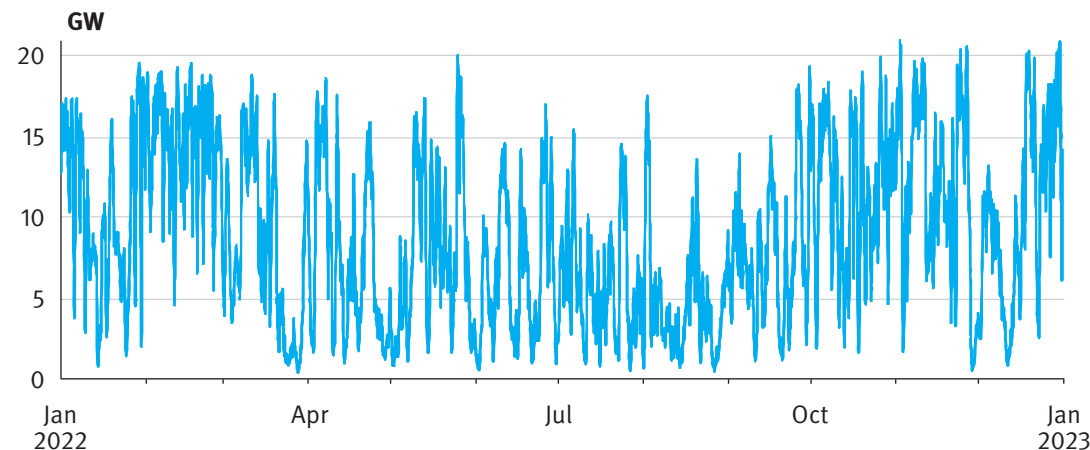


Figure 6 Hourly electricity production from wind farms in Great Britain over the course of 2022. Prolonged periods of high output are visible (e.g. during February) as are prolonged periods of low output (e.g. the end of March and early December). Data from (Drax, 2023).

The intermittency of wind power highlighted in Figure 6 can be addressed by pairing with energy storage systems such as batteries or pumped hydrogen storage. Surplus power generated during periods of high wind energy resources and low electricity demand can be stored and dispatched during periods of low supply and/or high demand, ensuring a more reliable electricity supply without a need for backup fossil fuel generators. In the UK's future decarbonised power system, electricity generation will be dominated by variable renewable electricity sources such as wind energy and so there will be demand for energy storage across a range of time and capacity scales. Whilst batteries are well placed to meet shorter-term, smaller-scale demand, storing electricity over long durations is not cost-effective (as the cost of storing an additional kWh of energy is very high). For example, lithium batteries typically offer 2 hours of storage, that is, discharging four batteries in sequence will consume eight hours of storage which is 4x more costly (and getting a month's storage can be as high as 360x the cost) (Schmidt & Staffell, 2023). Hence, there is a

clear need for MW-scale, long-duration energy storage in the future UK energy system; the production of hydrogen using water electrolysis is regarded by many as having strong potential to meet this role.

Hydrogen Production

Hydrogen is a key constituent of fossil fuel molecules, and the majority of their energy is contained within the bonds between the carbon and hydrogen atoms. In its pure form, it is a gas which can be burnt to release energy without any carbon emissions, and it currently serves as a key chemical feedstock for a variety of industrial processes. One of the most notable industrial uses is the role it plays in fertiliser production through the Haber-Bosch process, without which the world's agricultural system would struggle to adequately provide for the 8+ billion world population.

However, there are significant technical barriers to the widespread use of hydrogen. While hydrogen has a high energy density per unit mass, this is very low per unit volume, so it must be compressed or liquefied to be transported and stored economically and safely. Hydrogen can cause mechanical damage to metal pipes and containers if not treated correctly (hydrogen embrittlement) and when combined with air in small amounts it can form explosive mixtures which easily ignite, posing significant safety risks which must be accounted for in

its transport and storage. Critics also cite the relatively low efficiencies in the production and use of low-carbon hydrogen when compared to electrification technologies such as EVs and heat pumps (Rosenow, 2022).

Practically all current hydrogen production is from fossil fuels such as coal, oil and gas, accounting for over 99% of global hydrogen production in 2021 (Tracking Reports, 2022). These production pathways are a significant source of greenhouse emissions, accounting for over 900 Mt CO₂ in 2021 (nearly 1% of global emissions) (IEA, 2021). Even if the potential demand from emerging applications such as heating and transport is not accounted for, demand for hydrogen is unlikely to fall over the coming decades due to population growth and the industrialisation of countries such as China and India. Decarbonising existing hydrogen production, whilst exploring the potential for low-carbon hydrogen to support decarbonisation in other sectors and through other applications, will be important for the world to transition to net zero by 2050 or earlier.

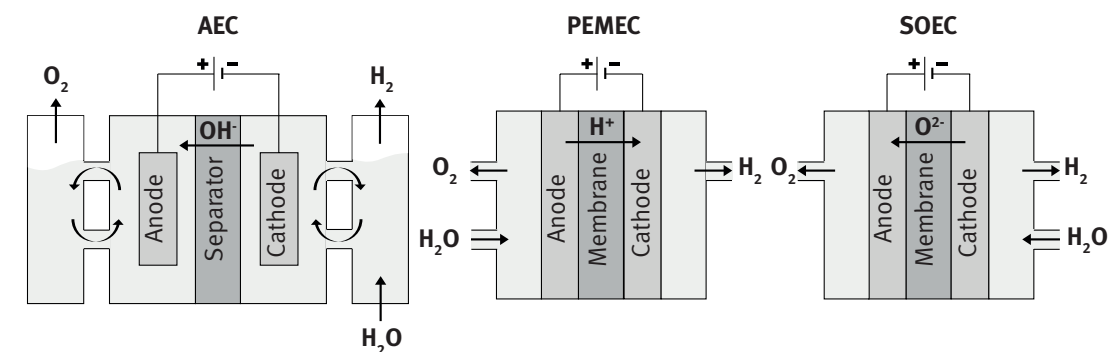


Figure 7 Schematic diagram showing the differences in operational set-up between the three electrolyser technologies (Schmidt et al., 2017)

Green Hydrogen Production

One of the most promising low-carbon production pathways is the electrolysis of water. Table 1 presents a comparison of existing electrolyser technologies, with a summary of the advantages, disadvantages and technological maturity of each technology. A schematic of the electrolyser technologies and their set-up is shown in Figure 7. All electrolysis technologies operate on the same principle, which involves passing an electrical current through water to

split its molecules into hydrogen and oxygen. When electrolysis is powered by renewable electricity sources such as wind or solar (“green hydrogen production”), the hydrogen produced has an operational carbon footprint close to zero. Green hydrogen could be used to decarbonise existing industrial hydrogen uses whilst facilitating the future decarbonisation of sectors such as domestic heating and road transport, which currently rely on fossil fuels as the energy source.

Table 1 Summary table of electrolyser technologies (Chatenet et al., 2022)

Technology	Maturity	Advantages	Disadvantages
Alkaline Electrolysis (AEL)	Mature – used since 1920	Low cost, high maturity, durable, high lifetime	Low flexibility
Polymer Electrolyte Membrane (PEMEL)	Commercial – partial deployment	High flexibility, short start up time, high hydrogen purity, high load not needed, high current density, millisecond-scale response time	High cost, complexity and non-standardised production reduces economies of scale
Solid Oxide Electrolysis Cell (SOEL)	Demonstration	High operating temperature, low material cost, high electrical efficiency, possible to use as a fuel cell or electrolyser	High cost due to immaturity, material degradation due to high operating temperatures

The UK’s Hydrogen Targets

The UK has a target of 10 GW of low-carbon hydrogen production to be deployed by 2030, as set out in the British Energy Security Strategy (2023). Within this target, there is an ambition for at least half of the 10 GW of production capacity to be met through green hydrogen production technologies (as opposed to hydrogen produced from steam methane reforming using carbon capture). Modelling conducted by the Committee on Climate Change in its Sixth Carbon Budget estimated that demand for low-carbon hydrogen across the whole country could reach 161–376 TWh annually by 2050, comparable in scale to the total electricity demand in the UK in 2022 (270 TWh) (Drax, 2022).

Global targets for electrolysis capacity deployment from national governments account for 140 – 150 GW by 2030, of which the UK’s target is the largest in Europe and the third largest in the world (IEA, 2022a) following India and Chile. It is also one of the few countries which has a specified target for low-carbon hydrogen production from fossil fuels using carbon capture and storage, which is up to 5 GW by 2030 with a pipeline of projects set to exceed this if Final Investment Decision (FID) is taken forward for all projects (George, 2022). With its ambitious targets relative to the rest of the world, the UK is seen as well-placed to develop a growing hydrogen economy over the next decade.

Pairing Hydrogen and Offshore Wind

Green hydrogen holds strong potential in addressing the intermittent nature of renewable generation sources, particularly wind and solar energy, which naturally fluctuate due to weather conditions. Offshore wind in particular is viewed as being a complementary technology to pair with green hydrogen production, due to three main factors: a) the high wind energy capacity factors offshore, b) the potential for large-scale deployment and c) hydrogen as a supporting technology for offshore wind energy integration.

The cost of green hydrogen is strongly influenced by the price of the electrolyser unit itself. If the electrolyser is run more intensively over the course of the lifetime of the plant, a larger volume of hydrogen will be produced and so the cost of the electrolyser will be spread out more, decreasing the cost per unit of produced hydrogen. If the variable renewable electricity source powering the electrolyser has a higher capacity factor, this will contribute towards a lower cost of hydrogen produced. Offshore wind in the UK typically has a higher capacity factor than onshore wind energy (up to 20%), and is around five times higher than solar, so pairing offshore wind with green hydrogen production is of interest.

Offshore wind farms can also be larger scale, due to increased availability of space and reduced restrictions on tip heights due to planning permissions. The average offshore wind turbine in the UK had a capacity of 3.6 MW in 2022, compared to just 2.5-3 MW for onshore turbines (National Grid, 2022). As there are fewer competing uses for space, offshore wind can not only have larger turbines but the wind farms can comprise many more turbines. Due to the specialist infrastructure requirements for hydrogen transport and storage, and the need for economies of scale to reduce the costs of production, pairing large-scale offshore wind

electricity generation with green hydrogen production could hold significant benefits.

Green hydrogen could also help address a key barrier to the UK’s energy transition, which is the current backlog for new connections to the grid, with developers having to wait 6-10 years to connect to regional distribution networks because of constraints on the grid (Financial Times, 2022). Hydrogen could be produced offshore and transported back to shore through pipelines or ships, bypassing the waiting time for new connections to the grid. It could also minimise the amount of curtailed wind electricity, where wind turbines are switched off when more power is being generated that can be transmitted through the grid. Green hydrogen could offer a way to store this surplus electricity generation avoiding wind energy from being wasted at these times, while simultaneously reducing the reliance of the grid on backup fossil fuel generation to ensure stability.

Hydrogen is a highly adaptable energy carrier with numerous potential applications and has been anticipated by some as playing a key role in the future energy system, especially when produced through electrolysis. It could support the full decarbonisation of “hard to decarbonise” processes within the UK industrial sector, offering a solution for areas which may be difficult to electrify or are heavily reliant on fossil fuels for high-temperature heat. When produced through electrolysis, it could be paired effectively as an energy storage technology with offshore wind, with the potential to store energy across seasons with little to no energy degradation and transport low-carbon energy internationally (Schmidt & Staffell, 2023). The UK – with its significant offshore wind energy resources and targets – could play a potentially leading role in producing green hydrogen to both help its pathway to net zero, and potentially create a valuable export industry.

The Cost of Offshore Wind Hydrogen in the UK

Cost will be a key factor that determines the extent to which hydrogen will be a part of the energy system, both cost relative to conventional fossil fuels and alternative zero-carbon technologies (such as electrification or biomass). In 2021, the cost of producing green hydrogen from electrolysis ranged from 3.2 - 7.2 GBP/kg, up to 9 times the cost of production from unabated natural gas, which ranged from 0.8 – 2 GBP/kg (International Energy Agency, 2022). The additional cost is due to the higher cost of electrolyzers and high electricity consumption of the electrolysis process compared to the mature technological processes used to reform fossil fuels into hydrogen. Technoeconomic modelling of green hydrogen production is important to advise the cheapest locations for renewable energy and on-site green hydrogen production to be located.

The typical measure used to compare the cost of hydrogen is the levelised cost of hydrogen (LCOH), which is the average cost per unit of hydrogen produced (Tracking Reports, 2022). This factors in all costs relating to hydrogen production over the system lifetime, and total production over that lifetime. The LCOH enables an easy comparison of the cost of building and operating a hydrogen production plant in different locations, accounting for different plant sizes, project financing and renewable energy potentials. This work conducted a levelised cost of hydrogen analysis for the UK offshore waters, to identify locations that would be of particular interest for green hydrogen production and benchmark the results against a) the cost of conventional production pathways and b) the extent to which green offshore hydrogen could meet current energy demands in different sectors.

An illustration of the techno-economic model that was developed for this work in Python is presented in Figure 8. It models an electrolyser that has been paired directly with the wind farm in an ‘islanded’ production configuration, where there is no connection to the grid to import electricity when the wind farm isn’t generating electricity. Importing grid electricity is possible and could reduce the cost of green hydrogen produced, but would not be ideal for far offshore wind farms which will be difficult and expensive to connect directly to the grid. It also introduces issues over the extent to which the hydrogen produced will be low-carbon, as if the grid electricity is imported at times of high fossil fuel generation the electricity will have a higher carbon intensity, which will be passed onto the hydrogen produced.

The main stages of the techno-economic model’s operation as follows:

1. All locations across the UK and its Exclusive Economic Zone (EEZ) are considered.
2. At each location, the model takes in an hourly profile for renewable electricity output from the deployed wind farm.
3. A dynamic model for electrolyser efficiency is used to calculate the amount of hydrogen that could be produced each hour, accounting for how the electrolyser efficiency varies with the power input.
4. The cost of the components is calculated, with the cost of offshore wind farms foundations and connection to the electrolyser dependent on water depth and distance to shore.
5. The capital and operating costs are combined in a discounted cash flow analysis with the hourly hydrogen produced to give the LCOH.

The technical configurations that are modelled in this work are:

1. For offshore wind, three types of foundation are considered (Fixed, Transitional and Floating), based on the water depth.
2. An alkaline electrolyser is considered, due to the maturity of the technology. The electrolyser stack capacity is optimised relative to the wind farm capacity to give the configuration of the minimum cost.
3. Three electrolyser configurations are considered a) onshore deployment, b) offshore deployment on a platform, and c) distributed electrolyser deployment in each individual wind turbine. For b) and c), offshore hydrogen pipelines are considered instead of electrical connections to transport hydrogen from the offshore electrolyzers to shore.
4. Water is desalinated on-site at the electrolyser, with an assumed cost of 1.6 GBP/ kg.

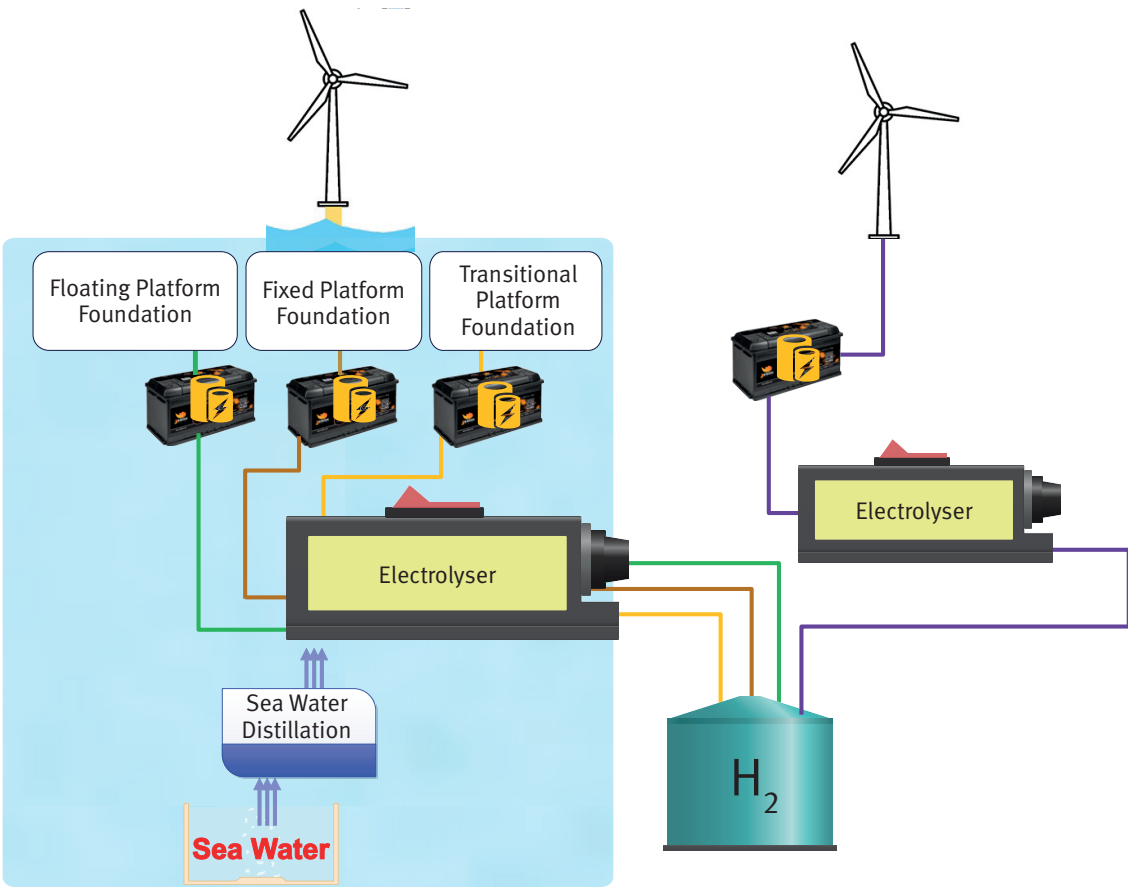


Figure 8 Schematic diagram and technical illustration of the offshore wind electrolysis for hydrogen production. As shown, three different wind platforms are considered in the technoeconomic model, and each scenario is connected to a battery storage system. The electrolyser and other component are offshore, and the produced hydrogen is transported onshore.

The total capital and operating costs are calculated for each location using relationships for the cost of wind turbine foundations with the depth and distance to shore and an assumption for the cost of the electrolyser (1200 USD/kW). Equation 1 shows the calculation of the LCOH, where $CAPEX_t$, $OPEX_t$ and $M_{H,t}$ represents the capital costs, operating costs and mass of hydrogen produced in year t and r represents the discount rate. The discount rate was taken as 3.8 and 2.6% for offshore and onshore respectively (IRENA Renewable Electricity Generation Costs 2021).

$$LCOH = \frac{\sum_t^N \frac{CAPEX_t}{(1+r)^t} + \frac{OPEX_t}{(1+r)^t}}{\sum_i^N \frac{m_{H,t}}{(1+r)^t}}$$

The size of the electrolyser relative to the wind farm is an important parameter to the cost of hydrogen produced as due to the intermittent nature of the weather, the wind farm will not be producing electricity at its rated capacity 24/7. An electrolyser that is the same size may likely be running idle for significant portions of its operational life, meaning that the system costs could be reduced by having a smaller unit without substantially reducing the amount of hydrogen produced. The techno-economic model that was developed optimises the size of the electrolyser unit relative to the renewable capacity (taken as 20 MW in this work) so to minimise the total LCOH. The configuration of the electrolyser (whether it is onshore, on an offshore platform or with small electrolyser sites 'in-turbine') was also selected to minimise the overall LCOH produced.

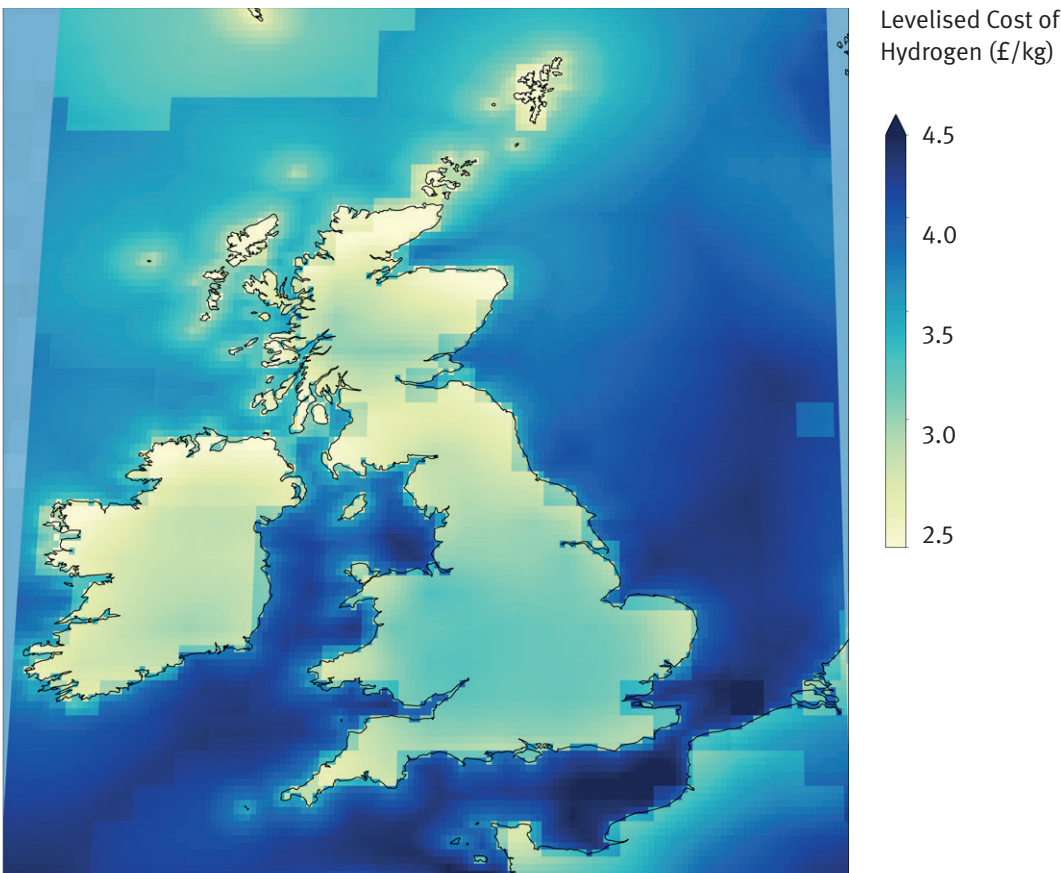


Figure 9 Heatmap showing how the levelised cost of hydrogen produced from co-located wind energy varies across the country.

A heatmap of the LCOH from solely wind-based production across the UK is shown in Figure 9. Onshore production of hydrogen is cheaper than offshore production, with an average cost of 3.06 GBP/kg compared to 3.82 GBP/kg, nearly 20% less. As shown in Figure 10a, this is due to substantially higher capital costs at offshore locations, driven by the cost of

grid connections/hydrogen pipelines and the offshore wind turbine foundations. Although at offshore locations there is a higher average capacity factor and so a higher annual hydrogen production, the positive impacts of the additional hydrogen production on the LCOH are outweighed by the impacts of higher capital costs at these locations. (Figure 10b).

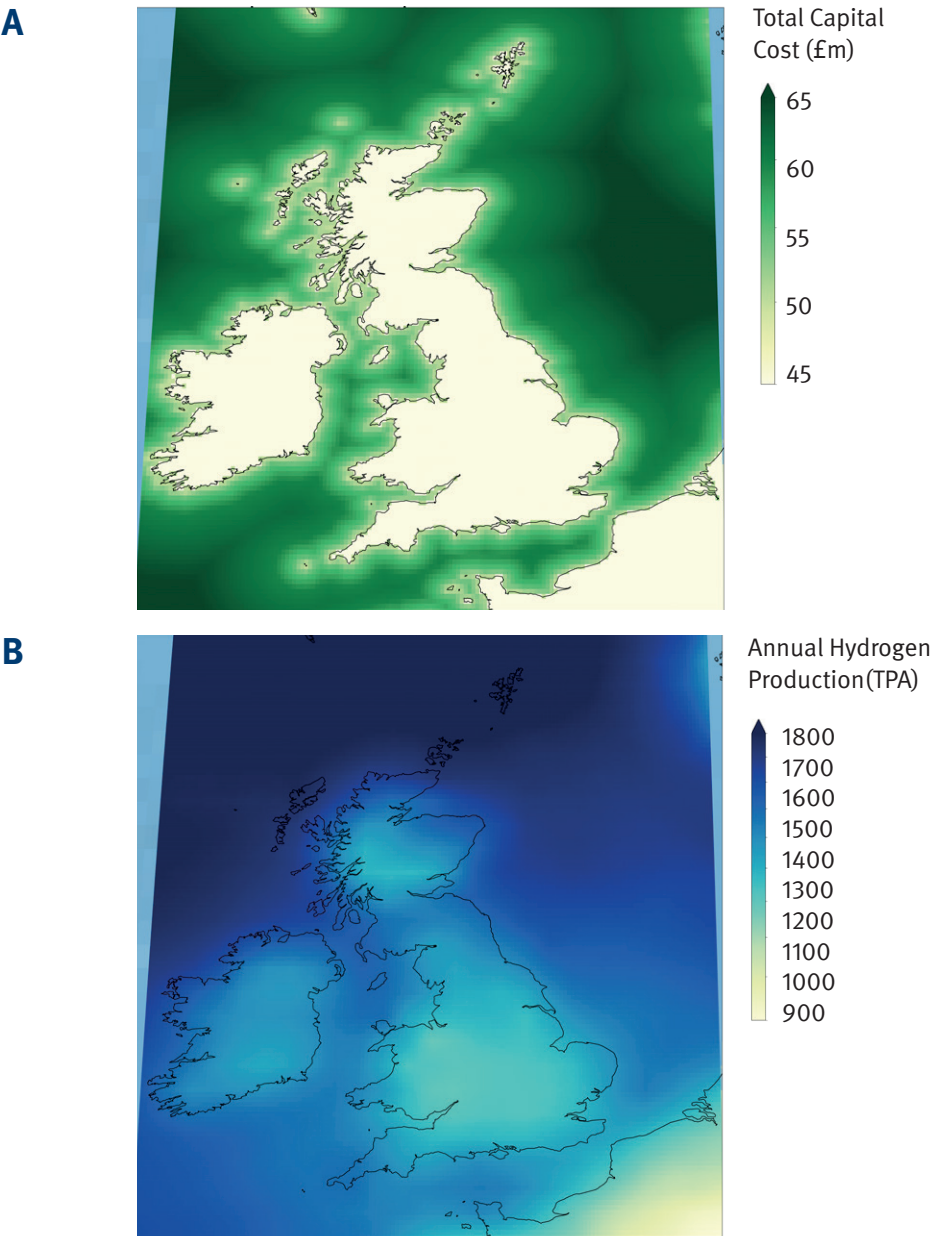


Figure 10 Heatmaps presenting a) the total capital expenditure for hydrogen production at each location across the UK, measured in £m and b) the average annual hydrogen production across the UK, measured in tonnes per 20 MW deployed wind farm.

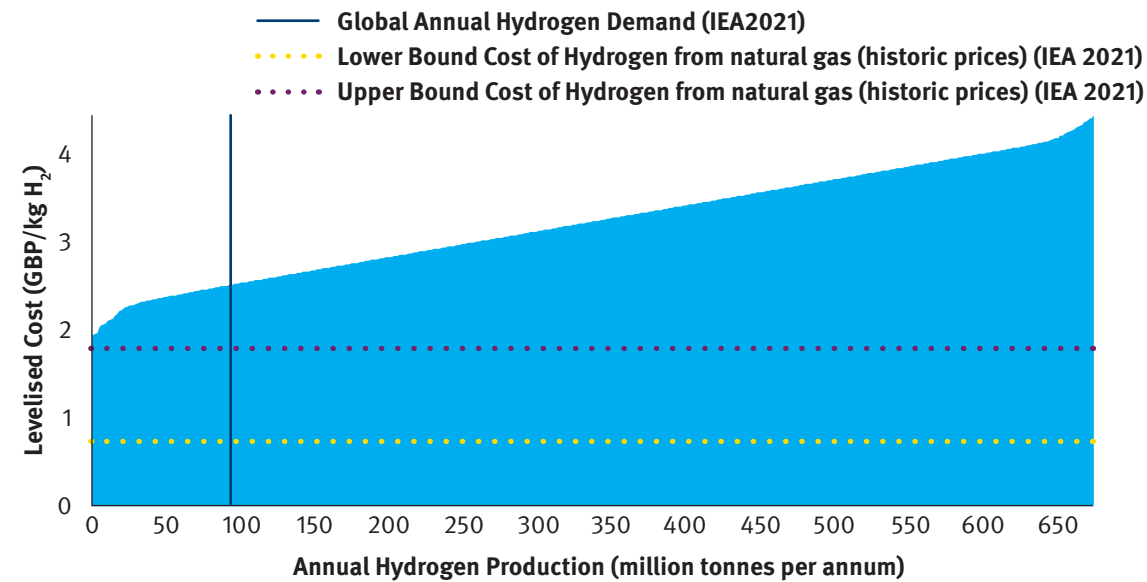


Figure 11 A supply cost curve for hydrogen production in the UK, detailing the relationship between the cumulative hydrogen produced and the marginal cost of hydrogen production for each supply volume.

The modelling also calculated the total technical potential of hydrogen production at each location, assuming that wind turbines could be placed at a density of 6.52 MW/km² (Bosch et al., 2017). These results were plotted on a supply-cost curve as shown in Figure 11, with the LCOH and annual hydrogen production plotted for each grid point and benchmarked against the range of production costs from natural gas-based steam reforming, taken from the IEA's Future of Hydrogen report (2021).

The cost was found to vary between 2.12 - 4.86 GBP/kg*, with an average cost at offshore locations of 3.83 GBP/kg. No locations could compete on cost compared to production pathways from natural gas (prices taken from 2021 and ranging between 0.8-2.0 GBP/kg) (IEA, 2022b), with the cost to meet the world's annual hydrogen demand in 2021 at a marginal cost of 3.0 GBP/kg. This represents an effective 'green premium' of over 100% when compared to the cost of producing hydrogen from natural gas in 2021. Russia's invasion of Ukraine in 2022 pushed gas prices to an all time high, which at prices in June 2022 in gas markets in Europe would push hydrogen production costs

from unabated natural gas to 3.84 - 6.24 GBP/kg, nearly three times the levels in 2021. Green hydrogen production from offshore wind would be cost competitive at these prices, but it is currently unclear how long this price situation will prevail. If gas prices fall again, the cost competitiveness of green hydrogen production will be reduced.

Over 10m tonnes of hydrogen per annum would be required to meet the current UK industrial energy demand (254 TWh per year) (BEIS, 2021a), which could be delivered at a marginal cost of 2.52 GBP/kg and would require 121 GW of wind energy capacity. However, this would still be 25% higher than the upper cost of hydrogen production from natural gas before Russia's invasion of Ukraine (2.0 GBP/kg*). If the current gas price high does not continue, government support is clearly required to improve the competitiveness of green hydrogen and accelerate its uptake in end-use sectors whilst electrolyser and renewable costs fall over the next few decades and enable true cost competitiveness with fossil fuel production routes.

* Converted using a 1.25 USD:GBP exchange rate.

Outlook for the Future

Currently, green hydrogen production using water electrolysis accounts for less than 0.1% of global dedicated hydrogen production (IEA, 2019b), though many net zero scenarios see this rapidly expanding over the next few decades to play a critical role in the energy system. For example, the IEA's Net Zero by 2050 Scenario sees global hydrogen demand increasing almost sixfold from around 90 million tonnes in 2020 to 530 million tonnes in 2050, of which 60% will be met by green hydrogen. The global supply chain for electrolysers and hydrogen infrastructure

will have to rapidly expand if green hydrogen production is to meet this future demand, which will drive rapid cost reductions in the capital cost of green hydrogen production. Figure 12 represents the UK Government's assumptions about how the capital expenditure for electrolyser technologies such as alkaline and PEM will fall over the next three decades (BEIS, 2021b). When combined with the continuing fall in renewable energy costs (IRENA, 2020), this will drive substantial reductions in the cost of green hydrogen.

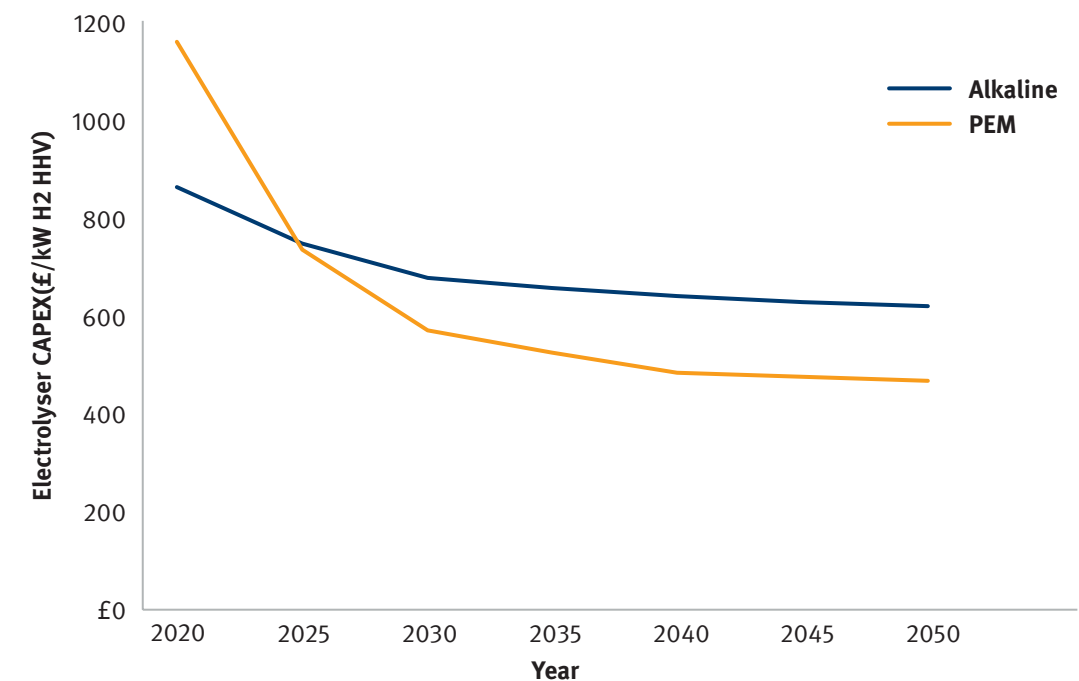


Figure 12 The UK Government's estimated cost reductions in the capital intensity of electrolysers up to 2050

Table 2 presents the total capital cost and renewable capacity that would be needed to meet the upper and lower bounds of demand for low-carbon hydrogen modelled by the Climate Change Committee’s scenarios, with green hydrogen produced using wind energy. These anticipate that by 2030, demand for low-carbon hydrogen in the UK could range between 250,000 to 700,000 tonnes per annum, expanding to 4.8–11.4m tonnes per annum by 2050 as the uptake of hydrogen in sectors such as industry, shipping, and heat increases. Meeting the UK’s demand by 2050 would require

a total capital expenditure of between £115bn to £290bn, far larger than the £30bn that the UK Government committed to domestic investment for the green industrial revolution at the Spending Review 2021 (HM Government, 2023). However, in reality most of these capital costs will be borne by the private sector operators who will be developing green hydrogen production plants in the future to meet the demands from industrial and other sectors for low-carbon hydrogen.

Year	Anticipated demand (tonnes per annum)	Capital Expenditure (GBP m)	Required Renewable Capacity (MW)	Marginal cost (GBP/kg)
2030	250,000	2,030	2,770	2.08
	700,000	15,720	7,550	2.11
	1,200,000	26,900	12,900	2.19
2050	4,800,000	115,000	55,000	2.43
	11,400,000	139,000	139,000	2.53
Current Industrial Demand	10,000,000	121,000	121,000	2.52

Table 2 Total capital expenditure and renewable capacity that would be needed to meet the upper and lower bounds of demand for low-carbon hydrogen

Recommendations

Two uncertainties as the hydrogen value chain in the UK begins to develop over the next decade are a) what end-uses hydrogen will meet and b) where these end-uses will be located.

In the short to medium term, green hydrogen from the UK will be more expensive than the production of hydrogen using steam methane reforming. The use of green hydrogen should be prioritised for sectors and processes that do not have an alternative, more cost-effective decarbonisation pathway (e.g., electrification technologies). Further research needs to be conducted into the end-use applicability of hydrogen across different applications, but it is clear that the use of green hydrogen – whilst still emerging – should be targeted at replacing existing hydrogen feedstocks and meeting a potential need for long-duration energy storage.

The production of green hydrogen is expected to take off past 2030. This is when economies of scale in the value chain will begin to develop and reduce the cost of electrolyzers and other related infrastructure, which will open new potential end-uses in transport, domestic heating, and high-temperature industrial processes. The use of hydrogen should still be prioritised and targeted, especially when in competition with electrification technologies due to the inherent inefficiencies in the hydrogen production process. Hierarchies such as the Clean Hydrogen Ladder have been developed to support the prioritisation of the future end-uses of hydrogen, based on the uses which are likely to be most competitive and/or do not have direct alternatives for decarbonisation (Liebreich Associates, 2021).

The UK Government’s policy position on green hydrogen production see domestic production being used to meet domestic demand in the first instance, which is reflected in the

modelling assumptions in the Committee on Climate Change’s pathways out to 2050. However, the UK has ambitious targets for low carbon hydrogen production, with the national target of 10 GW by 2030 (at least 50% met by green hydrogen) exceeding all other European countries and second only to India and Chile worldwide (IEA, 2022a). If these ambitions are realised, it could play a significant role in exporting to nearby countries such as France, Belgium and the Netherlands. This would support the European Commission’s ambitions under the REPowerEU Plan to import 10m tonnes of renewable hydrogen by 2030 (European Commission, 2022).

The development of green hydrogen production and the markets for its end-use will also need significant policy support from the UK Government. Green hydrogen is anticipated by many as likely to suffer from a ‘chicken or egg’ issue; demand is likely to be inhibited by current costs of green hydrogen production, which as calculated in this work are two to three times higher in the UK than conventional hydrogen production, but without demand-pull factors, investments into green hydrogen production will remain too risky for the large-scale expansion of supply that will drive cost reductions. To meet the 160–376 TWh of demand for low-carbon hydrogen in 2050 modelled by the Committee on Climate Change in its Sixth Carbon Budget – or even the 8.3–23.3 TWh modelled by 2030 – the UK Government has an important role to play in supporting the developing hydrogen market. Production, distribution, storage and end-uses of hydrogen will all have to be supported by Government policy if the UK is to meet its 10 GW of ambition by 2030 and develop a “hydrogen economy” in the UK.

To date, the UK Government has announced several policies to support the emerging hydrogen sector in the UK, set out in its Hydrogen Strategy in May 2021. It has committed to a 'twin track' approach to hydrogen production, supporting both green electrolytic and carbon capture-based hydrogen production routes with the aim of at least 5 GW of green hydrogen production by 2030. To support the development of the hydrogen economy in the UK, the Government is providing both co-investment for low-carbon hydrogen projects to 2025 through the Net Zero Hydrogen Fund (NZHF) and long-term revenue support through the Hydrogen Business Model (i.e., supporting selected producers by paying them a subsidy per unit of hydrogen). Further policy support that would support the scaling up of the production of offshore hydrogen will be important; as presented in this work, offshore production of hydrogen is likely to be more expensive.

In the meantime, political will is needed to advance green hydrogen production and see it through the cost reduction phase. This approach has been pioneered and mastered for offshore wind in the UK already, and it is a key reason for the UK's internationally leading role in the sector. Rolling out large-scale hydrogen production will also be mandatory in the light of any real alternative. This requires policy makers and politician to closely assess the current situation. The supply chain issues that are plaguing offshore wind must be addressed decidedly. At the same time, as cost of capital is increasing sharply, driven by inflation, which should be addressed by creating a safe investment environment for investors, just as was done for offshore wind before. Policymakers might want to assume a more governing role in early hydrogen projects to achieve their energy policy objectives, ensuring an economically efficient pathway delivering projects, while being mindful of the overall systems picture. De-risking is a key challenge, considering the high risks of project failure at the moment (e.g., the halting of one of UK's offshore wind farm developments over cost concerns)

(Sinclair & Lewis, 2023). However, the cost reduction trajectory is promising for offshore wind, assuming the current spike in financing cost can be overcome. The same applies for hydrogen electrolyzers, completing the picture of a future low-cost hydrogen production value chain.

Finally, creating a hydrogen production industry is a transition story for UK's oil and gas sector. The UK is one of the few countries that could produce more hydrogen than it consumes in hydrocarbons today. It is located in the centre of a vast resource, which premediates positioning itself at the centre of the European hydrogen supply chains. Investing now to reduce costs and benefit from the generated value of exported hydrogen would make a reality out of the ambition to become the "Saudi Arabia of Wind".

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