Role of hydrogen in decarbonising UK power generation - Whitepaper

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How can Hydrogen support electrification?

To achieve the Paris Agreement temperature goal to **limit global warming** to below 2°C, the UK Government has set a target to **reduce emissions by 78%** by 2035 compared to 1990 levels.

There are several steps that have been taken towards achieving this goal and many more that will be needed. One such crucial step is **electrification** in transport and heating, and decarbonising industry. It is forecast that this will require at least doubling of electricity generation capacity.

This increase in electricity generation capacity will need to be largely met through various forms of **renewable** energy generation, particularly **wind and solar**

There are several **challenges** associated with relying on renewable sources, particularly around the **intermittent** / non-controllable nature of its generation. It also creates **locational** challenges as solar and wind farm sites are often not located in the areas of high demand.

Energy storage is becoming increasingly important to mitigate the intermittency and locational challenges of renewable generation. This could be in the form of electrochemical (e.g. batteries), thermal, mechanical (e.g. flywheels) or chemical (e.g. hydrogen).

Amongst other technologies, **hydrogen** can avoid curtailment of renewables by enabling storage of excess renewable power and generating electricity when there is a later need. It can be easily **stored and transported**, so can play a role in shifting large amounts of energy from areas of high generation (e.g. Scotland) to areas of high demand.

Stored **hydrogen** can be used to generate electrical **power** (in some cases, alongside useful heat energy) when and where there is demand. Technologies allowing for hydrogen-based power include **internal combustion engines, turbines and fuel cells**. It is expected that a combination of technologies will be needed but **Solid Oxide Fuel Cells (SOFCs)** present a suitable solution to power generation in a number of cases, for example to provide power to data centres.

The **UK hydrogen market and SOFC** technology is in its **nascency**. Whilst we cannot predict exactly what the future energy landscape will look like, it is clear a **combination of technologies** will be **needed** to achieve decarbonisation targets. **Hydrogen to Power** can provide an important **piece of the puzzle** but there will need to be **increased certainty and clarity** provided by the government to encourage **investment** and **technology developments. In particular, more support is needed for smaller-scale, distributed low-carbon power generation**.

As illustrated on the map below, a number of factors mean that a hydrogen economy can develop more efficiently in certain regions. As this whitepaper **demonstrates there is no 'one size fits all approach'** and what we expect to see is a **decentralised, regional approach which utilises different technology combinations depending on what is most appropriate for a particular region**. For example, hydrogen clusters will develop where there are areas of high industrial demand, local storage solutions, and hydrogen production facilities. In other areas, factors such as constraints on the local electricity network or local geography will mean that microgrid solutions (some utilising SOFCs), could be the most suitable approach. In dense urban areas particularly heat networks could offer the most efficient heating solution.

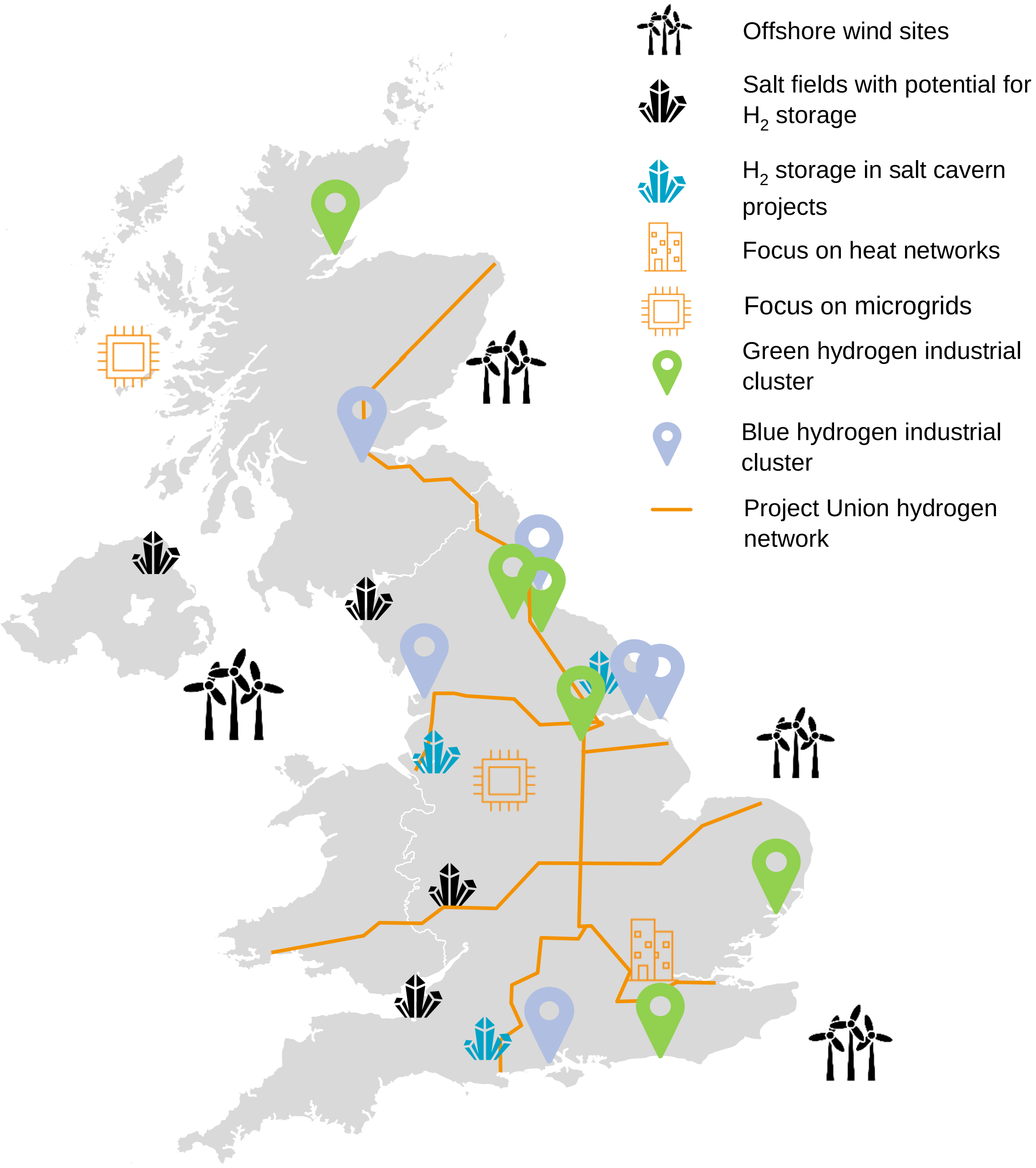


Figure 1: Illustrative map of potential regional energy technology solutions.

In summary, **hydrogen and electrification can work together** to decarbonise the UK's power sector by leveraging their respective strengths and overcoming their limitations. Developing national hydrogen and transport infrastructure can enable renewable energy sources to reach their full potential without overloading the grid or increasing costs. It can also provide clean and flexible energy for sectors that are hard to electrify or require high energy density. Electricity can still be the main driver of decarbonisation for sectors where it is more efficient or convenient than hydrogen. **Analysis carried out by Guidehouse, has also demonstrated that an integrated energy system, strategically utilising both electricity and hydrogen, could result in up to £38 billion of energy system savings, when compared to an energy system with limited integration.**[1] **By combining these two solutions, taking a whole-system approach that does not consider either electrification or hydrogen in isolation, the UK can achieve its net zero target by 2050 and create new opportunities for innovation and growth in the energy sector.**

To realise the benefits from this integrated energy system, the Government will need to introduce **more support** for the hydrogen sector. In particular, there has been a gap in policy support for **smaller-scale, distributed assets, such as hydrogen turbines, engines and fuel cells**. It's critical that the Government does not close any doors at this stage and provides the support necessary to allow these technologies to contribute to achieving net zero.

1. Introduction - the challenges of increasing electrification

Hydrogen will be a key component of the energy transition and can help alleviate the challenges associated with increasing electrification.

UK Decarbonisation Targets

The UK, alongside other countries, has committed to actions to **limit temperature rises to 1.5°C** and has set ambitious targets in its sixth Carbon Budget to reduce emissions by 78% by 2035, compared to 1990 levels.[2]

Electrification is considered to be one of the most practical approaches to reduce carbon emissions across sectors like heat and transport to achieve net zero. According to a Department of Energy Security and Net Zero (DESNZ) analysis, UK electricity demand in 2050 will increase to 575-672 TWh (to more than double the current demand), partly due to increasing electrification.[3]

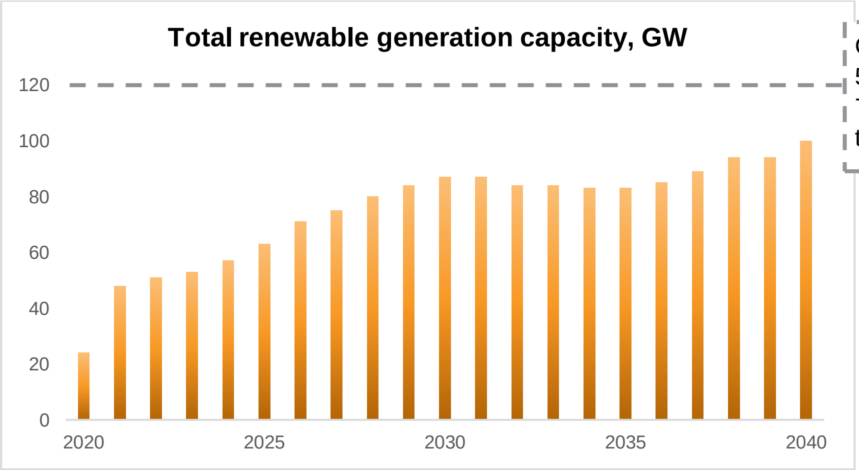
UK carbon emissions

78%

by 2035

Role of electrification

To reach net zero by 2050 and keep up with the increasing power demand, the UK needs to at least double its **renewable electricity generation capacity**.[4] The UK has set a goal to have 50GW offshore wind capacity by 2030 and increase solar power fivefold by 2035 up to 70GW.[5] However, according to Figure 2 below, renewable generation capacity is projected to hit only around 80GW by 2035 when modelled using planned and implemented policies, and central estimates of economic growth and fossil fuel prices.



Government **target** of 50GW offshore wind and 70GW solar (**120GW** in total) by 2035.

Figure 2: Total electricity generation capacity from renewables, modelled using the reference scenario based on central estimates of economic growth and fossil fuel prices, policies that have already been implemented, and planned policies.[6]

National Grid have reported that by 2035 they expect 13 times more heat pumps and 23 times more electric vehicles than they have on their distribution network today.[7] However, electrification alone will not allow us to meet decarbonisation targets. This paper focuses on the **hydrogen to power** market and on the role **Solid Oxide Fuel Cell (SOFC)** technology could play. SOFCs are the most efficient fuel cell type to date which are fuel-agnostic and emit fewer emissions compared to traditional combustion technologies. This paper will demonstrate their use cases and how SOFCs can support an increasingly electrified energy system.

Challenges of electrification

Intermittency

As the sun is not always shining and the wind is not always blowing, renewables present a new challenge to the grid: intermittency (varying electricity generation level). **This is why traditional power generators that can easily be turned on/off (such as gas power plants), are still needed to support base demand and generate power when required.** Recently, National Grid ESO reported that **gas contributed to 33.7%** of electricity generation in March 2023, which is around the same level as the 2022 average.[8] The Department for Energy Security and Net Zero predicts that natural gas will contribute to 23.9% of electricity generation in 2030, and 28.7% in 2040.[3]

Grid constraints

As power demand increases with electrification, there will be a lot more electricity that we need to distribute using the electricity grid. However, the grid is already stretched, and it will be a real challenge to ensure that it has the capacity to withstand the increasing load. The grid needs to be upgraded (or in other terms, reinforced) to keep up, but this requires large investment cost and lead times of any such projects are expected to be long.

There is also a challenge to connect distributed generators to the grid. Distributed generation refers to having onsite power generation equipment that is not part of a central power plant, for example solar PV rooftop at office buildings, hydrogen gensets, or fuel cells. Distributed generation is an efficient way for companies to quickly decarbonise. **However, grid operators (DNOs) are limiting the number of distributed generation installations and not allowing existing ones to be connected to the grid until the reinforcement work has been completed.[9]** There are already cases where companies with distributed generation systems have been informed to wait until 2037 to connect to the grid.[10]

Some solar customers waiting up to

10 – 15 years

for a grid connection

Locational constraints

Another challenge is that the location of electricity generation often does not align with where the demand is. For example the constraints on the electricity grid at the Anglo-Scottish border is already causing significant costs to the GB network.[11]

How can hydrogen support?

Hydrogen can help address the issues created by dependence on electricity as a single energy vector. Hydrogen and natural gas have obvious similarities – both are in gaseous form that can be used to generate energy, although hydrogen clearly has an advantage in terms of Net Zero goals because it does not produce carbon emissions during conversion and is the most abundant chemical element in the universe. Furthermore, when used in power applications such as fuel cells which involve an electrochemical reaction rather than combustion, hydrogen becomes even cleaner and more efficient. Green hydrogen, unlike several other fuels, is **not constrained by resource availability, but by the level of investment** in production.

Hydrogen storage can provide a solution to renewables' intermittency and can also help take the burden off the electricity network. Renewable electricity can be used to produce green hydrogen, which can then be transported and used as fuel to generate electricity. This way, we can avoid large investments into building new transmission and distribution networks to connect renewable generation sites to where the demand is. This would avoid a grid that is sized for peak demand a few days of the year, where the cost burden would be high, instead optimising between hydrogen and electricity.

There is a growing market for hydrogen in the UK and some ambitious targets for the production of low carbon hydrogen. The UK Government has set a target of 10GW low carbon hydrogen production capacity by 2030, half of which is set to be electrolytic.

Hydrogen is emerging as a potential **key pillar** of the move towards net zero, offering a solution to several issues associated with electrification. The market is still in its nascency and there is a range of views on how hydrogen should be produced, stored, distributed, and used. What is clear is that hydrogen will play a growing role, as demonstrated in the National Grid ESO FES 2023 scenarios in Figure 3 below.[12] Government analysis suggests that by 2050, **the UK will need between 250 and 460TWh of hydrogen, delivering 20-35% of the UK's final energy consumption – equivalent to the UK's total energy consumption today**. [13] For this to happen there will need to **be clarity and confidence** in the market regarding hydrogen technologies to encourage investment.

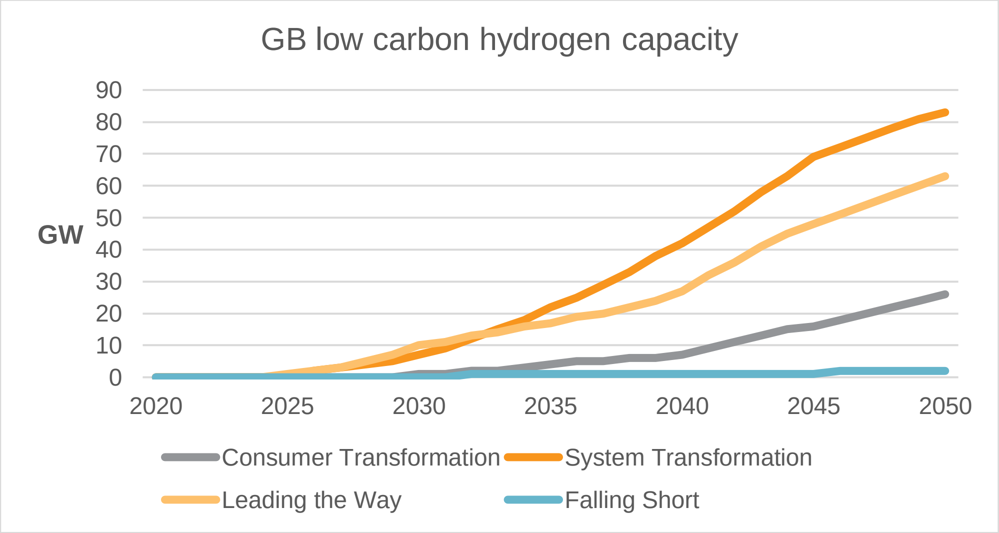


Figure 3: GB Low carbon hydrogen production capacity, FES 2023 scenarios. (National Grid ESO, 2022)

2. Decarbonisation of power sector trends in the UK

The UK's commitment to decarbonising the power sector has set the stage for a transformative shift towards a greener energy landscape.

Decarbonisation of power targets

The UK's commitment to decarbonising the power sector has set the stage for a transformative shift towards a greener energy landscape. The UK has ambitious targets to decarbonise the power sector, which means reducing the emissions per unit of electricity generated. The average carbon intensity from electricity generation in the UK was reported as 157 gCO_2/kWh by end of March 2023, with 47% of the electricity coming from clean sources.[14] The UK plans to continue this trend and ultimately **generate all electricity from low carbon sources by 2035**. In that scenario, renewables are projected to account for up to 85% of the generation capacity. This equals around 200-250 TWh, with wind energy as the main contributor to the mix.[15,16]

Regulations and policies

The British Energy Security Strategy is the UK's latest national plan for decarbonising power, combining renewables and low-carbon power generation to have 95% of electricity produced from low-carbon sources by 2030.[17] There are several policies in place to support this, for example the Electricity Market Reform (EMR) that provides financial incentives and long-term contracts to low-carbon electricity generation, particularly through the Contracts for Difference (CfD) mechanism. Most recently, the government has published the consultation outcome for the Review of Electricity Market Arrangements (REMA) which focused on creating a market framework that facilitates the transition to a low-carbon power system.

It is however important to note that aside from these, the UK is still open to new investments for fossil fuel production, with plans to continue exploration in the North Sea.[18]

Overview of challenges of meeting the decarbonisation targets

Decarbonising power through electrification using renewable electricity presents challenges in ensuring a continuous electricity supply and minimising the technical burden put on the power systems. Using unabated natural gas-fired power plants for baseload or dispatchable power may be a short-term solution to this challenge but is antithetical to achieving decarbonisation goals. Additionally, a lot of these larger-scale plants are reaching their end-of-life. Building new ones will ultimately mean continuing to rely on fossil fuels, potentially with carbon capture technology, unless made hydrogen-ready to move to 100% hydrogen or low carbon ammonia is used. But even so, low-carbon fuels are not the only solution.

Using low-carbon fuels for power generation comes with challenges in technological readiness and fuel supply. Utility-scale gas turbines that can take 100% hydrogen and ammonia are still being developed by major manufacturers. There's the 'chicken and egg' dilemma where stakeholders are cautious about investing in low-carbon power generation equipment as current and future availability of low carbon fuels is uncertain.

Alternatives exist, for example energy storage, clean energy microgrids, or using virtual power plants to aggregate power generation from residential solar PV and batteries to support the grid. However, these state-of-the-art solutions may face supply chain issues and uncertainties in securing investment, which make it challenging for the market to scale up exponentially in the next 5 years.

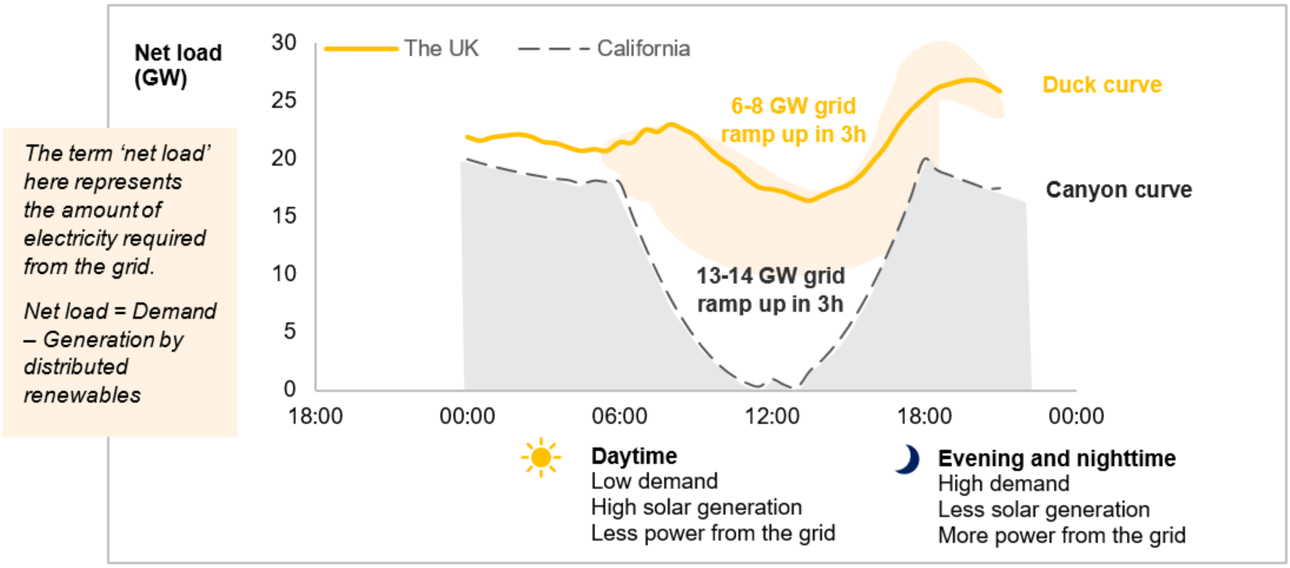
The costs associated with decarbonising the power sector are significant**. The UK Government is predicting that its goal to decarbonise the power system will require £275-375 billion of public and private investment, in addition to £50-150 billion of investment in reinforcing the electricity networks.**[19]

Is full electrification practical?

This depends on the power system design in a particular country, but there are several challenges associated with an increasing reliance on electricity.

Intermittency

The UK is ramping up renewables, however they are intermittent - meaning that renewable generation varies throughout the day and seasons. This results in what's known as *generation variability*. The overall generation variability in the UK in 2022 was around 12% and is projected to reach 25% by 2050 when there will be a higher share of renewables in the generation mix.



The term 'net load' here represents the amount of electricity required from the grid.

Net load = Demand – Generation by distributed renewables

Figure 4: Net load curves showing the amount of electricity needed from the grid to satisfy demand across various time of the day. The duck curve for the UK is based on LCP's Enact dashboard as of 29-April-2023. The example canyon curve for California is based on CAISO's dashboard on 16-April-2023.

Figure 4[20] shows the net load for the UK and California, showing how having more renewables can result in more noticeable variability throughout the day. We can see that the UK's net load is the lowest around noon and the highest in the evening, creating a duck-like shape. This is an example of the *duck curve,* first introduced by California ISO, which illustrates how much the grid must ramp up or down flexibly to compensate with the varying net load throughout the day as observed in California in 2018.

California's duck curve now, however, is shaped more like a *canyon*, as there is now more solar in its generation mix compared to that in 2018, creating a significant difference in net load throughout the day.[21] The greater the fluctuation, the greater the risk of system instability, as the grid will need to ramp up/down quickly. There is also the risk of overgeneration when demand is lower but solar generation is reaching its peak. The UK's net load curve today has a relatively small dip, but as we add more solar PV into the mix[22], it's a possibility that it will become canyon-shaped soon, which may be difficult for the current grid to support.

Certain measures are needed to ensure that customers have continuous electricity supply and that the grid stays fit for service despite the increasing variability. To date, the UK mostly still relies on natural gas to compensate for the varying power generation level and provide both flexibility and resilience to the power system.

The UK has one of the longest connection queues in Europe, with over 200GW on the waiting list and waiting times of over 10 years.

Grid constraints

The UK's existing network grid was not designed for renewables or growing demand for electricity. With increasing electrification, the amount of electricity that needs to be distributed through the grid will significantly rise. More customers using electricity will also mean that more connection points are needed, making the grid network even more congested.[23]

The current grid infrastructure is already experiencing constraints to withstand the increasing load from both the demand and supply sides. Growing distributed renewable generation only compounds this issue. Reinforcing the grid is necessary to keep up with the increasing demand, but there are substantial costs associated with these upgrades.

Locational constraints

Increased renewable generation also creates locational challenges in terms of a mismatch of generation and demand across the UK. Solar and wind farm location depends on a number of factors, including technical factors (e.g. wind speeds, solar irradiation, land value and network connections) as well as the policy environment. The large distances between generation and demand can cause congestion in the electricity grid, as seen in recent years with congestion caused by high levels of wind generation capacity in Scotland.[24]

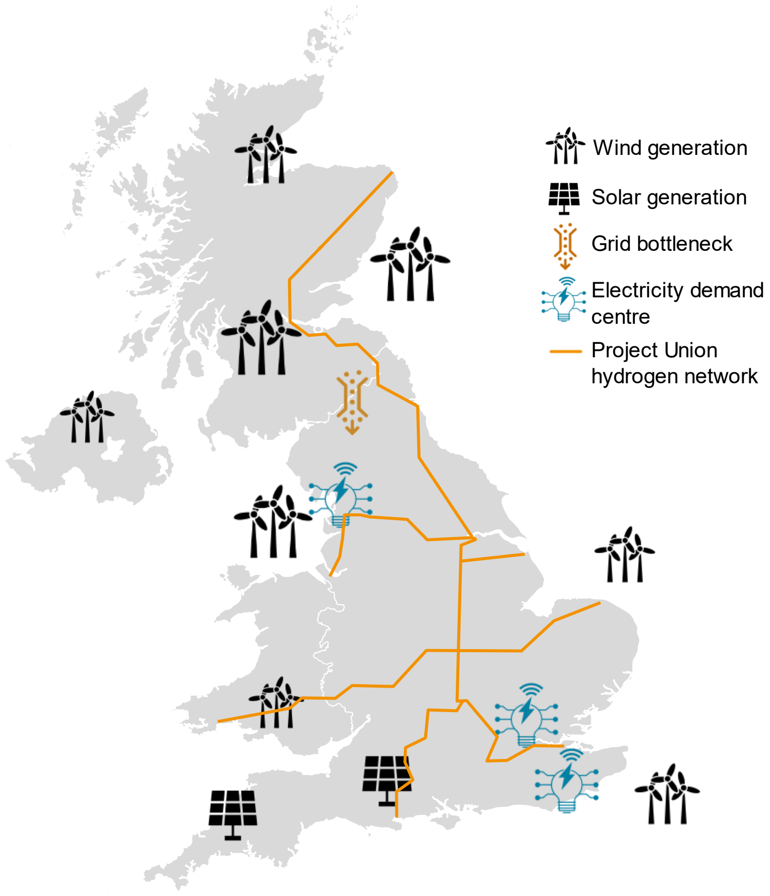


Figure 5: Illustration of locational challenges associated with increased electrification

Without storage technologies, or significant grid reinforcement, we can expect an increasing number of scenarios where in some parts of the UK renewable generation is being curtailed despite there being demand in other regions of the country. According to a report by LCP Delta, the cost to the UK of turning off wind farms to manage the electricity system was £300 million in 2020, rising to £507 million in 2021.[25] Hydrogen can be moved and stored at scale to address mismatch in supply and demand and address seasonality in energy demand.

How the power generation sector will need to adapt to meet targets

With more demand expected, and the urgency to produce as much clean electricity as possible without putting pressure on the grid, the power system needs to transform and become more decentralised. This can be done by deploying customer-owned assets (e.g. heat pumps and energy storage), distributed generators, and community-owned assets (e.g. solar PV panels, small wind turbines, fuel cells).

There are several different solutions to decarbonise power generation in the UK, and it is likely there will be no ‘one size fits all’ approach with solutions to vary regionally. Hydrogen is expected to be one component of the mix and the following chapter explores what role it could play.

3. Hydrogen's role in decarbonising UK power generation

Hydrogen is expected to become a key pillar in the decarbonisation of power in the UK.

Hydrogen in the wider UK context

Hydrogen has numerous potential uses, such as decarbonising industrial processes, heating, fuelling transport and producing power. The UK Government has shown a strong policy focus for hydrogen with several emerging use cases.

The UK has set ambitious targets of 10GW low-carbon hydrogen production capacity by 2030, half of which is to come from electrolytic (green) hydrogen. In the short term, this twin track approach backed by the UK is likely to yield lower hydrogen costs by accepting blue hydrogen developments alongside green hydrogen and enable production volumes to scale up, resulting in a higher availability of clean hydrogen for utilisation.

There will be annual allocation rounds for electrolytic hydrogen projects, moving to price competitive allocation by 2025 or as soon as legislation and market conditions allow so that up to 1GW of electrolytic hydrogen is in construction or operational by 2025. The shortlisted projects for the first allocation round were announced in Q1 2023. The UK Government have set targets, deadlines for decisions and funding streams for the production, distribution, storage, and use of hydrogen.

There is already evidence to suggest that progress towards these targets is slow**.** **In 2022, the UK's operational electrolyser capacity totalled 13MW.** Analysis from LCP Delta's hydrogen projects database, HYbase, estimates that this is **on track to grow to 130 MW in 2023, 0.85 GW in 2025, and around 4 GW in 2030**.[26] The UK is lagging behind other European markets such as Germany, Denmark, and Spain, who each hold >10% market share in planned electrolyser capacity over the next five years.

There is also a significant focus on the production of hydrogen but there are gaps in policy and regulation around the storage, distribution and utilisation of hydrogen which is causing uncertainty in the industry. Hydrogen to Power is one area which has less focus from the UK Government. A recent House of Commons report acknowledged that **hydrogen 'has the potential to contribute to the delivery of the government's commitment for a fully decarbonised power sector by 2035' but there is currently no support mechanism in place to support this.**

> ***“The UK’s grid is highly constrained which is affecting new grid connections and time to power for customers looking to increase their imported capacity. We are seeing a shift towards distributed, behind the meter generation to solve this issue and see Hydrogen to power as a promising solution either through fuel cells or other Hydrogen ready generation. Currently, market support is focused on hydrogen production but there needs to be more support or incentives for the utilisation of hydrogen.”***
>
> **Electricity North West (Construction and Maintenance)**

How can electrification and hydrogen can work together to decarbonise?

As the energy transition accelerates, there is a growing awareness of the challenges presented by dependence on intermittent renewable generation; hydrogen can help to reduce many of these.

Intermittency **1**

The wide fluctuations in output from renewable generators require some form of buffering. Hydrogen can help to support this and avoid curtailment of renewable assets.

2 **Grid constraints**

Increasing electrification puts strain on the grid at times of high demand. Using hydrogen that has been generated at times of high renewable supply can help ease this.

Locational constraints **3**

The production of renewable energy isn’t always close to areas of demand. Molecules are easier to store in large quantities and move than electrons, so hydrogen can support.

Hydrogen and electrification are two complementary solutions that can work together to decarbonise the UK's power sector and achieve net zero emissions by 2050. The UK has set ambitious targets for renewable electricity generation, but transporting and integrating large amount of variable power (e.g. generated by offshore wind) into the grid poses significant issues, such as grid congestion, gaps between supply and demand, and curtailment of renewable generation. Hydrogen can offer a viable alternative to electric cabling for offshore wind and can be a versatile energy carrier for other sectors that are difficult to electrify, such as heating some homes, industry, and transport.

Offshore wind farms can either convert their power to hydrogen on site (via offshore electrolysis) or near the shore (onshore electrolysis co-located with the wind farms) and transport it via pipelines to the demand centres. Hydrogen pipelines are cheaper to lay down and require less maintenance under the sea than electric cables.[27] **Research has shown that the cost of direct electrical transmission per MWh delivered can be up to eight times higher than for hydrogen pipelines**.[28] Moreover, hydrogen can help reduce the load on the grid and avoid bottlenecks that currently limit the transmission of power from regions with high renewable potential (e.g., Scotland, Wales) to regions with high demand (e.g., London and South-East England).

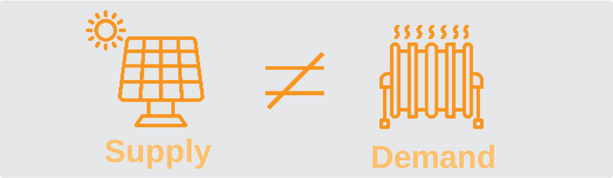
> ***“There needs to be some form of system benefit [to using hydrogen as an energy store]. It might be that it unlocks constrained power grid networks – it’s easier to move hydrogen than electrons.”***
>
> **Prof. Nigel Brandon, Imperial College**

Hydrogen can play a key role in decarbonising sectors where electricity will struggle to penetrate, such as heating for homes not suitable for heat pumps, industry, heavy goods vehicles (HGVs), large commercial fleets, aviation, maritime applications, and hard-to-electrify sections of the rail network. Hydrogen can provide clean and flexible energy for these applications, either through direct combustion or via **fuel cells** that convert hydrogen to electricity. Hydrogen can also be blended with natural gas or biogas to lower their carbon intensity or be used to produce synthetic fuels or chemicals.

Electricity, on the other hand, can still be used to decarbonise sectors where it has a clear advantage over hydrogen, such as passenger vehicles and home heating in some cases. Electricity can also be used to produce hydrogen when there is excess renewable generation or low demand on the grid.

> ***We need solutions that address the intermittent and seasonal challenges of a decarbonized grid. Batteries are great for short-term storage, but hydrogen is an ideal long-term storage solution to balance electricity supply and demand over the course of the year. Hydrogen SOFCs provide an efficient way to convert hydrogen to electricity without combustion***
>
> **Bloom Energy**

Hydrogen storage



Hydrogen can help address the challenges of increasing electrification by providing a vector for storage. Increasingly, **renewable** generators are being **curtailed** due to a mismatch in supply and demand and the grid not being able to cope with excess energy, leading to clean energy being wasted. **The cost of curtailment was estimated to be £300 million in 2020, rising to £507 million in 2021.**[29] To bridge the gap between renewable energy production and consumption, energy storage is being increasingly rolled out using a myriad of technologies, including battery energy storage and pumped hydro. Each technology has its advantages and disadvantages and there will be no single solution to delivering enough storage; a combination of storage technologies, including hydrogen storage, will be needed to achieve net zero in the most efficient and cost-effective way.

Hydrogen can be stored and either then used as a gas or converted back to electricity via turbines or fuel cells when demand peaks. Hydrogen can be stored in a range of forms; gaseous, liquid, or solid-state, and in different storage vessels:

The different forms of storage allow the approach taken to be tailored to the location depending on what is most effective in that areas, which will depend on other factors including regional geography (e.g. availability of geological storage), the local hydrogen network (e.g. is there a local hydrogen pipeline) and the ability to utilise the hydrogen locally (e.g. industrial hub).

A key method of hydrogen storage is utilising geological storage. However, there are concerns about the deployment of geological storage at the pace that is needed as there are lengthy development times and requires coordination with a number of stakeholders.[30]

Hydrogen as long duration energy storage

Hydrogen is best suited to longer duration energy storage rather than short duration (under four hours), which can be provided by batteries. Longer duration energy storage will be crucial for decarbonising UK power supply. **Research has shown that £13-24bn savings to the electricity system could be achieved between 2030 and 2050 through long duration energy storage, supplied mainly by hydrogen**. These savings are through reducing network constraints and seasonal imbalances from intermittent renewables.[31] A Guidehouse report, found that in all their modelled scenarios, '**hydrogen storage is critical in supporting whole energy system demand during peak demand periods and low wind days'**.[1]

> ***"Hydrogen is the only way you can achieve weeks of strategic energy storage. Built off the back of large-scale wind, we will need tens of TWh of storage to buffer shortfalls in the winter. Pumped hydropower can't store the amount of energy we need, but hydrogen can."* –Prof. Nigel Brandon, Imperial College.**

In the UK, there is a significant gap between when renewable energy sources generate the most energy and when demand for energy is highest. More energy is needed in the winter months due to high energy demand for heating. The need for inter-seasonal storage will depend on the future energy mix, with the National Grid ESO forecasting that it will vary between 11-56 TWh in 2050, with the variation largely being dependent on the rollout of hydrogen.[32] Meanwhile, an Edinburgh University project[33] has estimated that 150 TWh of hydrogen storage is required to replace natural gas in the UK's gas grid with hydrogen. The project also estimated that there is potentially up to 6,900 TWh of hydrogen storage in gas fields and a further 2,200 TWh of potential in saline aquifers. However, this storage potential needs to be unlocked by more investment into storage projects. As an example, Centrica's Rough storage now provides half the UK's total natural gas storage and Centrica have announced the long-term ambition to turn the gas field into the largest long duration low carbon energy storage facility in the world, capable of storing both natural gas and hydrogen.[34]

Hydrogen is considered to be one of the best options to balance seasonal differences in supply and demand. According to written evidence submitted to the UK government by SGN, the *"electricity grid's ability to satisfy heat demand during a winter cold spell is significantly restricted by the challenge of storing electricity at scale at an affordable cost. Currently, renewable electricity must be used to supply a demand, otherwise it is wasted. Converting renewable energy to hydrogen could allow the utilisation of renewable energy from generators currently paid to turn off when supply exceeds demand*."[35] [36]

In their 2020 report, *Modelling the Electricity System*, BEIS found that without hydrogen, the minimum electricity system cost was found at carbon intensities of 10-25gCO2/kWh, while with hydrogen, the minimum system cost was found at intensities of 5-15gCO2/kWh; also system costs with hydrogen were lower than those without hydrogen. This was in a scenario where the total amount of hydrogen-fired generation was 20TWh or less, with hydrogen twice as expensive as natural gas.

Hydrogen-based distributed energy system

Hydrogen to power systems can be classified into three main types: turbines, engines, and fuel cells:

Hydrogen **turbines** are similar to conventional gas turbines, but they use hydrogen instead of natural gas or other fossil fuels to combust and drive a turbine. The advantages of hydrogen turbines are high efficiency at large volumes, low emissions, and flexibility to operate with different hydrogen blends however they are subject to increased NOx emissions.

Hydrogen **engines** are internal combustion engines that use hydrogen as a fuel to power vehicles or generators. Hydrogen engines can offer lower emissions and lower noise than conventional engines. The drawbacks of hydrogen engines are low efficiency, high fuel consumption, and technical difficulties such as pre-ignition, backfire, and NOx formation.

Hydrogen **fuel cells** are electrochemical devices that convert the chemical energy of hydrogen and oxygen into electrical energy and water. Their benefits include very high efficiency, low emissions, low noise, modularity, and reliability. The challenges of hydrogen fuel cells are high costs and system integration. These benefits and challenges are discussed further in Section 4.

Scales of hydrogen power systems

Large-scale power generation (>50MW)

This scale of generation is currently served by turbines or heat engines. They are both mature technologies; which have been in the market for decades and have established supply chains, whilst fuel cells are a less mature market.

Pre-2030, hydrogen faces difficulties in its viability for large-scale power generation. Hydrogen will struggle to compete with natural gas from an economic standpoint without higher carbon prices, though this may change post-2030. Another barrier is availability: even with 10GW low-carbon hydrogen production coming online by 2030, the volumes of hydrogen that will be required for large-scale power generation will far outstrip production capacity. The UK will need to import hydrogen, which brings in the question of cost.

Microgrids (Typically 1MW – 20MW)

A microgrid is a clearly defined energy system concept. The most critical characteristic of a true microgrid is its ability to operate independently (in island mode) in the event of grid failure. It is this characteristic, which is key to its ability to provide resilience, both to itself and to the adjacent grid.

Microgrids are becoming increasingly popular as they can provide several benefits compared to solely relying on the main electricity grid. A key benefit of microgrids is providing increased resilience for customers, providing a solution to operate independently of the main grid in the event of a disruption to supply. Significant disruptions to power supply have been seen in recent years with storms Arwen, Malik, and Corrie, and with increasing reliance on electricity and increasing extreme weather events caused by climate change, power outages are expected to become an increasing challenge.

> ***"Up to 1-10 MW is the sweet spot for fuel cells, but at 100 MW that advantage goes away because heat engines and gas turbines become more efficient the larger they get. The only disadvantage there is that burning hydrogen in a heat engine creates NOx emissions, but in the future there won't be so many large, centralised power plants. There will be many smaller systems distributed across the grid where needed. There is no reason why we can't use hydrogen for that."***
>
> **Prof. Nigel Brandon, Imperial College**

Microgrids are considered to be one of the key solutions to delivering a more resilient energy system, and fuel cells could play a key role in delivering them; according to industry experts, anywhere up to 10 MW is a 'sweet spot' for capturing their high efficiencies.

Case study: Esslingen District Heating Scheme

2G Energy, Cummins, BMWi, BMBF

The Neue Weststadt is an almost climate-neutral urban quarter in Esslingen am Neckar, Germany, that combines energy-efficient buildings, renewable energy generation, and hydrogen technology. The core of the energy supply concept is a central energy centre that converts surplus green electricity from local and external sources into hydrogen by electrolysis and stores it for later use. The electrolysis process uses a rapid response PEM (Proton Exchange Membrane) electrolyser by Cummins that produces up to **260 kg of high purity, fuel cell grade hydrogen per day**. The electrolyser can ramp up and down flexibly to take advantage of variable renewable generation. The hydrogen can be used for various purposes, such as heating, cooling, mobility, and industry. The heat generated during the electrolysis process also contributes to the district heating network.

The district also has a biomethane cogeneration unit, a gas peak-load boiler, an electricity storage tank, and photovoltaic roof systems to optimise the energy supply and consumption. **The cogeneration unit generates most of the heat and electricity for some of the blocks and runs on 100% hydrogen**. It has a capacity of **1.5 MW_{th} and 0.5 MW_{el}**. There is also a feed-in station to the natural gas network, as well as a hydrogen filling station for fuel cell vehicles.

The project is one of six urban planning lighthouse projects funded by the Federal Ministry of Economics and Energy (BMWi) and the Federal Ministry of Education and Research (BMBF). The project aims to reduce energy consumption and greenhouse gas emissions without compromising comfort and quality of life. It demonstrates the potential of hydrogen as a key technology for the transition to a renewable energy system in Germany and beyond.

Building-level power generation (100kW – 5MW)

Fuel cells offer a promising solution for <5MW generation. One of their main benefits is their high efficiency at smaller scales. Unlike turbines and engines, which suffer from significant losses due to thermodynamic limitations and mechanical friction, fuel cells can achieve efficiencies of up to 60% for electricity generation and over 90% for combined heat and power (CHP) systems. This means that fuel cells can reduce fuel consumption and greenhouse gas emissions compared to conventional technologies.

Another advantage of fuel cells is their flexibility and responsiveness. Fuel cells can operate at variable loads and start up and shut down quickly, making them suitable for providing backup power and grid services. For example, proton exchange membrane fuel cells (PEMFCs) can ramp up and down within seconds and have a high power density. However, PEMFCs require high purity hydrogen as a fuel, which can be expensive and challenging to store and transport. Alternatively, solid oxide fuel cells (SOFCs) can use a variety of fuels, such as natural gas, biogas or hydrogen, with minimal pre-processing. SOFCs can also operate at high temperatures (600-1,000°C), which enables them to produce high-quality heat for CHP applications. However, SOFCs have a slower response time than PEMFCs, however, once at temperature, the modulation response time for load following is efficiently fast enough to comply with grid codes. In addition, when combined with a small battery in a microgrid, this is a small issue.

One of the potential use cases for fuel cells is to provide power for new buildings that face long delays or high costs for grid connections. According to interviews with industry stakeholders, there are waiting times in excess of five years for new connections in some regions, which can hinder the development of new housing and businesses as well as uptake of distributed renewable generation. Fuel cells could offer a viable alternative to diesel generators or grid extensions, as they can provide clean and reliable power on-site until a grid connection is available.

Other potential decarbonisation solutions

Besides hydrogen and electrification, there are other potential decarbonisation solutions that can utilise renewable electricity and captured or biogenic carbon to produce synthetic fuels and chemicals. These are collectively known as power-to-X (PtX) products, and they include ammonia, e-methanol, synfuels, and others.[37] PtX products can offer several benefits for the energy transition, such as reducing greenhouse gas emissions, enhancing energy security, diversifying energy sources, and creating new value chains.

E-methanol and synfuels are examples of PtX products that are made by reacting green hydrogen with CO2. The CO2 can be captured from industrial emissions or from the atmosphere, making these fuels carbon-neutral or even carbon-negative. If the CO2 is biogenic (e.g. from biomass), the fuels can also contribute to the circular economy. E-methanol and synfuels can then be used in the same way as their fossil-based equivalents (e.g. as jet fuel, diesel, gasoline, etc). This means that they can be compatible with existing engines and infrastructure and provide high energy density for long-distance transport.

Ammonia is another PtX product that is made by combining green hydrogen with nitrogen from the air. Ammonia can be used as a fuel for power generation, shipping, or fertiliser production. Ammonia has a higher volumetric energy density than hydrogen. It can store and transport more energy per unit volume than hydrogen and lose less energy in the conversion process. However, ammonia also has some drawbacks, such as its toxicity, corrosiveness, and low flame intensity.

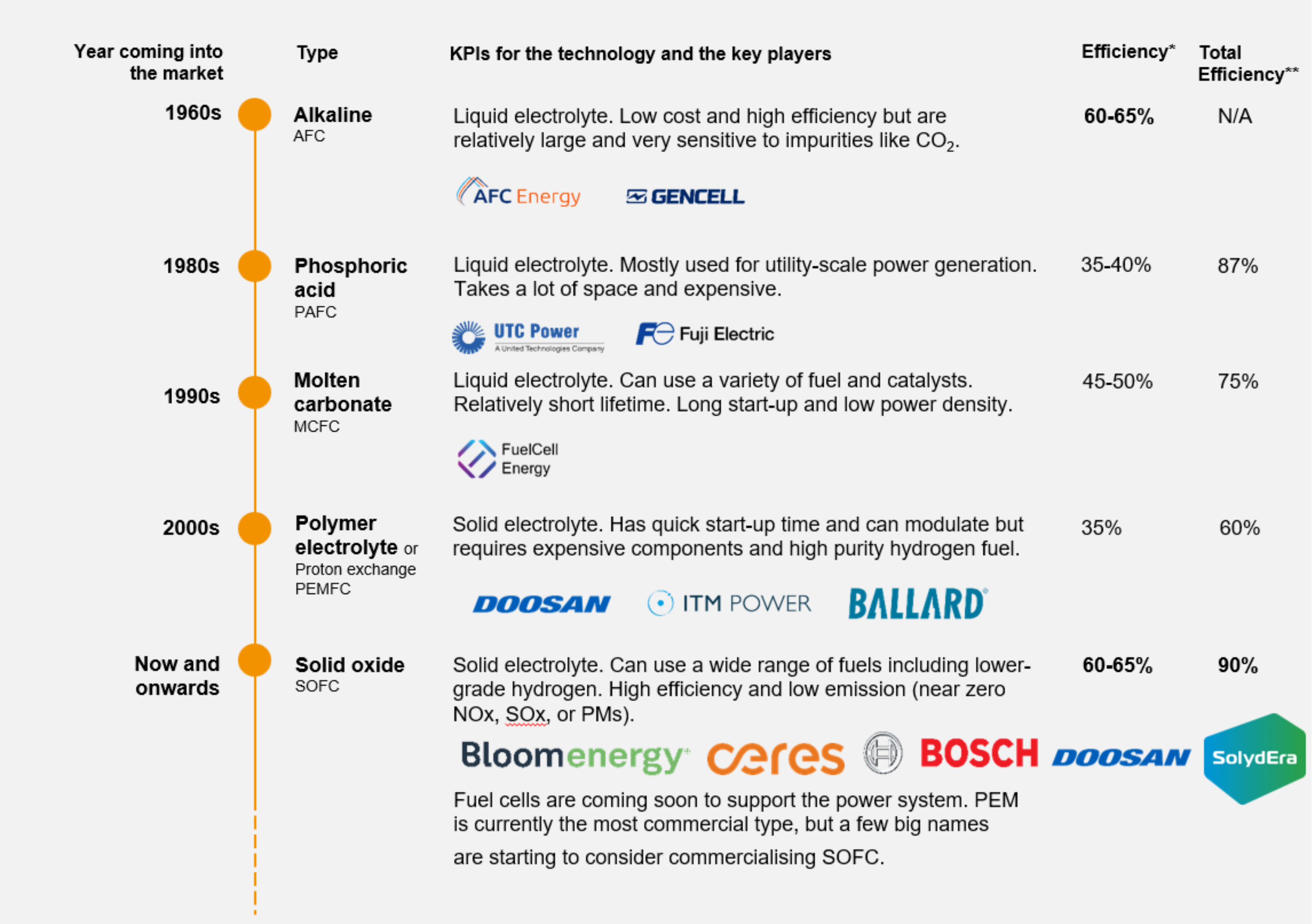
In summary, PtX products are alternative decarbonisation solutions that can use renewable electricity and carbon to produce synthetic fuels and chemicals. They can help reduce emissions, increase energy security and diversity, and create new value chains. They can also provide clean and flexible energy for sectors that are hard to electrify or require high energy density. However, they also face some challenges, such as high costs, low efficiencies, technical barriers, and environmental impacts. Therefore, they should be carefully assessed and compared with other solutions such as hydrogen and electrification.

4. SOFC Technology

A fuel-flexible solution offering high efficiency and low emission.

Evolution of fuel cells

Fuel cells were initially developed by the space and military sectors for power generation. Various types of fuel cells were then established to suit different performance requirements. Figure 6 for the development of fuel cells technology.[38,39,40,41,42]



Year coming into the market	Type	KPIs for the technology and the key players	Efficiency*	Total Efficiency**
1960s	**Alkaline** AFC	Liquid electrolyte. Low cost and high efficiency but are relatively large and very sensitive to impurities like CO_2. AFC Energy GENCELL	**60-65%**	N/A
1980s	**Phosphoric acid** PAFC	Liquid electrolyte. Mostly used for utility-scale power generation. Takes a lot of space and expensive. UTC Power A United Technologies Company Fuji Electric	35-40%	87%
1990s	**Molten carbonate** MCFC	Liquid electrolyte. Can use a variety of fuel and catalysts. Relatively short lifetime. Long start-up and low power density. FuelCell Energy	45-50%	75%
2000s	**Polymer electrolyte** or Proton exchange PEMFC	Solid electrolyte. Has quick start-up time and can modulate but requires expensive components and high purity hydrogen fuel. DOOSAN ITM POWER BALLARD	35%	60%
Now and onwards	**Solid oxide** SOFC	Solid electrolyte. Can use a wide range of fuels including lower-grade hydrogen. High efficiency and low emission (near zero NOx, SOx, or PMs). Bloomenergy ceres BOSCH DOOSAN SolydEra Fuel cells are coming soon to support the power system. PEM is currently the most commercial type, but a few big names are starting to consider commercialising SOFC.	**60-65%**	**90%**

Figure 6: Fuel cells throughout the decades

*LHV electrical efficiency for stationary power generation
**Total efficiency for CHP

SOFCs

Solid Oxide Fuel Cells (SOFCs) work based on electrochemistry principles to produce energy. Electrochemical reactions take place in the positive and negative sides of the fuel cells, ultimately producing electricity and heat as the output. These reactions are facilitated by an electrolyte, a medium that connects the positive and negative sides, allowing chemical molecules to move between sides and go through the full electrochemical reaction series.

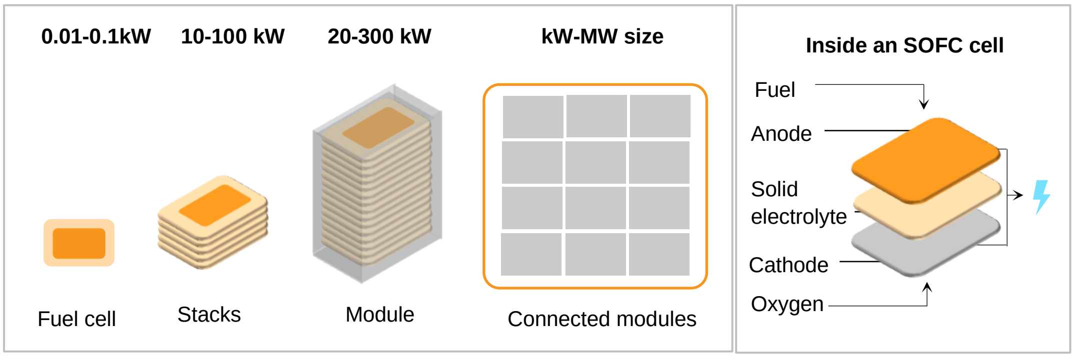


Figure 7: How a fuel cell works

SOFCs, as the name suggests, use solid materials like ceramic or oxide as the electrolyte instead of liquid. These ceramic electrolytes need high temperatures to conduct chemical molecules, which is the reason that SOFCs operate at a high temperature (600-800°C).

What are the benefits of SOFCs over other types of electricity generation technology?

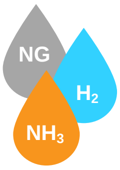
Higher efficiency

Commercial SOFCs can have more than 60% electrical efficiency and the overall efficiency can go beyond 90% when used in CHP mode.[43] In comparison, combustion technologies such as gas engines and turbines generally only have 30-40% electrical efficiency.[44] In addition, SOFCs have a very high-efficiency even at part load.

Fuel flexibility

All types of fuel cells require hydrogen and oxygen ions to produce electricity through electrochemical reactions. Common fuel cell types like PEM and alkaline fuel cells need to use high-purity hydrogen as fuel since both are sensitive to impurities (like carbon monoxide). This causes most fuel cells to require additional hydrogen purification processes or fuel reforming equipment if other fuels are used, which can result in higher costs.

SOFCs can use various types of fuel such as natural gas, LNG, biogas, and ammonia due to their high operating temperature that breaks these fuels' chemical bond, allowing them to release the hydrogen ions. Fuel flexibility – without the need for additional retrofit or upgrades – is one of SOFCs' key strengths that makes this technology relevant for use in the present and onwards. This comes with no major impacts on the output level. In comparison, using hydrogen for converted natural gas combustion engines would reduce the power output by approx. 25%.[45]



Lower emissions

When hydrogen is used as fuel, fuel cells provide a true clean energy solution, unlike hydrogen combustion which generates NOx emissions and particulates that require additional treatment. With hydrocarbon fuel, SOFCs produce only half the amount of CO_2 emission compared to traditional hydrocarbon combustion due to the increased efficiency and the fundamental difference between electrochemical processes in fuel cells, and combustion. SOFCs do not require oil for lubrication, unlike turbines and engines, reducing the CO_2 intensity even further. Additionally, SOFCs emit near zero NOx or particulates.[46]

Limitations

Fuel cell technology was invented more than six decades ago, but they are still seen as niche products due the limitations listed below.

Price	Higher CAPEX compared to conventional gas engines or turbines. However, as has been observed with other energy technologies, such as solar PV, the cost can decrease as volume production increases and as subsidies and incentives are established to support the technology.
Power density	SOFCs currently have a low power density, in terms of kW / m^2, however this is expected to improve as the technology matures.
Flexibility	SOFCs need a considerable amount of time to ramp up or down from cold start since they operate at high temperature. As such, SOFCs may not be the best option as traditional backup power generators for critical business processes – they work best as base load power, always on so removing the need for traditional back up gensets. However, once on, they can be flexible in operation between 30-100% load in line with UK grid requirements.

5. *Use cases for SOFCs*

Solid Oxide Fuel Cells have a part to play in a range of potential use cases that showcase their high efficiency and fuel flexibility.

There are already some examples of hydrogen and SOFCs being used for power generation in various sectors, but they are still nascent technologies that need further development and demonstration. In this section, we will present some of the existing and planned projects that showcase the potential of these technologies.

Data Centres

On-site generation for power, heating, and/or cooling

Microgrids

Powering and increasing resilience for microgrids

Utilities

Supporting the grid by providing baseload or peaking power

Marine

Providing auxiliary power using high power density fuel like LNG

C&I

On-site power or CHP e.g. for industrial processes or hospital

Space / Military

High power density and efficiency suitable for this specific application

Figure 8: Use cases for SOFCs

One of the regions that has a large installed base for SOFCs is California, where they are mostly used in facilities that cannot afford to have power outages, such as hospitals and data centres. SOFCs were chosen by these industries mainly due to the strict NOx emission limits for onsite power generation in California. SOFCs can meet these standards without requiring expensive after-treatment systems, unlike turbines and engines.

Another example of SOFC deployment is the microgrid project in Brooklyn, New York, led by Con Edison, the local utility company. The project aims to provide reliable and resilient power for a residential area that has a very high population density and faces network congestion and high grid reinforcement costs. The microgrid consists of a 1.8MW SOFC system, used for baseload power, and a 300kW photovoltaic system and battery, which can operate independently or in parallel with the grid to provide flexibility. The project is expected to reduce greenhouse gas emissions by 1,800 tonnes per year and save $700,000 per year in energy costs.

A recent initiative that explores the use of SOFCs for maritime transport is the Shell-led consortium that includes Korea Shipbuilding & Offshore Engineering Co., HyAxiom, Doosan Fuel Cell Co., JP Morgan, and DNV. The consortium aims to design, manufacture, and install a 2x300kW SOFC auxiliary power unit on a Shell-chartered LNG vessel for a year of testing in 2025. The trial aims to test the technology's decarbonisation potential, prove its scalability as a propulsion solution for shipping and enable wider industry acceptance of fuel cells. An SOFC can be designed to run on LNG today, in addition to all plausible future fuels, including hydrogen. Due to this flexibility, this technology could be critical in enabling the transition from the marine fuels in service today, to the fuels required in the future. [47]

Case Study: Electricity and heat for Erkelenz hospital Multi-SOFC Project[48]

Robert Bosch GMbH and Hydrogenious LOHC NRW GMbH

The Hermann Josef Hospital (HJK) in Erkelenz (Germany) is looking to demonstrate an innovative combination of two novel hydrogen technologies by the end of 2026.

The Multi-SOFC project focuses on the use of SOFC system developed by Robert Bosch GmbH for supplying electricity and heat. In a subsequent expansion stage starting in early 2025, Hydrogenious LOHC NRW GmbH will supply the project with hydrogen by means of liquid organic hydrogen carrier (LOHC) technology. A pilot installation consisting of ten fuel cell units with a performance range of 100kW will supplement the existing combined heat and power plant..

In the first phase of the project, the SOFC system will run on natural gas. This offers advantages in comparison with the existing gas engine as the **SOFC system can achieve 60%** electrical efficiency, while the gas engine‘s efficiency is 36%. As a result, the SOFC system will emit almost **40% less CO_2** than the gas engine when generating electricity using pure natural gas. The heat generated when the natural gas in converted into electricity in the SOFC system will initially be used to heat the hospital. With this combination (of electricity and heat), the SOFC system can achieve an overall **higher level of efficiency** at the beginning of its life cycle.

As the project proceeds, the partners plan to gradually increase the proportion of hydrogen in the gas mixture of the SOFC system and thus achieve further reductions in carbon emissions.

6. Conclusion

This whitepaper has explored the challenges and opportunities of decarbonising the UK's electricity system, with a focus on the role of hydrogen to power and solid oxide fuel cells (SOFCs) in supporting intermittent renewable generation. It is evident that a single solution cannot address this complex problem, and a combination of diverse technologies is essential to achieve net-zero targets.

Hydrogen has a role to play in decarbonising the UK's energy system but it requires significant infrastructure and investment to facilitate the transition to a hydrogen economy. Adopting hydrogen to power, through turbines, engines and fuel cells, could not only lead to a lower carbon power system but also reduce overall system costs. However, whilst decarbonising the power sector is essential it is also very expensive, and policies will need to be designed to encourage investment and innovation in this area.

Analysis on the routes to achieving net zero have demonstrated that an integrated energy system, using both electricity and hydrogen, can achieve significant cost savings and support the achievement of decarbonisation goals. For example, research carried out by Guidehouse, demonstrated that an **integrated energy system, strategically utilising both electricity and hydrogen, could result in up to £38 billion of energy system savings, when compared to an energy system with limited integration**.[1]

In order to realise these savings a GB-wide hydrogen network will be required and increased certainty on this is needed imminently to drive investment in the hydrogen economy**. A hydrogen backbone in GB would connect producers with consumers and allow the system to access the full benefit of using hydrogen storage to reduce curtailment of renewable energy.** In addition, incorporating hydrogen into the energy system resolves issues of relying on a single energy vector and can increase our energy system resilience.

The UK is falling behind other nations in terms of investment in hydrogen[49], and there is a lack of clarity and certainty from the government on how to support the development of the hydrogen market. Other European governments have made quicker progress towards enabling hydrogen pipeline infrastructure, facilitated by the EU ten-year development plan.[50] More funding, support mechanisms, and policy frameworks are needed to overcome the barriers and risks associated with hydrogen deployment.

Any policies must recognise the significance of the synergies between the diversity of low carbon power technologies, fuels, asset sizes, configurations and locations that can help decarbonise the whole energy system, rather than considering technologies in isolation. There will be no one silver bullet to achieve decarbonisation goals and it's crucial that the Government provides support for a variety of technologies that can work together, rather than in competition. Whilst increased support has been provided for larger-scale generation, there is still a gap in the support for smaller-scale, distributed assets (such as part of a microgrid) which can provide a number of benefits to the energy system, including providing resilience, reducing grid capacity issues and lowering electrical upgrade costs. Decentralised generation, particularly fuel cells, can also offer significant efficiency gains when compared with centralised solutions, such as OCGTs. Fuel cells can offer an electrical efficiency of up to 60% and, when combined with heat recovery, can provide an efficiency of 90%, alongside avoiding electrical distribution losses and providing low carbon heat.

An example of how to support these technologies has been provided through Ireland's recently-released hydrogen strategy, which stands out from other countries by placing focus on short-term quick wins for establishing a hydrogen market – such as the use of fuel cells for power generation in data centres. The UK would benefit from taking a similar approach eventually building up to higher-capacity centralised power generation.

We are at a critical stage on our road to decarbonisation and it is essential that the Government does not close doors and a takes a holistic view of the energy system, providing support for the range of technologies, including smaller-scale, distributed generation, that are needed to support this transition. Many companies will be looking to make decisions now about how they power their business for the next 10-20 years but there is not the support in place for them to choose smaller-scale hydrogen-ready technologies. If a suitable policy framework is in place, smaller distributed generation assets can be deployed faster than larger centralised systems, allowing quicker progress to developing the UK hydrogen economy and achieving decarbonisation goals.

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