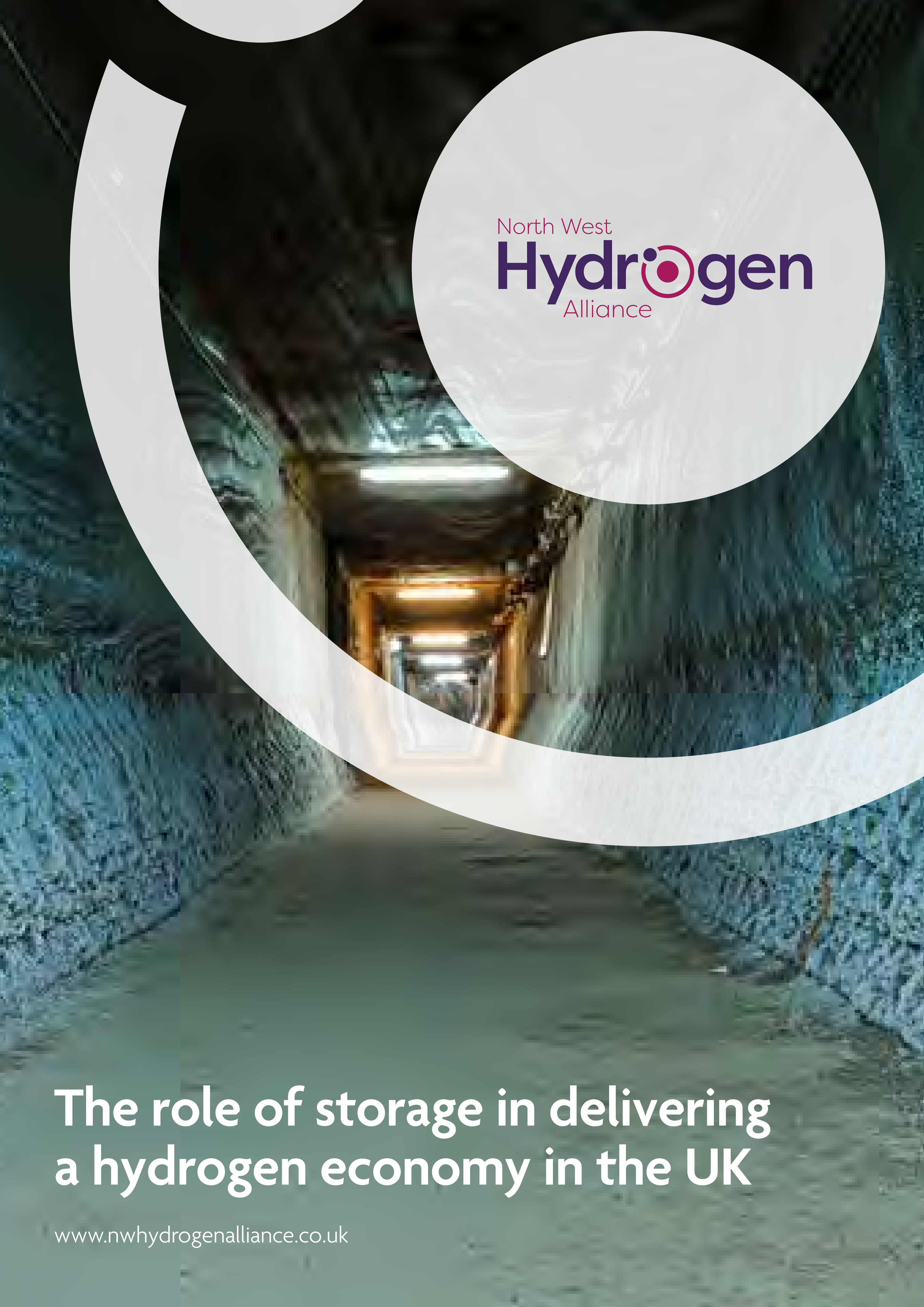


North West Hydrogen Alliance

The role of storage in delivering a hydrogen economy in the UK

www.nwhydrogenalliance.co.uk

North West Hydrogen Alliance

Low Carbon Hydrogen is one of the key solutions available to decarbonise the UK energy sector. The importance of hydrogen to the sector was recently reflected in the UK Government's decision to double the hydrogen production target from 5GW to 10GW by 2030 in its Energy Security Strategy.[1] Whilst much attention has been focussed on developing mechanisms, most notably the Hydrogen Business Model and the Net Zero Hydrogen Fund, to support hydrogen production there has not been sufficient attention on the enabling infrastructure required to deliver hydrogen at scale. Storage, vital to unlocking the full potential of hydrogen, has been a notable area of the hydrogen puzzle where government thinking is underdeveloped and where policy action has been slow.

Specifically, the government's Energy Security Strategy launched on the 7th April sticks to their unambitious and inadequate 2025 deadline regarding the release of the hydrogen storage business model. A hydrogen storage business model is needed to reduce the high levels of risk associated with the construction and operation of hydrogen storage facilities by providing some degree of certainty regarding return on investment. Ultimately, the timely release of the business model is key to unlocking final investment decisions on hydrogen storage facilities with long project lead times and therefore must be expedited to catch up with the hydrogen production business model which is soon to be opened to contract.

[1] British Energy Security Strategy (2022).

[1] Fortune Business (2020)

1. The need to address hydrogen storage

Large scale storage is necessary for hydrogen to deliver its vital role in decarbonising the UK economy for six main reasons.

1. To balance hydrogen produced with intermittent renewables

Large scale hydrogen storage is necessary to provide a constant supply of hydrogen from the intermittent hydrogen production process of renewably powered electrolysis. Wind and solar power in the UK operate at load capacities of 35.5% and 11.2% thus entailing that there will be periods of time when electrolytic hydrogen is not being produced.[2] However, demand in some hydrogen end use sectors, such as transport and industry is expected to be predictable and fluctuate little. A stored supply of electrolytic hydrogen, produced during periods of high renewable electricity generation and released during periods of low renewable electricity generation, is therefore vital to balance hydrogen production and demand in a world of ever-increasing renewable energy capacity. This is supported by the BEIS Long Duration Energy Storage report which concludes that, if hydrogen technologies are available then hydrogen can provide the majority of the necessary long duration storage, as it has the durations required to support a wind dominated system.[3]

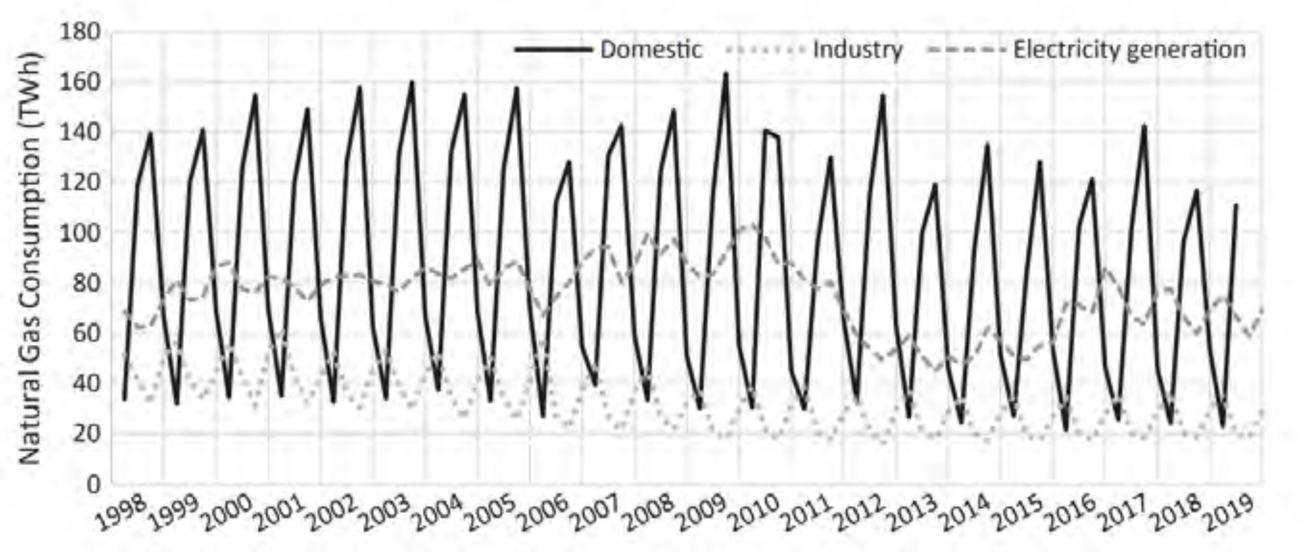
2. To maximise the efficiency of CCUS enabled hydrogen production facilities

Hydrogen storage allows the efficiency of Carbon Capture Utilisation and Storage (CCUS)-enabled hydrogen production facilities to be maximised. If there is a suitable hydrogen storage site, CCUS enabled hydrogen plants can operate at a consistent high load capacity all year round irrespective of daily, weekly, or seasonal demand. The ability to produce hydrogen at a high load factor, and hence to maximise revenue from the plant asset, will be crucial in convincing investors to commit the high upfront capital investment required for CCUS-enabled hydrogen production plant construction. It will also mean that once operational the fixed cost per kg of hydrogen produced by the plant will be reduced relative to the plant operating solely in response to demand fluctuation.

[2] BEIS (2021) DUKES 6.5. [3] Benefits of Long Duration Electricity Storage (2022).

3. To balance the energy supply to meet the variable demands of commercial and domestic heating

Large scale hydrogen storage is necessary to unlock the unique ability of hydrogen, initially through blending and eventually on its own, to meet the UK's daily and seasonal fluctuating heating energy demands in a low carbon manner. Most notably, the demand profiles of commercial and domestic space heating vary by season. In the winter demand is high, whereas in the summer it is low. Moreover, heating demand inside the winter is driven by cold snaps which are notoriously hard to predict more than a couple of weeks ahead. For instance, during the 2018 "Beast From The East" winter storm the hourly national natural gas demand peaked at 214GWh; a level which is around 46 per cent higher than the median hourly winter peak of around 140GWh, and much higher than the average hourly summer demand of around 35GWh.[4] Hydrogen therefore can play a key role time-shifting energy production to meet seasonal and shorter period spikes in heating demand that is currently met by natural gas storage in line pack or large-scale underground form.



Mouli-Castillo et al (2021) [5]

[4] UKERC, (2018). [5] Mouli-Castillo et al (2021).

4. To balance energy supply to meet the variable demands for electricity

As aforementioned, renewable electricity generation is inherently intermittent and therefore requires a fast dispatchable source of power to maintain supply during periods of low generation. Currently the majority of this dispatchable power is met by gas fired Combined Cycle Gas Turbine (CCGT) peaking plants that come online when renewable electricity generation is low and/or demand is high. As UK renewable electricity generation capacity is set to grow rapidly to achieve the UK government's net zero 2035 grid electricity target, intermittency of overall electricity generation will rise, and the need for low emission dispatchable power capacity operating at reducing load factors will only grow.

Hydrogen powered CCGTs are one of the most promising solutions to help meet this increased grid requirement for dispatchable power capacity. In order to allow hydrogen-powered CCGTs to achieve their grid balancing potential, there needs to be large scale hydrogen storage that is both quickly accessible and price competitive.

5. Energy Resilience

Beyond accommodating the expected fluctuation in hydrogen production from renewables and in heat and power gas demand, additional hydrogen storage capabilities beyond the minimum expected requirements can play a crucial role in providing national energy security and resilience. Unlikely and probabilistically unquantifiable but highly significant "black swan" events must be considered when planning critical infrastructure, such as the energy system, over long-time horizons. A major critique levelled at the current UK energy system is the low and declining levels of natural gas storage capacity (around 2% of total UK annual gas demand) which some argue has led the country to be left vulnerable to natural gas price spikes.[6] Notably, the UK has been unable to pre-empt future gas price volatility that may arise during the winter of 2022/3 by building up stored natural gas supplies given that its limited storage facilities are already operating at 90%+ of capacity[7].

In the hydrogen energy system context black swan events could be either supply or demand side. On the supply side given that hydrogen has to be produced rather than simply extracted, the hydrogen system will require levels of resilience to production outages. Some examples of black swan events on the supply side may include renewable electricity generation (and hence electrolytic hydrogen production) being significantly below predicted levels as a result of prolonger winter anti-cyclones or CCUS enabled hydrogen facilities being offline due to unexpected storm damage.

Meanwhile, on the demand side an example of a black swan event may be a particularly bracing "once in a century" winter leading to extremely high demand for gas heating. At best these demand-inducing and supply constricting black swan events may lead to spiking hydrogen prices, while at worse they may lead to energy rationing. Having buffer reserves of hydrogen stored can help the country to react more agilely to an array of (often unknowable) black swan events. This therefore ensures that in the short-term economic activity can continue relatively unaffected and that in the long-term consumer, business, and investor confidence in the energy transition will remain intact.

6. Blending balancing

A level of storage is likely to be critical if the government decides to proceed with up to 20% hydrogen blending in 2023 following from their blending value for money assessment. This is since hydrogen input into the gas distribution network will need to be smoothed over time to ensure that the safe 20% hydrogen blend limit for existing gas appliances is strictly kept to across the entire network.

[6] New Statesman, (2021). [7] Aggregated Gas Storage Inventory, (2022). 92.21% as of 31/05

2. Current UK gas storage

The UK currently has 1500 million cubic metres (mcm) of estimated working gas volume across salt caverns and depleted oil and gas reservoirs (excluding Liquefied natural gas (LNG)).[8] At a volumetric density of 36.1 MJ/M^3 this amounts to around 15TWh of storage capacity.[9] Per day this storage capacity can provide 115 mcm of estimated natural gas volume to meet unexpected demand increases.

Most significantly for the North West is the Stublach salt cavern storage facility in Cheshire operated by Storengy which has an estimated working gas volume of 400mcm across 20 caverns with a maximum withdrawal rate of 33 mcm per day. Also significant in size is the Holford salt cavern gas storage facility also in Cheshire which is operated by Uniper and has an estimated size of 237mcm with a maximum withdrawal rate of 22mcm per day.

Overall, the UK pales in comparison with the rest of Europe in terms of the size of its gas storage facilities in proportion to its national gas usage. The UK's 15TWh gas storage represents 1.7% of the UK's 2019 total gas consumption or around 6 days of UK average demand.[10] In comparison Germany and France have the ability to store 239TWh and 133TWh of natural gas providing them with both a far greater buffer stock of gas for resilience purposes and a larger number of potential storage sites to convert to store hydrogen.[11] It must however be noted that the UK has been able to cope with low storage levels in the past due the role of its North Sea gas reserves in increasing production to respond to demand fluctuations alongside the significant capacity of interconnectors with Norway and the rest of Europe.

[8] Ofgem (2021). [9] UK Gov (2021). [10] BEIS (2020). [11] GIE AGSI (2022).

3. What scale of hydrogen storage will be needed?

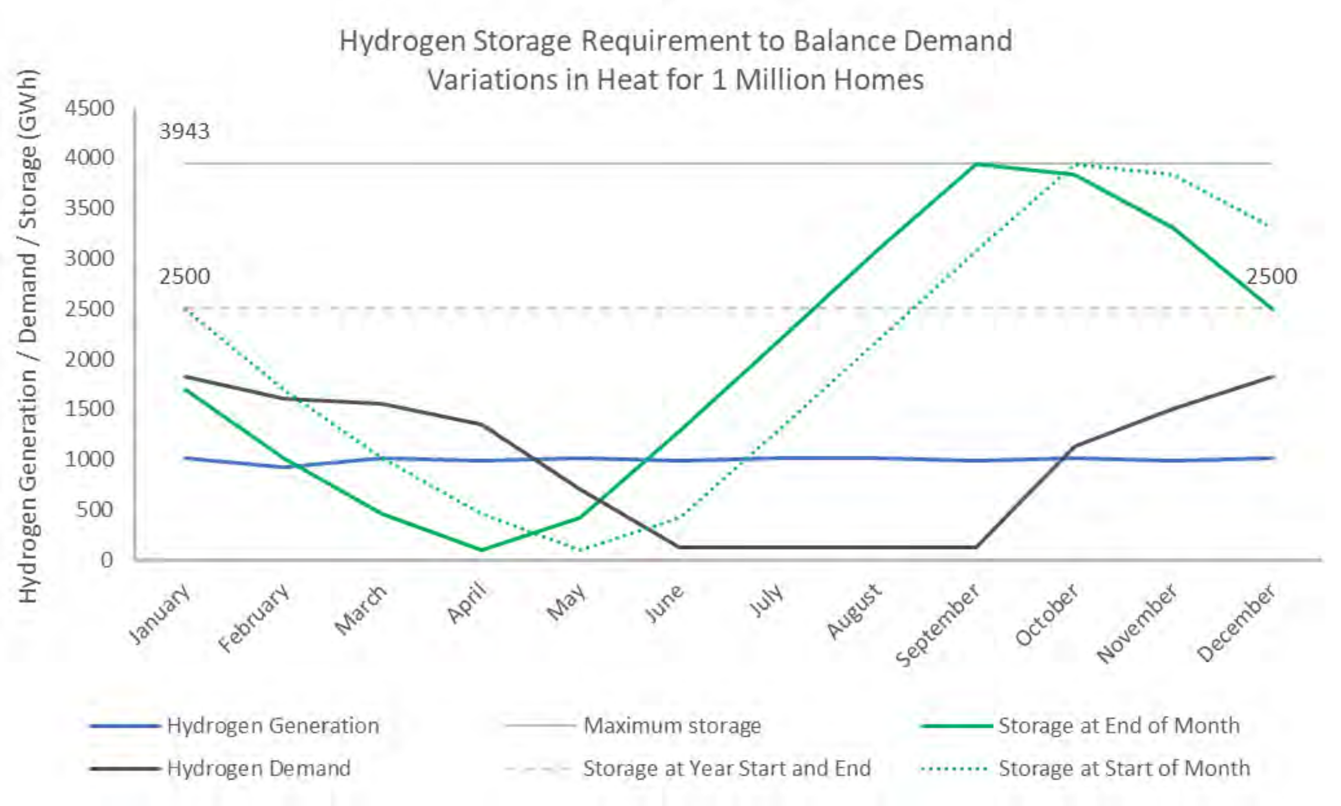
Initially, until demand from dispatchable power and commercial heating is realised, only small-scale daily hydrogen storage may be required. The storage solutions deployed will likely be similar to those currently used by existing industrial and transport users of hydrogen.

Early hydrogen production is likely to be strongly linked to its specific end uses, notably in industry and transport, that will have hourly storage needs that can be serviced by compressing hydrogen in a metal cylinder tank between 15MPa (for industry) and 100Mpa (for a transport refuelling station). Moreover, if in 2023 hydrogen blending onto the gas distribution network is permitted by the Government and there is a form of revenue support available, then surplus hydrogen from early hydrogen producers will have a last resort off taker and will therefore not have to be stored at large scale underground to prevent temporary production pauses.

However, as seasonal storage demand for hydrogen from dispatchable CCGT plants and from commercial and domestic heating is realised, the scale and time profile of small-scale hydrogen cylinder storage will neither be spatially or economically feasible. This is primarily due to the compression process requiring a large amount of energy and the high material costs that are a consequence of high-pressure storage over a long period of time.[12]

Mouli-Castillo, Heineman & Edlmann provide a sense of scale of the seasonal hydrogen storage levels required for UK domestic heating in their 2021 paper. Specifically, they predict that in a low carbon future if the existing domestic heating demand was to continue to come from gas that 77.9TWh of underground hydrogen storage would be required, a figure equivalent to around 25% of the UK total energy from natural gas currently used for heating annually.[13] They note that whilst this is a large amount of hydrogen storage when compared to the UK's gas storage capacity today (see section 2), geologically this is far below the amount of storage potential that can be provided by salt caverns and depleted oil and gas fields located in the UK (see section 4).

More specifically, we estimate almost 4 TWh of hydrogen storage would be required to balance the seasonal variation in hydrogen demand for 1 million homes. The monthly hydrogen generation, demand and storage position is shown on the graph below. The analysis assumes a 95% load factor of hydrogen generation and no additional storage for resilience so in reality, storage requirements would be larger than in this scenario to provide energy security. However, there are other considerations such as greater diversity of supply and demand that could impact this estimate. While within a similar range, at 33% this analysis finds a slightly larger proportion of storage to annual demand than the paper mentioned in the Mouli-Castillo, Heineman & Edlmann paper.



ITEM	VALUE	UNIT	SOURCE
Annual Hydrogen Demand Per Household	12,000	kWh	Ofgem
Monthly Proportion of Hydrogen Demand	1-15%	%	Assumption
Hydrogen Generation Capacity	1.44	GW	Assumption
Hydrogen Generation Load Factor	95%	%	Assumption

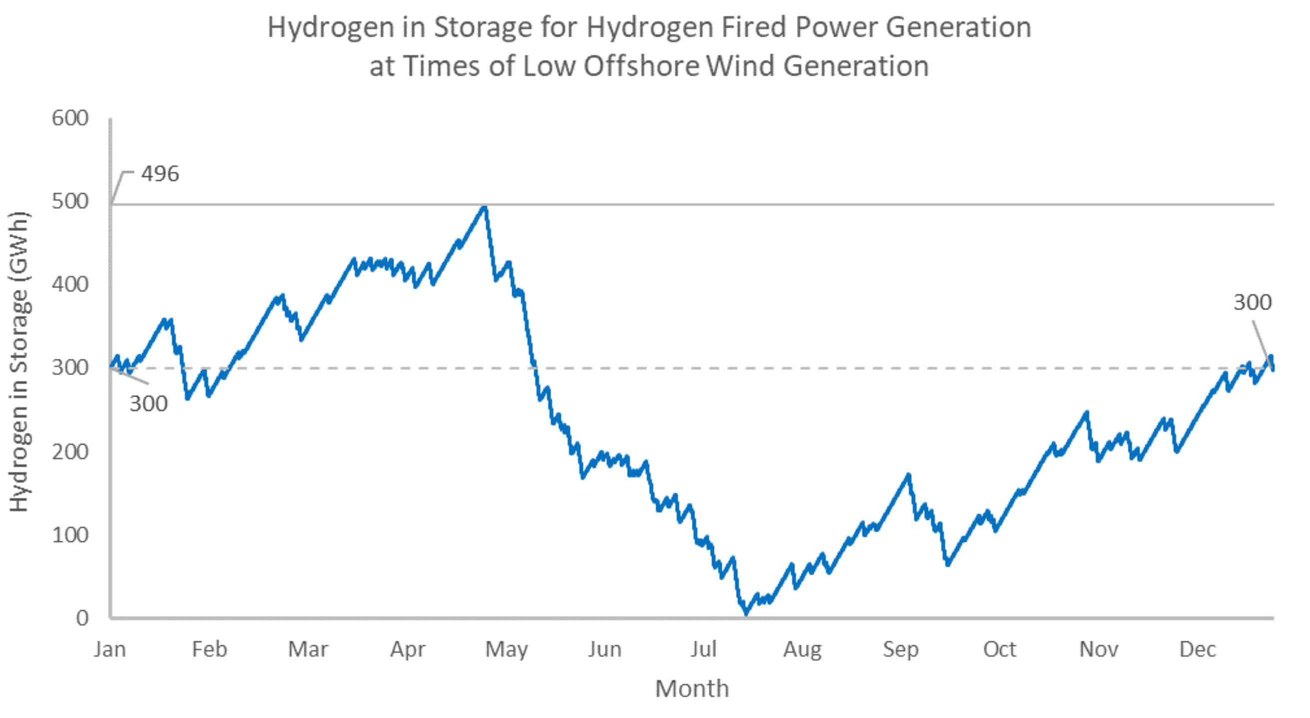
[12] HyResponse. [13] Mouli-Castillo et al, (2021).

While hydrogen is likely to have a dispatchable role in power generation, estimating storage requirements for hydrogen fired power generation is challenging. This is due to uncertainty in the load factor and load profile that hydrogen power generation will operate at. Aurora estimate that hydrogen will be the most cost-effective form of dispatchable power at load factors less than 20%[14]. However, this estimate does not allow easy estimation of a hydrogen power generation load profile. As offshore wind is likely to be the dominant form of power generation in the UK's future electricity grid, the following analysis assumes that hydrogen power generation turns on when offshore wind generation is below 20% of capacity using the hourly electricity generation of an offshore wind farm. This gives a load factor of hydrogen fired power generation of 19.7%, in line with Aurora's estimate of its cost-effective use.

Despite reflecting some of the intermittency of renewable energy and therefore the requirements of dispatchable power to meet electricity demand, this assumption is flawed as it does not take into account other forms of electricity production, variations in demand or the potential for demand side response. However, in the absence of a full energy systems model it gives an indication of the scale of hydrogen storage required for low load factor hydrogen power generation.

The analysis estimates that an 810 MW_e hydrogen fired gas turbine, the same size as Rocksavage Power Station would require approximately 500 GWh of hydrogen storage. This is estimated by assuming constant hydrogen generation feeding a storage asset which in turn provides hydrogen to the power plant. The graph below shows the hydrogen in storage at any point in time with the amount of hydrogen in storage at the start and end of the year at 300 GWh. It should be noted that the storage requirement of 596 GWh does not provide resilience to external factors which may require a more dispatchable power for example low renewable generation or a colder than average year. Therefore, in the real-world additional storage would be required to provide this energy security.

Item	Value	Unit	SOURCE
Hydrogen Power Generation Efficiency	57.8%	%	Element Energy
Hydrogen Power Generation Load Factor	19.7%	%	Model Output
Hydrogen Power Generation Capacity	810	MWe	Assumption
Hydrogen Generation Capacity	290	MW	Assumption
Hydrogen Generation Load Factor	95%	%	Assumption



[14] Aurora (2020).

4. What types of hydrogen storage options do we have?

In the UK there are two main types of geological hydrogen gas storage options. Salt Caverns (both existing and newly created) and depleted oil and gas reservoirs.

Salt Caverns

Salt caverns are the current gold standard for storing large quantities of hydrogen at low cost and high efficiency due to their extremely suitable characteristics. The halite (rock salt) that makes up salt caverns is viscoplastic, self-healing and gas tight. Most notably salt cavern chambers are large and relatively open, meaning that the rate of flow/dispersion of gas is not interrupted. This characteristic facilitates high gas discharge rates permitting fast responses to hydrogen demand spikes; a characteristic that will be strongly valued by future hydrogen dispatchable power generation plants. Finally, given the inert nature of the halite, there is a low risk of contamination of the stored hydrogen which hence reduces operational purification costs upon extraction.

Notably, unlike many of the technological requirements of the future hydrogen economy, the technology to both construct and operate salt cavern hydrogen storage is highly mature. Firstly, the process of constructing salt caverns, by drilling a borehole, cementing in steel piping and then leaching the planned cavern with water, is well established globally. Secondly, real world operation of hydrogen storage facilities have been ongoing safely for 50 years. In fact, the UK is home to the world's oldest salt cavern hydrogen storage facility in Teesside which opened in 1972 and has a capacity of 3 caverns at 70,000m^3 each[15]

In addition, the potential for building new salt caverns in the UK for hydrogen storage is bright. Fortunately, the UK, and specifically the North West, is blessed with a geology that permits the building of further salt caverns. The British Geological Society estimate that there is 284TWh significant potential for hydrogen storage caverns in the Cheshire Salt basin alone and more is expected to be found in the yet to be fully evaluated east Irish Sea.[16] Whilst it is important to remember this figure is only a resource estimate and does therefore not take into account the economic or social feasibility of the creation of salt caverns, it does still demonstrate that even in high hydrogen demand scenarios that the North West could physically have its resultant storage needs met by salt caverns.

Moreover, there is also significant existing salt cavern storage capacity used for natural gas that can be converted to store hydrogen in a relatively faster timeframe and at a lower cost. In total the UK has a potential hydrogen storage capacity in its six natural gas salt cavern facilities of 2.8TWh. Given that these salt cavern storage facilities are often in separate adjacent chambers, it would be possible to convert individual facilities from natural gas to hydrogen in stages mirroring the UK's wider gas transition.

[15] HyUnder (2013). Williams, J et al. 2020. [16] Theoretical capacity for underground hydrogen storage in UK salt caverns. Unpublished ACT Elegancy project report number 5.4.1e

Porous Rocks

After salt caverns, depleted oil and gas reservoirs formed from porous rocks, notably sandstone in the UK, are the most promising prospect for large scale hydrogen storage. Prior to closure of the Rough storage facility in the North Sea, the UK relied primarily on depleted fields for its natural gas storage requirements. This ex-facility, alongside other depleted gas fields, could play an important role in hydrogen storage if salt caverns are not feasible due to cost or locational constraints. Overall, it is estimated that the UK has a total theoretical hydrogen storage capacity in porous gas fields of between 2660TWh and 6900TWh; an order of magnitude in advance of even the most ambitious UK hydrogen future storage requirement scenarios[17]

However, unlike converting existing salt caverns, converting depleted oil and gas fields to store hydrogen is more challenging. Notably, not all depleted fields can store hydrogen. Only those with high enough salinity (over 30% NaCl equivalent) and temperature (>120C) conditions to prevent the growth of hydrogen-metabolising bacteria can be considered suitable due to the hydrogen losses and contamination that would be incurred otherwise.[18]

Moreover, porous rocks have numerous other characteristics that make them less attractive as a potential hydrogen storage facility. Most notably they have a far slower withdrawal rate than salt caverns due to their porous nature which impedes the flow of gas. This consequently makes porous rock storage more suited to deliver seasonal storage requirements than for shorter term hydrogen demands. Secondly, depleted oil and gas reservoirs have the presence of both rocks and remnants of hydrocarbons that will contaminate the stored hydrogen. This entails that purification upon extraction will be required for the hydrogen to be used in fuels cells. Unlike salt caverns where no impurities are introduced to the hydrogen during storage, porous rock storage adds significant costs to the storage process upon extraction.

Above ground storage technologies

The options outside of geological storage are currently technologically immature and not expected to be ready to meet the UK's heat and power generation hydrogen storage demands of the 2030s. The brightest non-geological hydrogen storage technologies are adsorption, whereby molecular hydrogen is adsorbed into another material and held by weak Van Der Waals bonds, and chemical, whereby atomic hydrogen is bonded more strongly chemically to a metal or another lighter element. These solutions are still only in initial research stages and are expected only to be financially feasible for large scale storage where salt cavern or porous rock storage is not geologically possible.[19]

[17] HyStorPor (2021). [18] HyStorPor (2021). [19] Andersson & Gronkvist (2019)

5. Hydrogen Storage in the North West

In the North West there are a number of pioneering hydrogen storage projects. Firstly, the HySecure project, a collaboration between Storengy and INEOS, was seeking to demonstrate the deployment of grid-scale storage of hydrogen in a single salt cavern. Phase 2 of the project (not currently funded) aims to construct a new bespoke single hydrogen storage salt cavern sized 350,000m3 at Stublach via solution mining. The cavern could be filled with electrolytic hydrogen produced at INOVYN's Runcorn Site to provide a reliable hydrogen supply for future fuel cell electric buses, ferries, HGVs, and trains across the North West.[20]

Secondly, INEOS has planning consent in mid Cheshire, at the Holford Brinefield, for another large scale salt cavern gas storage facility. Known as the Keuper Gas Storage Project, it will consist of 19 salt caverns capable of storing 450mcm of natural gas if developed. As part of the HyNet project, INEOS are currently applying for a change of planning consent and with Costain are undertaking an engineering study to convert the project for the storage of hydrogen gas. Once fully developed the project will be capable of storing 1.3TWh of energy as hydrogen gas and will be the largest such facility in the world. The facility will be capable of acting as both a summer / winter store and means of daily balancing of the HyNet hydrogen network to keep customers supplied during the peaks and troughs of demand and dispatchable power generation

Thirdly, there are several innovative hydrogen storage projects being funded by BEIS's £68million dual stream Long Duration Energy Storages Competition (LODES) across the UK. The innovation competition has provided grants to projects that will accelerate the commercialisation of breakthrough long duration energy storage technologies ranging from electric, to thermal, and power[21]. Specifically for hydrogen in the North West, a grant has been awarded to the HEOS project led by Gutteridge, Haskins & Davey Ltd to conduct a feasibility study into storing grid generated hydrogen in their patented metal hydride at the Thornton Science Park in Cheshire.[22]

[20] Inovyn (2020). [21] BEIS (2022). [22] Hydrogen Central (2022).

6. Recommendations

Accelerate the Business Model for Large Scale Hydrogen Storage

Crucial to investment decisions being made on the construction of large-scale hydrogen storage is the provision of a business model that guarantees potential hydrogen storage providers an investable rate of return. We recommend that BEIS move forward their 2025 timeline for the large scale hydrogen storage business model by at least a year given the long lead times (up to 7 years) that new and converted hydrogen storage facilities face so that the UK can start to have the necessary scale hydrogen storage by the late 2020s. Prior to the issuing of the first contract in 2024, we recommend that BEIS open a consultation on this business model by at least Q1 2023 (Q4 2022) and provide a draft heads of terms by at least the end of 2023. Ultimately, the time disconnect of BEIS' CCUS-enabled hydrogen production business model (open for contract in 2023) from the large-scale hydrogen storage business model is deeply worrying given the aforementioned critical nature of storage to unlocking the full potential of hydrogen.

Action	Delivery Date
Consult on the Hydrogen Storage Business Model	Q1 2023
Issue a draft heads of terms on the Hydrogen Storage Business Model	Q4 2023
Issue the first contracts with the Hydrogen Storage Business Model	2024

There are two types of policy mechanism that could form the hydrogen storage business model. The first potential option could be a cap and floor mechanism similar to that used successfully by Ofgem in the regulation of large scale electricity interconnector projects.[23] This policy mechanism works by capping high storage revenues and sharing them with consumers while correspondingly providing a floor during periods of low storage revenue. This mechanism would spread some of the risk associated with hydrogen storage and encourage potential storage providers to make the long-term investment decision in storage that are required to deliver large-scale hydrogen storage. A price band would also ensure that during most periods of their operation storage facilities would still be incentivised to maximize efficiency so that they can charge market competitive prices to their storage customers.

The second potential option for the hydrogen storage business mechanism is to guarantee a full revenue stream through the Regulated Asset Base (RAB) model that has been proposed to finance new nuclear power stations.[24] The allowed revenue stream for the storage facility would be set by an independent regulator taking into account all necessary project expenditure during the construction and operation phases, and would also include a reasonable return on capital invested. In a RAB model government protection for investors against specific remote, low probability, but high impact events would also likely be provided. Ultimately, this option would likely be effective in attracting finance for storage projects but may be politically more difficult than a cap and floor due to the large levels of risk transfer from private finance to the Government and end-use consumers that it would involve.

In depth analysis will need to be conducted into the most suitable policy mechanism for the hydrogen storage business model once BEIS have released their consultation into the matter.

[23] Ofgem(2021). [24] BEIS (2019)

Small Scale Storage inclusion in the hydrogen production business model

In the nearer term it is vital that hydrogen production business model funding for small scale storage costs associated with early electrolytic hydrogen production projects is provided for in order to unlock the pending investment decisions for these projects. These projects are aiming to be operational before the launch of the hydrogen storage business model so will need support in shouldering the extra costs of their small-scale storage requirements. Fortunately, the hydrogen production business model heads of terms was released on 8th April 2022 and does state that the strike price of the revenue support mechanism, which aims to reflect the hydrogen price a producer needs to cover its costs and an allowed return on investment, will include both the capital and operational costs associated with small scale storage infrastructure. BEIS note that the level of this support will be negotiated on a project-by-project basis taking into account several factors including necessity, affordability and governmental value for money.[25]

Develop network and storage infrastructure in tandem

It is crucial that the hydrogen transport network and hydrogen storage infrastructure grow together in tandem. Large scale hydrogen storage necessitates transport infrastructure for hydrogen to reach its end users. While this may only require short distance transport for centralised users such as power generation plants located very close to hydrogen storage and production facilities, decentralised users such as domestic heating require a far more extensive network of transport infrastructure in order to move hydrogen from storage to end use. We recommend that the FSO coordinates with the key players in hydrogen to ensure that both hydrogen networks and storage are built and/or repurposed in tandem to unlock the full potential of hydrogen and avoid efficiency losses due to imbalances in their respective scale ups.

[25] BEIS (2022)

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