This is an extract from the final report – please find the complete document in the full documents section of the website.

Storage

Energy storage systems for wind turbines have a vital role to play in effectively optimising the efficiency and reliability of wind energy. Often, wind turbines capture and produce significantly more energy than is required at that immediate point in time (Ampowr, 2024). Therefore, an energy storage system is crucial when considering the varying scales of supply and demand. If excess energy from long periods of high wind can be stored and readily available for use at a time in the future when the wind may be limited, or during periods of abnormally high demand, it maximises the capability of wind energy and helps to ensure a stable and dependable energy supply. There are several different types of energy storage systems (ESS) that have been considered for the storage of excess wind energy including battery storage, flywheel storage, air energy storage and hydrogen storage.

Battery Energy Storage

Battery storage systems (BSS) are widely used for wind energy because of their scalability - especially in large-scale commercial production. They can be conveniently placed on offshore platforms within containers, requiring no modifications (Yessica Arellano-Prieto et al., 2022). Energy is stored in charged batteries and discharged when needed, providing reliable support for wind energy production. BSS offer rapid response times, high efficiency, and adaptable scaling to meet varying requirements (Ampowr, 2024). They come in compact sizes and can be optimized for backup power during peak demand. Lithium-Ion batteries and Vaanadium Redox Flow batteries are commonly studied for the purpose of large-scale energy storage systems (Kim et al., 2021).

The Lithium-Ion Battery (LIB) offers the flexibility to be combined across different energy sources such as solar photovoltaics' to store excess generated power. Various studies have evaluated the feasibility of an economically viable LIB system for hybrid wind and photovoltaic energy and suggesting that there is short term profitability potential, but highlighted limitations due to their relatively short life cycle (Kim et al., 2021). Despite the LIB being widely used and mass produced, it can be a much more expensive route for energy storage than other options (MIT Technology Review, 2018). Additionally, lithium-ion batteries can be very sensitive to high temperatures during rapid charging, therefore, when used for wind energy storage, lithium-ion batteries are usually buried in the ground which would come at a considerable economic cost when considering their offshore potential.

One of the greatest concerns regarding the use of LIBs for the purpose of storing renewable energy, is their sustainability. Not only is the mining, processing and manufacturing of their raw and rare materials for the batteries tremendously energy intensive, but the disposal of used lithium-ion batteries is extremely environmentally damaging (IER, 2023). When lithium-ion batteries are disposed of in landfill, their cells can release harmful toxins, like the heavy metals, that can leak into the landfill and groundwater. This can also increase the risk of landfill fires that can burn for years on end.

The Vanadium Redox Flow Battery (VFB) is another type of rechargeable flow battery that uses four different oxidation state vanadium ions to store energy in the form of chemical potential (Kim et al., 2021). Different to a lithium-ion battery, a VFB has a long cycle life and can be scaled up with substantial flexibility, showing the potential of the VFB for seasonal energy storage in the power grid. However, VFB can come at a high technological cost, limited energy density and can exhibit degradation within the cell due to the harsh environment caused by the chemicals in the battery (Lourenssen et al., 2019). Nevertheless, VFB components are assumed to be around 95-100% recyclable compared to that of the lithium-ion batteries that are only 80-90% recyclable (Onu, 2021).

Flywheel Energy Storage

Flywheel energy storage works by rotating a rotor at high speeds, essentially converting the excess electricity into kinetic energy as a way of storage. To obtain the stored energy again, the rotor is decelerated, and the kinetic energy is converted back to electrical energy (Yessica Arellano-Prieto et al., 2022). However, flywheel energy storage comes with a variety of challenges as they generally have a lower energy density than the likes of compressed air energy storage or battery storage, in addition to short duration times for storing the kinetic energy (State of Green, 2017). This would make flywheel energy storage less feasible for large, commercial scale energy production.

Air Energy Storage

Liquified air energy storage (LAES) and compressed air energy storage (CAES) are efficient ways to utilise the air for storing excess energy (Ondřej Burian and Dančová, 2023). Like their names describe LAES stores energy in the form of liquified air and CAES in the form of compressed air, both of which utilise the thermal cycle for energy discharge.

Both CAES and LAES share the same storage options and working cycle, i.e., utilising a charge period for storage of energy and then a discharge period for releasing energy, however, both have different energy charge storage systems. LAES stores energy in thermal form at extremely low temperatures, below air boiling point (-195 degrees C), whereas CAES stores highly pressurised air at ambient temperatures (Ondřej Burian and Dančová, 2023). Due to the system in LAES store energy, the process of air cooling can reduce efficiency and lead to energy losses as well as requiring large amounts storage space (Khatana, 2023), therefore, for the purposes of our energy island design, CAES will only be considered.

Compressed air energy storage systems can be stored in naturally occurring underground salt caverns and when power is needed for electricity, the air is released which then propels turbines and generates energy. Studies have found that adiabatic CAES (CAES that are based on air compression and storage in underground geological voids) can be profitable when combined with a wind farm (Zhang et al., 2019). Figure 38 illustrates how compressed air energy storage can utilise underground salt caverns (naturally found in the ground around the UK) for storage purposes (Colthorpe, 2017).

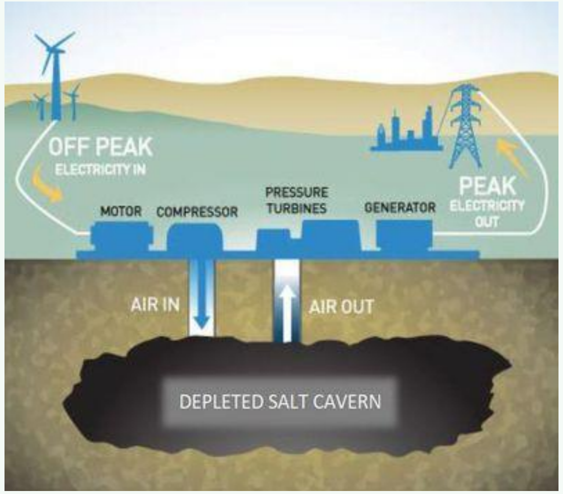

Figure 38- Naturally occurring salt cavern for compressed air energy storage (Colthorpe, 2017)

CAES are more environmentally friendly than batteries as they don't rely on rare or hazardous materials. Additionally, CAES have longer duration energy storage, with a lifespan of 20-40 years and a typical capacity of 500MWh- 2.5GWh (Energy Systems and Energy Storage Lab, 2024). Companies such as Corre Energy are making huge strides in the development of CAES and Hydrogen storage for offshore wind energy (Corre Energy, 2024). Their extensive research has proven that salt resources, excellent grid connections, existing infrastructure, and gas and hydrogen supply are ideally situated to serve as storage platforms for offshore wind, providing a roadmap of additional CAES and hydrogen storage projects on a global scale.

Hydrogen Energy Storage

Offshore wind farms offer a distinctive opportunity for large-scale production of green hydrogen utilizing desalinated seawater. Hydrogen is produced sustainably through electrolysis, using electricity to split the hydrogen and oxygen molecules in water. Excess electricity generated from the wind turbines can be used to power this process, making the entire hydrogen production chain carbon free, unlike alternatives like grey or blue hydrogen. Producing and storing hydrogen can enhance overall energy production efficiency by optimizing wind farm sites and minimizing transmission losses (Ramboll, 2024). Furthermore, repurposing existing assets in the North Sea that face future decommissioning for hydrogen production and storage, offers a value-added product to investors that are obligated to decommission rigs once their operation has ceased. Not only is this approach modular and scalable, but the option for geological hydrogen storage in porous rocks both within the North Sea and on land, has the capability to offer large-scale storage across diverse timescales.

To utilise seasonal storage of hydrogen, the capacity required is much larger than the typical storage tanks used above ground. Subsurface hydrogen storage, however, can meet the significantly larger scale required while providing an economically viable energy storage solution in both seasonal and short-term timescales (Energy Technologies Institute, 2018). Types of subsurface hydrogen storage options include, saline aquifers, depleted hydrogen reservoirs, or salt caverns. Thus far, commercial hydrogen storage has only utilised salt cavern systems. An example of this is the SABIC H2 facility at Teesside where the facility has three shallow caverns that can store up to 30 GWh of working gas (Cline, 2022). Although utilising salt caverns is influenced by geological considerations, the geotechnical requirements for hydrogen storage are similar to that of natural gas and is well known to be successful.

Expanding upon the potential of wind energy by utilising green hydrogen production with offshore or onshore hydrogen storage has the capability to accelerate the UK’s transition to Net Zero by providing a solution to storage issues while also aligning with the interests of investors.

Case Study: Shell’s Cross Wind Consortium with Holland Hydrogen 1 Plant

A 200 MW electrolyser is planned to be constructed on the Tweede Maasvlakte in the port of Rotterdam and will produce up to 60,000 kilograms of renewable hydrogen per day (Shell, 2022). In electrical terms, the energy density of hydrogen is equal to 33.6 kWh of useable energy per kg. Comparing this to diesel, which only holds around 12-14 kWh per kg (RMI, 2019)

The electrolyser will be powered by renewable energy sources from an offshore windfarm partly owned by Shell called Hollandse Kust (Noord). The green hydrogen will be transported by the HyTransPort pipeline to the Shell Energy and Chemicals Park in Rotterdam.

Shell acknowledges that offshore wind projects produce intermittent electricity, and that balancing the highs and lows of supply and demand will require a variety of new technologies to support the energy supply (Shell, 2020). This is why the offshore wind farm is also including a floating solar park; short term battery storage; turbines that are optimised and tuned to the network to minimise the negative ‘wake’ effects that the turbines have on each other; as well as the green hydrogen made by electrolysis.

Cavern Storage Capabilities

Underwater compressed gas energy storage (UWCGES) is one of the most viable solutions to large-scale offshore energy storage as it can make up for the shortages that come with more traditional energy storage and supply systems offshore (Hu Wang et al., 2022). However, there are many challenges that come with large scale UWCGES such as structural stability under cyclic loads, vortex-induced vibration, local scouring near foundations, biofouling of marine organisms and gas escape from the storage system. Despite these challenges, the large demand for clean energy will likely help to accelerate the development of offshore compressed gas storage alongside the advance in offshore energy production technologies. Figure 39 shows how UWCGES can be used in various applications, in both the short and the long term.

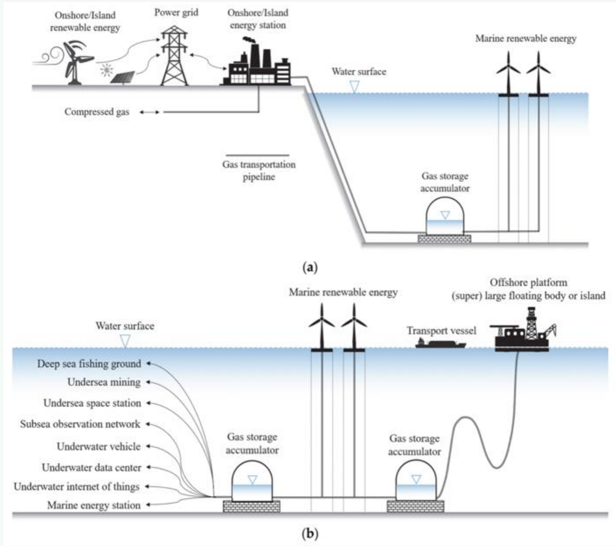

Figure 39- UWCGES (Hu Wang et al., 2022)

For the scope of this report, compressed air energy storage and hydrogen energy storage have been considered. Presently, CAES shows merit due to its predicted reliability with service life and low environmental impact, however, can show relatively low efficiency, energy density and variable economics. Despite the variable economics, CAES still has a lower cost than battery energy storage for large-scale applications.

Hydrogen energy storage (HES) shows a promising future in terms of application in industry, likely to play a huge role in the energy transition, however, presents various challenges when comparing the technology to CAES as there can be issues during production, transportation and utilisation (Hu Wang et al., 2022). When considering using hydrogen energy storage or compressed air energy storage, generally, underground storage facilities are utilised. For offshore underground storage systems, there are three options to consider: a newly drilled cavern which is made specifically for the new storage purpose; repurposing old oil or gas wells for the new energy storage system; or the use of existing, naturally occurring salt caverns within the earth geology.

Salt Caverns

Solution-mined caverns in salt structures are already being widely used as onshore subsurface energy storage for natural gas in the UK. This technology can be easily utilised for subsurface hydrogen energy storage (HES) or compressed air energy storage (CAES) due to the impermeable, inert and self-healing nature of the salt (Prof. Jürgen Adam et al., 2020). Research has found that in the Southern North Sea there is an abundance of salt structures that are located near current and future offshore wind projects, with the capacity to support a huge economic potential of CAES and HES up to 290 GWh of wind energy storage (Prof. Jürgen Adam et al., 2020). Studies from Shell, NAM and Store Electric in the Dutch sectors are well underway and should provide reliable data on the potential of offshore CAES and HES.

Similar to offshore, storing green hydrogen in onshore salt caverns has proven to be one of the most efficient and economical ways to store large volumes of hydrogen. The technology of using onshore salt caverns to store compressed gas is a mature technology as it has been done within the UK since the 70's

(Storage Working Group, 2022). Salt caverns have a low temperature naturally and their leakproof nature make the solution low risk to unwanted microbial or chemical reactions affecting the quality of the hydrogen that is stored. This low temperature also allows hydrogen to be compressed more efficiently than in above ground scenarios with low land and operational costs associated. These factors, alongside the strong geomechanical structure of hydrogen salt caverns, leads to the option having approximately a 100x higher volumetric energy density than CAES of the same size as well as being cheaper than battery storage options by a factor of 100 (costing less than £0.50 per kgH2) (Storage Working Group, 2022).

However, there are challenges associated with utilising salt caverns for compressed gas storage such as hydrogen as they aren't always widespread geographically and can have a limited size. Constructing new salt caverns can be done, however the high economical cost can often discourage investors, as well as the 7–10-year timescale that it can take to build new facilities. To construct a new salt cavern facility, a process called leaching is necessary and can take well over a year to complete, often requiring additional infrastructure to prevent environmental damage to freshwater from the brine that needs to be disposed of safely.

Rock Caverns

With significant geological adaptability, the use of rock cavern storage can present a viable alternative where other options aren't possible such as salt caverns. As an emerging technology, rock caverns are created through rock excavation in underground rock formations. After rocks have been excavated, a layer that seals the cavern is applied to prevent leakage of the gas (Department for Energy Security and Net Zero, 2024). The construction process for rock cavern storage is more intricate and expensive when comparing to other forms of storage as the excavation process is expensive, requiring significant drilling and blasting before the additional lining costs. However, despite these extra costs, rock cavern storage may offer a viable alternative if other options aren't available. Lined rock caverns for hydrogen storage is currently being piloted in Sweeden (Department for Energy Security and Net Zero, 2024) that may provide an insight into the potential of using the technology in the UK.

Depleted Oil and Gas Reservoirs

Depleted hydrocarbon reservoirs that were once utilised for the offshore oil and gas industry has been studied to propose a very suitable option for offshore compressed gas energy storage like HES (Storage Working Group, 2022). Not only are they sufficient in size, but they can seal natural gas and oil well, with 74% of natural gas already being stored within these depleted fields globally (Amid et al., 2016). Data and research for these fields are readily available as they have been utilised for the extraction of oil and gas for years, allowing an adequate understanding of the nature of the reservoir before construction begins. Repurposing the depleted wells minimises environmental impact and land usage as there would be reduced need for drilling and constructing new reservoirs or connections, minimising CO_2 output from large plant and construction methodologies, and reducing impact on the marine environment.

Additionally, the existing pipelines and infrastructure connecting to these reservoirs will considerably reduce capital costs of the gas transport. The H21 report describes the process as more cost effective than creating new salt caverns when comparing cost per unit volume of storage (Amid et al., 2016). However, there are still several challenges to overcome that are associated with the planning processes, as each case will have site specific circumstances. This includes understanding the differences between repurposing an oil reservoir rather than a gas reservoir as oil reservoirs will require a much more complex process of repurposing due to the nature of the leftover oil residues. There are also issues associated with the physical, chemical and microbial processes as sulphate reducing bacteria have the potential to contaminate the oil and gas reservoirs. Furthermore, the risk of hydrogen diffusion into the porous media is an issue that is raised frequently in the engineering community as compressed gas molecules like hydrogen are much smaller than methane molecules, however, recent findings suggest that the losses from diffusion and dissolutions can be minimised to 0.1% (Amid et al., 2016).

Despite the challenges, new modelling technologies allow the prediction of multicomponent flow behaviours, allowing design to limit base gas and working gas from mixing, mitigating risks that have previously been a concern within the industry such as ‘viscous fingering’ and ‘gravity override’ (Hassanpouryouzband et al., 2021). Research projects such as the HYStorPor and HyUSPRe investigated this issue and found no significant losses during laboratory testing. Additionally, recent studies suggest that the risk of geochemical reactions between hydrogen and the minerals in the storage reservoirs is unlikely within the timespan of hydrogen that is seasonally stored.

Various feasibility studies and reports by the groups such as the Oil and Gas Technology Centre, have identified that by completely repurposing a typical large offshore asset, circa 20,000kg of hydrogen could be produced per day (Marram Wind, 2024) (equivalent to 0.0006666 TWh a day and thus, 0.243309 TWh a year (Idealhy, 2024)). Additionally, HyUSPRe (Hydrogen underground Storage in Pourus Reservoirs) have indicated that the average depleted gas field converted for hydrogen storage will have a capacity of 1-5 TWH (HyUSPRe, 2023).

Aberdeen Proposal:

Considering the research discussed, the capacity for offshore energy storage and the storage needs of an energy island constructed off the coast of Aberdeen, both hydrogen energy storage (HES) and compressed air energy storage (CAES) present viable options, each with their own considerations.

CAES, particularly adiabatic CAES has been shown to be profitable when combined with wind technology, offering efficient energy storage solutions that are environmentally friendly and avoid reliance on rare of hazardous materials. The CAES systems have long duration energy storage, with lifespans ranging from around 20-40 years and capacities of around 500 MWh to 2.5 GWh.

However, HES offers a unique potential for mass production of offshore green hydrogen, utilising excess offshore wind energy to produce green hydrogen through electrolysis. Prospects for offshore HES can offer large scale hydrogen energy production and storage that may present as an investment opportunity for current owners of offshore assets in a UK climate that is preparing to switch their industries from the burning of fossil fuels to a carbon neutral alternative.

Tractbel and partner companies have designed one of the first offshore infrastructure and processing facilities for the storage of offshore hydrogen (Durakovic, 2021). The development outlines a scalable large-scale offshore hydrogen storage solution that facilitates the compression and storage of 1.2 million cubic meters of hydrogen. The design features a platform and underground salt caverns that can be used for storage and buffer for the hydrogen produced before transporting the gas via a pipeline network to the onshore grid. In response to predicted future mass H2 energy demands, Tractebel believe that offshore sites are key to industrial scale hydrogen production and from that developed the offshore hydrogen platform concept in 2019, followed by an improved and scalable version in 2020 and now developments into its design, Figure 40 shows this representation (Durakovic, 2021).

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Figure 40- Offshore Hydrogen Platform (Durakovic, 2021)

The concept is based on converting 2GW of green offshore wind power into hydrogen, however, allows for extensions or individual adaptations. Tractbell designed storage and compressor platforms that would process 400,000 Nm3/h of hydrogen that is stored within underground salt caverns at a pressure of up to 180bar. The salt cavern storage systems buffer the production peaks while optimising the flow rates so that the export pipeline is efficiently and economically designed. Furthermore, the geological nature of the North Sea is well suited for the solution as there are underground rock salt formations that could facilitate the large storage volume needed for hydrogen storage.

However, when considering under water compressed gas energy storage (UWCGES), there is debate over the utilisation of naturally occurring salt caverns compared to repurposing depleted hydrocarbon reservoirs. By utilising depleted hydrocarbon reservoirs for offshore compressed gas storage, particularly when considering HES, there are numerous advantages compared to the use of natural salt caverns, such as the established knowledge that these wells have sufficient capacity for gas storage. Their appropriate volume and the availability of existing infrastructure will significantly reduce capital costs for hydrogen transport and need for capacity expansion. The locations of these reservoirs are known, with existing rigs in nearby proximity for transport of personnel, equipment and maintenance support to potential storage facilities.

Additionally, there is readily available, accessible data and research of the hydrocarbon fields in the North Sea from years of oil and gas extraction, providing a comprehensive understanding of the reservoir characteristics before construction begins and therefore minimising uncertainties in design.

One option within the scope of this project would be the oil and gas reservoirs underneath and nearby the Buzzard Platform. Figure 41 shows the buzzard platform, with the module to the right (circled in red), positioned directly above an oil reservoir.

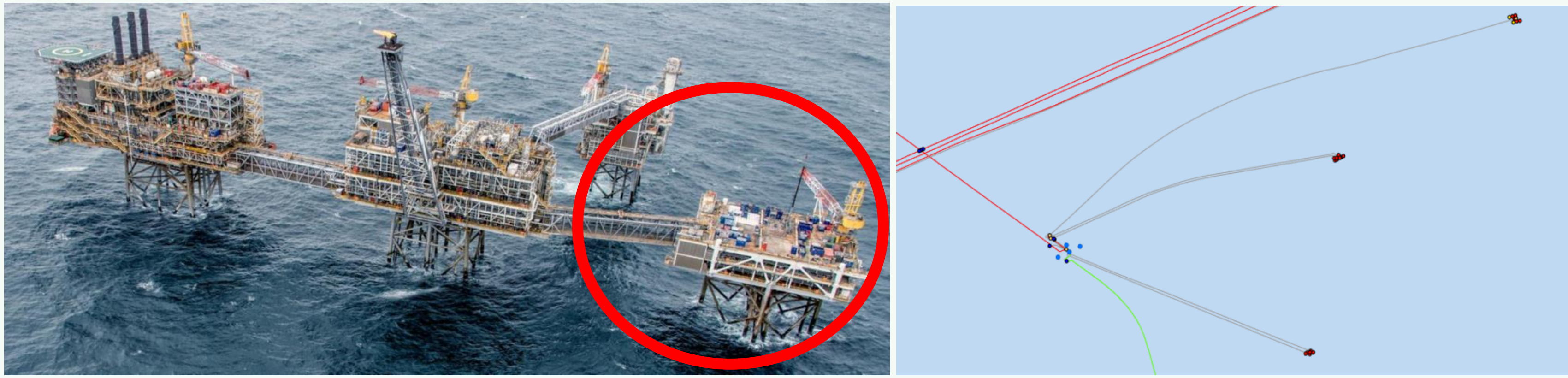


Figure 41- Buzzard Platform and GIS Distance to Oil Wells

Figure 41 shows the GIS map of additional oil/gas wells nearby, all with connections to the Buzzard platform. The red clusters show the location of oil/gas wells, the grey lines are the pipeline connections (all within 5km of the platform), and the blue dots show the location of existing platforms. This provides an opportunity for future expansion of offshore hydrogen storage within the scope of the energy island and the potential to increase renewable energy production significantly.

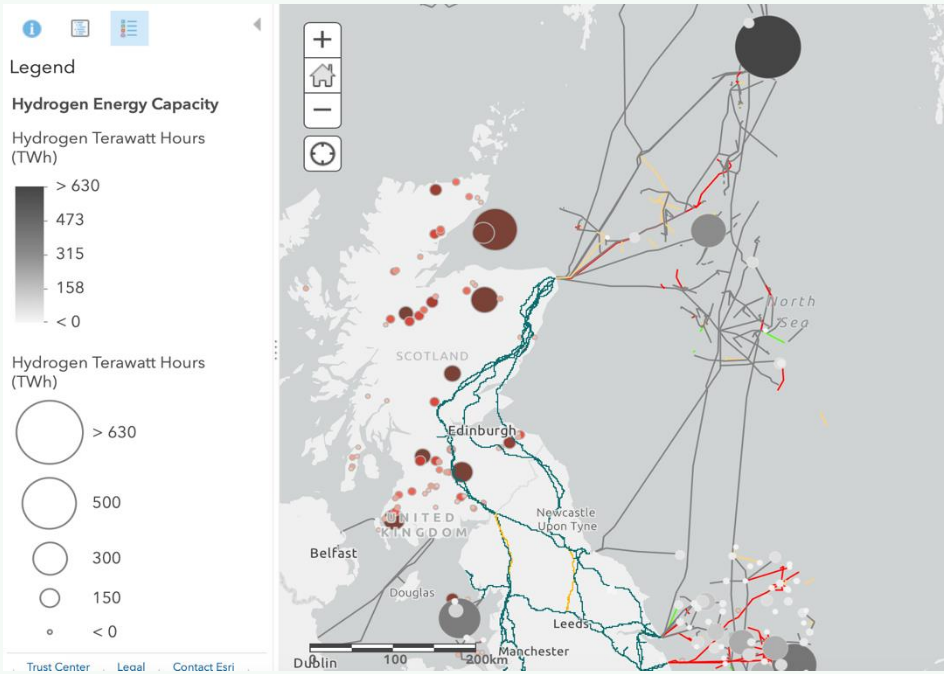
Similarly, at the Golden Eagle platform, there is an oil well located underneath one of the modules on the rig. Figures 42 and 43 show the Golden Eagle platform and the GIS image that identifies the reservoirs and pipeline infrastructure that are near the Golden Eagle platform, respectively.

Figure 42- Golden Eagle Platform

Figure 43- Oil Wells around Golden Eagle shown on GIS

Edinburgh University have identified through their accessible ArcGIS mapping database the Hydrogen storage potential in geocryological formations across the UK (including salt caverns, rock caverns and depleted gas fields). The map shows an approximate capacity of 158 TWh of hydrogen energy storage in depleted reservoirs (The University of Edinburgh, 2024) in a region relatively close to the Buzzard and Golden Eagle platform in the North Sea (Figure 44).

Repurposing the depleted reservoirs minimises environmental impact and land usage as there would be reduced need for drilling and constructing new reservoirs or connections, minimising CO2 output from large plant and construction methods, therefore reducing impact on the marine environment. Challenges presented associated with the physical, chemical and microbial processes when repurposing existing oil and gas wells such as the contamination due to sulphate reducing bacteria are currently being researched, alongside mitigation measures for these issues. Recent findings suggest that losses due to hydrogen diffusion and dissolution can be minimised with the aid of new technologies that have the capacity to predict multicomponent flow behaviours so to prevent these hydrogen losses.



Overall, the repurposing of depleted hydrocarbon reservoirs in the proximity of the Buzzard and Golden Eagle platforms for the purpose of offshore hydrogen energy storage, offers a unique combination of appropriate storage capacity, existing infrastructure, accessible data and continuing technological advancements in the

Figure 44- UK Hydrogen Storage Database: Map of North Sea (The University of Edinburgh, 2024)

industry that make this a highly favourable option. Providing that the potential challenges can be effectively mitigated with careful planning, using underwater green hydrogen storage within depleted hydrocarbon reservoirs provides a cost-effective solution for offshore energy storage that minimises environmental impact and surpasses the limitations of compressed air energy storage or the utilisation of salt caverns.