This is an extract from the ***final report*** – please see the complete document in the full documents section on 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).

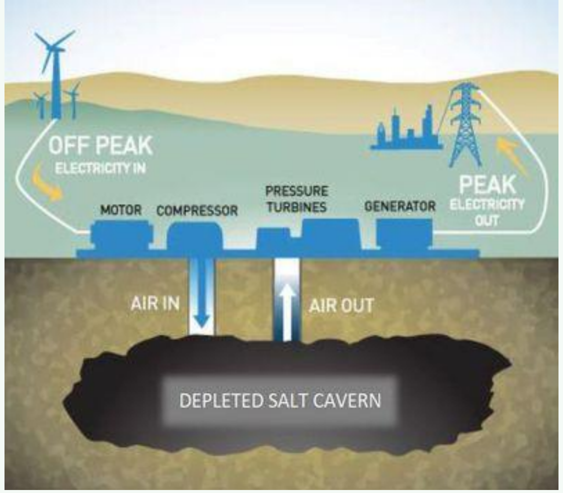

Figure 38- Naturally occurring salt cavern for compressed air energy storage (Colthorpe, 2017)

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.

<u>Cavern Storage Capabilities</u>

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.

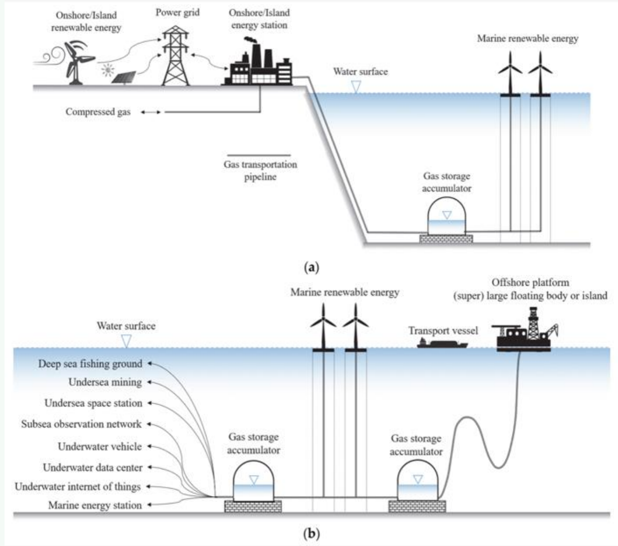

Figure 39- UWCGES (Hu Wang et al., 2022)

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.

<u>Salt Caverns</u>

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).

Shetland Proposal:

From the research outlined, compressed air energy storage (CAES) and hydrogen energy storage (HES) were considered the most suitable storage options for the Shetland energy island, with both options utilising onshore underground salt caverns for storage. Although CAES was carefully considered for a variety of reasons above other technologies such as battery storage, there were several factors that highlighted why HES would be the preferred option.

Hydrogen stored in salt caverns can provide around 100 times higher volumetric energy density than CAES systems of the same size, with a low economic cost of less than £0.50 per kgH_2. The technology that utilises onshore salt caverns for compressed gas like hydrogen is a mature technology that has a reliable track record in the UK, meaning that the system is reliable and low risk. As salt caverns have a naturally low temperature, they reduce the risk of unwanted chemical or microbial reactions in the cavern, ensuring that the hydrogen maintains a good quality standard and reducing the risk of contamination. This low temperature also allows the hydrogen to be compressed much more efficiently than in above ground storage facilities which will reduce its operational cost, alongside the natural geological strength of their structure. Furthermore, geological salt caverns have an inert nature as well as being naturally leakproof, making them a suitable option for hydrogen storage.

Utilising the existing caverns minimises the need to construct new storage facilities, therefore further reducing the economic cost associated with creating the facility. Additionally, the environmental impact will be lessened as CO_2 emissions from heavy plant will be reduced and land use will be minimal. However, despite these advantages, there are challenges associated with planning to utilise existing geological salt caverns for hydrogen storage as there is little information available or mapping of the abundance of salt caverns both on and around the Shetland islands. New caverns can be constructed; however, they take around 7-10 years, with the leeching process alone taking at least a year. Furthermore, constructing new salt caverns comes at a high capital cost and the leeching process must be carefully monitored to ensure there is no environmental damage to surrounding ecosystems. Alternatively, rock cavern storage may be utilised where salt caverns aren't possible, following a more comprehensive understanding of their challenges and benefits.

There are several studies currently researching the capability of above ground hydrogen storage technologies, many funded by the Long Duration Energy Storage Competition. The studies focus on a variety of innovative technologies or processes, such as the utilisation of nuclear waste products for hydrogen storage, metal hydride technologies, Corres's patented Carbon280 Hydrilyte hydrogen carrier system, and a practice known as linepacking where hydrogen can also be stored within the gas transmission and distribution network. Additionally, there is active research into the use of ammonia for not only carrying hydrogen but as a fuel itself.

The SHyLo (Solid Hydrogen at Low Pressures) project has just secured £4.3 million from the governments Low Carbon Hydrogen Supply Competition to develop their storage system in the Orkney Islands. This aims to surpass the limitations of compressed gas storage systems as they can have efficiency limitations and high compression costs. Storage savings can be increased by 55% by removing the need for compression, reducing operational costs to an estimated £0.20 per kg by 2028. The research is relatively new but promising when considering the limitations of underground storage options.

Overall, hydrogen storage in salt caverns is the most robust and viable option for long-term energy storage needs on the Shetland energy island, offering both economic and environmental advantages. If there are little or no available options for the utilisation of a natural salt cavern on Shetland, the construction of a new salt cavern or rock cavern storage options should be considered. Additionally, with continued research and innovation, above surface onshore hydrogen storage technologies have the capability to play a crucial role in the energy transition and should be kept as an open discussion throughout the development of the Shetland energy island.

There is already a considerably good understanding of the green hydrogen production process on the Shetland islands due to the presence of the Pure Energy Centre that manufactures hydrogen systems in a variety of scalable sizes. This would be significant for the Shetland based production as the local knowledge could be utilised for the hydrogen plant on the nearby energy island. Furthermore, Pure Energy is involved in the development of a variety of renewable energy schemes, including green energy storage technologies that would be beneficial to the energy island project throughout its life cycle (Scottish Government, 2024a).