Net zero – Environmental implications of energy storage technologies

Chief Scientist's Group report

March 2025

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Dr Robert Bradburne
Chief Scientist

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1 Executive summary

Introduction: The UK has a legally binding target to bring greenhouse gas (GHG) emissions to net zero by 2050 (DESNZ, 2022). As evidenced by HM Government's (2020) Ten Point Plan for a Green Industrial Revolution, the generation of electricity from renewables will be key part of achieving net zero. However, electricity generation from renewable sources such as wind can be unpredictable. This means that energy storage technologies are needed to enable energy to be stored when demand is low and subsequently released when demand is high. This study aimed to answer two related questions for six energy storage technologies:

1. What are the expected deployment trajectories of the technologies in England?
2. What are the foreseen environmental impacts associated with the construction, implementation, operation, and end-of-life of these technologies?

Approach: Desk-based research was undertaken to determine the expected deployment trajectories. Targeted internet research identified Government strategies, policies and plans, alongside information published by businesses and research projects and trials. Evidence on environmental impacts was identified through a bottom-up approach which involved a literature search.

Findings: Table 1 lists the six technologies considered and summarises current and planned storage for each technology. Planned sites include ongoing research projects.

Table 1: Summary of current and planned sites/projects for the six technologies

Technology	Current sites	Planned sites/projects
Hydrogen storage	Above ground – no active sites in England Underground – existing large-scale site at Teesside	Above ground – HyDUS (Hydrogen in Depleted Uranium Storage), Corre Energy Consortium and SHyLO (Storage of Hydrogen at Low pressure) Underground – Keuper Gas Storage Project (Cheshire), Rough (offshore) and Aldbrough Hydrogen Storage
Ammonia storage	Difficult to estimate given dynamic nature of the industry	Plans for sites at Liverpool (by Stanlow Terminals Ltd) and Immingham (by Air Products and Associated British Ports)
Compressed Air Energy Storage (CAES)	No commercial sites in England	StrataStore Project, Cheshire (by EDF, iO Consulting, and Hydrostor) aims to store more than 100 MW of power

Technology	Current sites	Planned sites/projects
Underground pumped hydroelectric storage (UPHS)	No evidence of sites in England	No evidence of sites in England
Thermal energy storage (TES)	Many examples e.g. aquifers (London Chalk basin), manmade (e.g. Gateshead district heating scheme)	EXTEND, led by Sunamp Ltd, aiming to extend thermal battery duration and capacity, and ADSorB (Advanced Distributed Storage for Grid Benefit), led by the University of Sheffield
Battery energy storage systems (BESS)	UK operational BESS capacity of 2.8 GW	1.6 GW of capacity under construction (UK level)

Beyond the general impacts of constructing, operating and decommissioning a facility, technology-specific environmental impacts include:

- Hydrogen: mining of metals and use of water for processing ores (for metal hydride storage); generation/disposal of brine (when creating salt caverns); use of persistent, bioaccumulative and toxic substances (when using liquid organic hydrogen carriers (LOHCs)); increased microbial activity and geochemical and geomechanical impacts (underground storage); leakage of fugitive hydrogen.
- Ammonia: impacts from release and fugitive emissions of ammonia, including knock-on impacts for the global nitrogen cycle and GHG generation.
- CAES: brine generation and disposal during cavern construction; emissions to air (where fossil fuels are used for decompression); impacts for geomechanical stability, microbial activity and chemical reactions within the caverns (due to changes in pressure); use of water as a coolant.
- UPHS: release of gases during construction; potential geological instability; use of water resources; potential for contamination of water dependent on system deployed (e.g. if disused mine workings are used as the lower chamber).
- TES: impacts from use and disposal of Phase Change Materials (PCMs) which may include toxic compounds; transfer of thermal energy to underground systems; salinisation; impacts for hydrology.
- BESS: impacts from mining (e.g. lithium); health risks of exposure to hazardous substances; leakage of heating, ventilation and air conditioning (HVAC) refrigerants; “thermal runaway” resulting in emission of harmful materials; leaching of fire water.

Conclusions: Current deployment of the six technologies varies by type, with some appearing more advanced (e.g. BESS) whilst others (e.g. CAES) are being researched. Environmental impacts are likely to result from all technologies, although the type and extent of impact varies. There may be additional impacts when technologies are upscaled to grid level or when specific sub-types of technology are further developed. For example, lithium-ion batteries are the favoured option for grid level storage for BESS, but other types do exist (e.g. redox flow batteries) and will have slightly different impacts. The Environment Agency’s regulatory role will need to develop over time to ensure impacts are suitably managed and monitored.

2 Introduction

2.1 Background and scope

2.1.1 Net zero

Net zero refers to the legally binding target to bring UK GHG emissions to net zero by 2050 (DESNZ, 2022), meaning that the volume of GHGs emitted from 2050 onwards should be balanced by the volume of GHGs sequestered from the atmosphere. This involves two main facets: increasing the use of zero-emissions technologies, and capturing, storing and using emissions from hard-to-decarbonise industries. A major way that the former point will be achieved is by increasing the use of zero-carbon renewable energy sources such as wind and solar power. The Government's Ten Point Plan for a Green Industrial Revolution highlights key policies that will be put in place to achieve this goal, including deployment of 40 GW of offshore wind to decarbonise the UK power system (HM Government, 2020). However, decarbonisation through renewable power sources comes with significant challenges, namely that wind and solar power generation is unpredictable and can fluctuate on a seasonal, daily, and hourly basis. These challenges to increasing the use of renewables within the UK must be resolved before net zero targets can be realised. One potential solution for this is increasing the UK's capacity for energy storage.

2.1.2 Energy storage technologies and their role in Net zero

In this report, energy storage refers to the conversion of energy produced from renewable sources to a form of potential energy in which it can be stored. This energy can be retrieved at a later date and converted back into a form (i.e. electrical or thermal energy) that is useful to households and other users. This potential energy may be chemical, gravitational, thermal, or pressure.

The storage of energy from renewable sources will allow for mitigation of the mismatch between energy generation and demand by storing energy during periods of high production and low demand and releasing it during periods of high demand and low production.

Energy can be stored by a multitude of different technologies including batteries, fuels, or in physical systems such as compressed gases, hydroelectric reservoirs, or as thermal energy. Each of these energy storage technologies comes with its own unique challenges which must be addressed before wide-scale implementation can be achieved.

2.1.3 Project scope and objectives

The challenges with implementation of energy storage technologies are technical, economic, social and environmental. This evidence synthesis report aims to present the status of the scientific understanding surrounding 6 different energy storage technologies with respect to the expected deployment landscape and timelines in England, as well as the potential environmental impacts resulting from their deployment. The energy storage technologies that are assessed in this report are:

- Hydrogen storage;
- Ammonia storage;
- Compressed air energy storage (CAES);
- Underground pumped hydroelectric storage (UPHS);
- Thermal energy storage (TES); and
- Battery energy storage systems (BESS).

The research questions that are answered through this evidence synthesis report are:

1. What are the expected deployment trajectories of the six energy storage technologies in England?
2. What are the foreseen environmental impacts associated with the construction, implementation, operation, and end-of-life of these technologies?

The purpose of this report is to inform the Environment Agency about the status of the understanding of these six energy storage technologies (ESTs) through a review of the academic and grey literature. This will inform and support regulatory decisions as the deployment of energy storage technologies in England proceeds.

2.1.4 Structure of this report

The individual chapters of this report refer to the individual energy storage technologies. A high-level introduction of each technology and its expected role in net zero are given, followed by an assessment of the available sub-technologies.

Evidence relating to the deployment of these technologies is then presented, considering various industrial strategies and real examples of planned and operational projects.

The potential environmental impacts of the ESTs are reported based on the research and evidence gathered from academic literature and studies of real facilities where available. Information on social impacts, as researched by the Environment Agency, is also incorporated.

The structure of this report is as follows:

- **Section 3:** Hydrogen storage;
- **Section 4:** Ammonia storage;
- **Section 5:** Compressed air energy storage (CAES);
- **Section 6:** Underground pumped hydroelectric storage (UPHS);
- **Section 7:** Thermal energy storage (TES);
- **Section 8:** Battery energy storage systems (BESS);
- **Section 9:** Overall conclusions;
- **Section 10:** Bibliography; and
- **Section 11:** Glossary.

2.2 Methodology

2.2.1 Deployment trajectories

Evidence for the expected deployment trajectories of the energy storage technologies was gathered using a top-down approach, where primarily grey literature such as Government strategy and policy documentation was identified for each technology by way of targeted internet searches. These documents were checked for relevant citations, which were in turn used to form the evidence base. This approach ensured that evidence for the deployment trajectories of energy storage technologies is based on the real-life activities taking place within the energy storage space.

2.2.2 Environmental impacts

Evidence for environmental impacts of energy storage technologies was gathered using a bottom-up approach, where targeted searches for academic literature were performed in the ScienceDirect database. The use of Boolean operators assisted in eliminating irrelevant articles and the outputs of these searches were exported as libraries into the Mendeley reference manager. The libraries were then screened at a high-level to identify potentially relevant articles of research which were added to a short-list. This shortlist was then used as the evidence base for synthesis. To supplement this evidence base, additional targeted searches were conducted to identify evidence that was not obtained from initial searches. Furthermore, to link these impacts to real-life applications, the authors consulted environmental impact assessments for planned and existing sites from the National Infrastructure Planning Inspectorate where available.

2.2.3 Social impacts

Alongside the work undertaken by RPA and RAB Consultants, the social science team within the Environment Agency investigated the social science evidence base on ESTs to complement the main project on their environmental impacts. As well as reviewing relevant existing knowledge about social scientific research and evidence on ESTs and other net zero technologies from within the social science team, a quick scoping review (QSR) was carried out using Scopus. This mapped recent social science literature on the specific energy storage technologies and ESTs more generally. The QSR focused on the following questions, with a geographical focus on England and the UK, but including research from other countries where relevant:

- What is the current evidence on public perceptions of energy storage technologies?
- What is the current evidence on (potential) social impacts of energy storage technologies?
- What are the gaps in the literature on the social impacts of energy storage technologies?

Search results were compiled in Endnote, screened for relevance and a bibliography was generated. Relevant literature was then analysed and coded to identify key findings and emerging issues.

3 Hydrogen Storage

3.1 Introduction

3.1.1 Overview

Hydrogen is a gaseous fuel which has had growing attention within the net zero space. It can be produced using renewable energy through electrolysis of water, known as “green hydrogen”, though most hydrogen is currently manufactured through steam reformation of methane, which is associated with carbon emissions. If these emissions are captured and stored using carbon capture use and storage (CCUS) technology, this is known as “blue hydrogen”. Hydrogen can be used both as a combustion fuel in internal combustion engines and in fuel cells where hydrogen is oxidised across an electrochemical system to produce a voltage.

The International Energy Agency expects hydrogen to be important for reducing carbon dioxide (CO_2) emissions across almost all industries across the globe (International Energy Agency, n.d.). Its primary use in reducing CO_2 emissions is as a clean fuel, where its gravimetric energy density[1] is higher than any fossil-based fuel. Combustion of hydrogen in oxygen from the air produces water as the only reaction product, though the high temperatures of hydrogen combustion can also facilitate the oxidation of atmospheric nitrogen, resulting in the generation of NO_x emissions. Hydrogen may be incorporated as a fuel in household heating systems, where all new boilers within the UK are expected to be ‘hydrogen ready’ as early as 2026 (British Gas, 2023). It can also be used as a fuel without burning, and instead is electrochemically reacted with oxygen in a fuel cell to produce electrical energy instead of heat (U.S. Department of Energy, n.d.). These hydrogen fuel cells are a rapidly growing technology and are anticipated to play a significant role in the zero-emissions transport industry, powering vehicles as well as commercial trains, ships and even aircraft. As well as its use as a fuel, hydrogen can also be used as a reducing agent which replaces coke within the steel industry to refine iron from its ores (European Parliament, 2020).

While hydrogen will be important for achieving net zero, its efficient storage, particularly at large scales, is problematic. Hydrogen is the lightest naturally occurring gas and is extremely flammable and explosive. This means its safe and efficient storage remains a challenge which requires significant investment in infrastructure and risk management.

This section will discuss the technologies which have been developed for the safe and efficient storage of hydrogen and their timeline for implementation within England in the context of achieving net zero goals. Once these technologies are implemented, they will

[1] Gravimetric energy density is defined as the chemical energy stored in a fuel per unit mass.

require close management and regulation to ensure their responsible operation and to limit impacts to environmental and human health.

3.1.2 Hydrogen storage technologies

3.1.2.1 The technologies

Hydrogen storage technologies can be largely divided into two categories listed below:

- **Above ground hydrogen storage technologies** which typically have relatively small storage capacities and would be used to supply hydrogen to a specific facility or industrial cluster. Above ground hydrogen storage technologies include:
  - Compressed hydrogen storage;
  - Cryogenic liquid hydrogen storage;
  - Metal hydride storage;
  - Chemical hydrogen storage; and
  - Adsorption storage.
- **Underground hydrogen storage technologies** which have potential for storing very large quantities of hydrogen in underground reservoirs or geological formations and would supply hydrogen to be used in the wider energy grid. Underground hydrogen storage technologies include:
  - Salt cavern storage;
  - Aquifer storage; and
  - Depleted hydrocarbon reservoir storage.

To understand the expected deployment timelines and environmental impacts of these technologies, it is important to understand their operational principles and implementation requirements. Therefore, the following section presents a brief overview of each of these hydrogen storage technologies and operational factors that have an effect on their deployment and environmental impact (Elberry et al., 2021).

3.1.2.2 Above ground hydrogen storage technologies

3.1.2.2.1 Compressed gas storage

Hydrogen can be compressed and stored in high-pressure tanks or cylinders made from carbon fibre-reinforced composites, steel or aluminium. In these containers, hydrogen can be compressed to pressures typically between 10 and 70 MPa but can be stored up to 83 MPa in some instances.

The type of storage vessel used is largely dependent on the capacity and pressure required by the end-user. A number of different vessel types are available, Table 2 below shows the different types of compressed hydrogen storage vessel as well as their maximum size and operating pressure.

Aside from those listed in Table 2, a number of other compressed gas storage solutions have been proposed. These solutions include repurposing of spherical natural gas vessels to store up to 27,000 kg of hydrogen at a pressure of 0.2 MPa, and storage of hydrogen inside the tubular tower of wind turbines at a pressure between 0.1-0.15 MPa, allowing storage of about 940 kg of hydrogen within a 1.5 MW turbine. These proposed storage solutions are, however, currently theoretical and no evidence suggests that these have been implemented in real systems (Elberry et al., 2021).

Table 2: Types of compressed hydrogen storage vessel

Type	Description	Typical size	Maximum pressure	Maximum stored hydrogen mass (kg)[a]
Seamless vessel	Made from high-tensile strength steels, commonly used for hydrogen fuel stations. Can be a part of a multivessel assembly, at the cost of more gas leak points.	6.1 m (internal diameter) × <12 m (maximum size)	65 MPa	3,840
Multifunctional layered stationary vessel	Developed to address various issues in hydrogen storage. It features a complex structure with multiple layers of steel, including inner and outer heads with different steel compositions, designed to withstand high pressure in a safe and efficient manner.	15 m (internal diameter) × 30 m (maximum size)	100 MPa	36,300
Steel-concrete composite pressure vessels	Use of steel-concrete composite improves manufacturing feasibility. Allows for leakage before bursting, reducing	2.2 m^3 (mock-up fabrication)	43 MPa	76

Type	Description	Typical size	Maximum pressure	Maximum stored hydrogen mass (kg)[a]
	risk of catastrophic failure			

[a] Calculated based on maximum pressures and volumes under the assumption that hydrogen behaves as an ideal gas at 298K.

Source: Elberry et al., 2021

The storage vessels described in the table above have a good degree of technical maturity (up to Technology Readiness Level (TRL) 9) and are currently used for small and medium-scale hydrogen storage operations (Elberry et al., 2021). However, seamless and layered vessels for hydrogen storage require large capital investment and compression costs, resulting in a levelised cost of storage (LCOS) of around £2 per kg of hydrogen. Approximately £0.70 of this cost arises from capital investment, while the remaining £1.30 is attributed to compression costs (DESNZ, 2023a).

Overall, hydrogen gas storage in pressurised containers is currently one of the most cost-effective solutions for small to medium-scale hydrogen storage. This is especially the case for industrial sites and clusters seeking to transition to low-carbon fuels, particularly while national infrastructure for delivery of hydrogen to these sites is being developed.

3.1.2.2.2 Cryogenic liquid hydrogen storage

Cooling and subsequent liquefaction of hydrogen gas allows for more volumetrically efficient storage as hydrogen is approximately 50% more energy dense in its liquid form than its compressed gaseous form[2]. Cryogenic liquefaction of hydrogen is a multistep process in which feedstock hydrogen of high purity is compressed to 2-8 MPa before the first cooling stage. The first cooling stage takes place at -193°C and is fed into the cryogenic cooling step which further reduces the temperature of the hydrogen to less than -243°C. Expansion of the cryogenic compressed hydrogen further cools it to around -253°C at a pressure of 0.1-0.2 MPa (note that -253°C is the normal boiling point for hydrogen; Bimbo, 2019). Finally, a separation procedure isolates the liquid hydrogen which is then stored in insulated tanks.

[2] Gaseous hydrogen at 70 MPa has a volumetric energy density of around 5 kWh/L and liquid hydrogen a value of 10 kWh/L.

Cryogenic liquid hydrogen is extremely susceptible to boiling off[3] if precise insulation conditions are not met. Firstly, the large temperature differential between the outside environment and the liquid hydrogen would result in rapid heating of the hydrogen if insulation were to fail. In addition, liquid hydrogen exhibits a quantum mechanical effect known as ortho-para conversion which further increases the risk of boil-off events. To avoid this, hydrogen must first be catalytically converted to para-hydrogen before liquefaction, increasing costs and process complexity (Zhang et al., 2023). To be technically feasible, cryogenically stored hydrogen requires state-of-the-art insulation materials. These insulation materials and boil-off mitigation technologies add a significant price premium to cryogenic hydrogen storage, with a current estimated LCOS of nearly $4 USD/kg hydrogen. It is predicted however, that this cost could fall in the future to become competitive with other less technologically demanding hydrogen storage technologies (Bloomberg, 2020).

3.1.2.2.3 Metal hydride hydrogen storage

The storage of hydrogen can be achieved by reacting the hydrogen directly with metals or with metal salts to form hydride species[4]. The reaction of hydrogen gas with these substrate materials is a reversible reaction under the right conditions, and therefore hydrogen gas can be removed from the hydride on demand. Metal hydrides are seen as a safer solution to gaseous hydrogen storage, as this technology allows hydrogen to be stored at much lower pressures and at high volumetric energy densities (Klopčič et al., 2023). Since hydride storage does not require high pressures, the volume of material stored can be scaled efficiently with little limitation arising from vessel size constraints.

Various materials are used to store hydrogen as metal hydrides, each with their own benefits and drawbacks, which can be tailored to the requirements of the storage facility. This point is illustrated by existing commercial operations, which provide tailored storage options dependent on space, how the hydrogen is to be used, etc.[5]. A summary of different hydride storage materials and their key performance indicators are given in Table 3.

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[3] Boil off is the term used to describe the rapid evaporation of cryogenic liquids, resulting in high gas concentrations in the surrounding area.

[4] A hydride is a formally negatively charged hydrogen atom which forms a part of a molecule or complex.

[5] Examples include GKN Hydrogen and Fuel Cell Store (Fuel Cell Store, n.d.; GKN Hydrogen, n.d.).

Table 3: Examples of materials used for metal hydride storage of hydrogen and their performance

Material	Gravimetric hydrogen capacity (Wt.%)	Volumetric energy density[b] (kWh/L)	Operating pressure[c] (MPa)	Operating temperature[e] (K)
Magnesium hydride (MgH_2)	5.5	2.65	-	593
Titanium-iron (TiFe)	1.5	3.25	0.41	265
Titanium-manganese ($TiMn_2$)	1.15	2.53	0.84	252
Lanthanum-nickel ($LaNi_5$)	1.28	3.53	0.18	285
Lithium borohydride ($LiBH_4$)	13.4	3.02	-	573
Sodium aluminium hydride ($NaAlH_4$)	3.7	1.58	-	473
Uranium hydride (UH_3)	Unknown[f]	Unknown[f]	Unknown[f]	Unknown[f]

Source: Klopčič et al., 2023; HyDUS, n.d.
[a] *Gravimetric hydrogen capacity is presented as its reversible capacity as a percentage of the mass of pure hydrogen within the raw material. Mass of the tank or ancillary equipment is not considered.*
[b] *Volumetric energy density is presented as the energy density of reversibly accessible hydrogen from the material without consideration of the tank volume or volume changes during adsorption or desorption of hydrogen.*
[c] *The pressure at which hydrogen adsorption and desorption are at equilibrium at 298K*
[d] *The hydrogen is stably bound to the material at 298K even under vacuum at 298K*
[e] *The temperature at which isotherms at 1 bar are achieved.*
[f] *Use of uranium hydride is being investigated by the HyDUS project (accessed at: https://hydus.org/ on 22 April 2024)*

As seen in Table 3, the major benefit of hydride storage is its large volumetric energy density when compared to compressed hydrogen, demonstrating an energy density increase factor of between 1.98 to 4.41 versus compressed hydrogen at 35 MPa. This increased volumetric energy density comes at a significant cost to gravimetric energy density, where metal hydrides are only able to store 1.15-5.5% of the energy as pure hydrogen per unit mass (Klopčič et al., 2023). Therefore, it is most likely that metal hydrides will only be used to store hydrogen for stationary applications.

3.1.2.2.4 Liquid organic hydrogen carrier (LOHC) storage

Similarly, to metal hydride storage, hydrogen can also be stored within liquid organic hydrogen carriers (LOHCs) in which a liquid organic molecule can be reversibly hydrogenated with hydrogen gas and stored at ambient pressures, followed by recovery of hydrogen by catalytic dehydrogenation of the LOHC. This technology is scalable, and the volume of hydrogen stored can be scaled efficiently since high pressure storage vessel constraints are not an issue as they are for compressed hydrogen. Instead, the limitations for LOHCs arise due to the large energy costs associated with hydrogenation and dehydrogenation of the liquid carrier molecules.

The current main applications of LOHCs are for bulk hydrogen storage and transportation, as well as for transoceanic transport and typically use the toluene/methylecyclohexane and dibenzyltoluene/perhydrodibenzyltoluene pairs (Chu et al., 2023).

A large number of LOHCs have been proposed or evaluated experimentally, though it is unclear the extent to which they are currently used. They are typically aromatic or polyaromatic hydrocarbons due to the large number of carbon-carbon double bonds which can undergo hydrogenation. The choice of LOHC can depend on various factors, including gravimetric hydrogen storage capacity, density, melting point, boiling point, hazard profile, and hydrogenation/dehydrogenation temperature and conditions. This makes LOHCs a flexible choice for the storage of hydrogen depending on the specific requirements of the facility. A number of commonly used LOHCs and their properties relevant to hydrogen storage are shown in Table 4.

Table 4: LOHCs used for hydrogen storage and their properties

Hydrogen storage agent	Hydrogen carrier	Hydrogen storage capacity (Wt.%)/(kg/m^3)	Meltin g point (°C)	Boilin g point (°C)	Dehydrogenat ion temperatures (°C)
Benzene	Cyclohexane	7.2/55.9	7	81	300-320
Toluene	Methylcyclohexa ne	6.2/47.4	-127	101	300-350
Naphthalene	Decalin	7.3/65.4	-31	187	320-340
Dibenzyltoluen e	Perhydro-dibenzyltoluene	6.2/57.0	-39	390	260-310
Biphenyl	Bicyclohexyl	7.27/-	3	227	310-330
Diphenylmetha ne	Dicyclohexylmet hane	6.66/-	-19	153	340-360
Carbazole	Dodecahydro-carbazole	6.7/-	65	124	150-170
***N*-ethylcarbazole**	Dodecahydro-*N*-ethylcarbazole	5.8/-	-84.5	-	170-200
Source: Chu et al., 2023					

The process of charging and discharging hydrogen from an LOHC can be a limiting factor, since the facility at which the hydrogen is discharged from the carrier must be able to undertake the catalytic dehydrogenation reaction for the specific carrier. While discussion of the types of catalyst and dehydrogenation processes required by different LOHCs is outside of the scope of this report, catalysts typically used for this process are metals such as palladium, platinum, rhodium, nickel, molybdenum, ruthenium, and copper, each with different characteristics which are selected depending on the specific requirement (Chu et al., 2023). A simplified process flow for the charge-discharge cycle of a LOHC is shown in Figure 1.

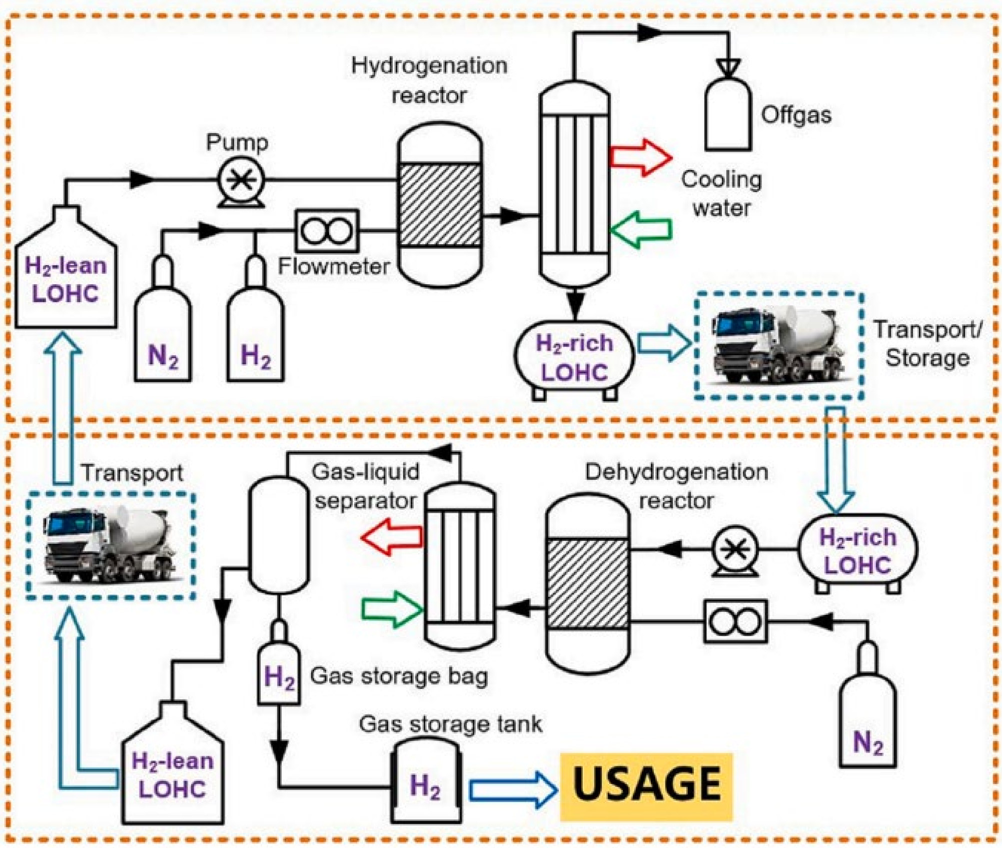

Figure 1: Simplified process flow for an integrated LOHC storage and release system. ***Source:*** Chu et al., 2023

3.1.2.2.5 Adsorption storage of hydrogen

Hydrogen can be stored through physical adsorption to high-surface area nanoporous materials such as zeolites, metal-organic frameworks (MOFs) or activated carbons. In these materials, charging the substrate with hydrogen gas at elevated pressures allows for more efficient storage when compared to simple compression (Chen et al., 2022). The nature of this sorption is analogous to the metal hydride storage methods described previously, though in this case, the dihydrogen molecule remains unreacted and is instead attracted to the substrate surface by Van-Der-Waals forces of attraction. The high surface area of these substrates allows for deposition of a monolayer of hydrogen gas onto the substrate surface to represent a significant mass uptake. Adsorbed hydrogen can then be removed at reduced pressure and utilised as a gas.

Currently the zeolites, MOFs and activated carbons can typically uptake 1-3 Wt.% of hydrogen depending on their loading conditions. This value can be higher if the substrate is stored at elevated pressures (Czarna-Juszkiewicz et al., 2020).

3.1.2.3 Underground hydrogen storage technologies

Gaseous hydrogen storage in salt caverns represents a notable advancement in the field of energy storage and distribution. These caverns are created through a process known as solution mining, where fresh water is injected into underground salt formations to dissolve the salt and create spacious voids (Lemieux et al., 2019). Once formed, these caverns serve as secure repositories for storing large quantities of gaseous hydrogen. In addition, it is possible that existing salt caverns used historically to store natural gas may be repurposed for storage of hydrogen. The use of salt caverns for hydrogen storage offers several advantages, including their ability to store hydrogen at high pressures, which minimises the need for additional compression, and their excellent sealing properties, which should ensure containment of the stored gas (Al-Shafi et al., 2023).

Aquifers are underground geological formations that consist of porous rock or sediment capable of storing and transmitting water (National Geographic, n.d.). These formations act as natural reservoirs for groundwater, which is essential for drinking water, irrigation, and various other uses. Aquifers typically consist of layers of sand, gravel, or rock with gaps or voids between the particles that allow water to be stored within them (UK Groundwater Forum, n.d.). Water from rainfall or surface sources can percolate through the ground and become stored in these underground aquifers. Gases such as hydrogen can be stored in deep saline aquifers which are distinct from the shallow aquifers that are typically used for everyday water resources. The hydrogen is stored by displacing the native brine or natural gas present in the aquifer. This method capitalises on the natural geological characteristics of the aquifers, which provide substantial storage capacity and the potential for large-scale, long-duration hydrogen storage (Al-Shafi et al., 2023).

Depleted hydrocarbon reservoirs, often referred to as "depleted oil and gas fields", are geological formations that once actively produced hydrocarbons but have reached the end of their economically viable production life. Once this occurs, they can be repurposed for hydrogen storage, representing a promising approach to hydrogen energy storage (Hydrogen UK, 2022).

The conversion of depleted hydrocarbon reservoirs into hydrogen storage facilities involves injecting gaseous hydrogen into the underground formation. This process uses existing infrastructure, including wells and pipelines, which were originally designed for hydrocarbon extraction, reducing the need for new infrastructure, and offering a cost-effective solution for large-scale hydrogen storage. The hydrogen, when injected, displaces any remaining natural gas or brine in the reservoir, occupying the pore spaces within the rock (Al-Shafi et al., 2023).

The appeal of using depleted hydrocarbon reservoirs for hydrogen storage lies in their geological stability, (i.e., a reduced risk of structural collapse when compared to man-made caverns) and the established infrastructure. These reservoirs are typically well-characterised, with extensive data on their geological properties, making it easier to assess their suitability for hydrogen storage. Low permeability surrounding rock formations can act as natural seals, helping to contain the injected hydrogen securely. However, considering the particle size difference between natural gas and hydrogen, surrounding rock formations may not prevent leaks of hydrogen as effectively as they do for natural gas.

3.1.3 The role of hydrogen storage in achieving net zero

Acknowledging the role of hydrogen in the future energy mix, in the April 2022 British Energy Security Strategy the UK government increased its production target from 5 GW to 10 GW by 2030 (Department for Business, Energy & Industrial Strategy et al., 2022). However, this ambitious goal is contingent on the parallel development of storage infrastructure. The urgency of the matter is highlighted by projections indicating the **need for 3.4 TWh of large-scale hydrogen storage by 2030, which is anticipated to rise to 9.8 TWh by 2035** in order to provide sufficient storage required by the 10 GW hydrogen production target (Hydrogen UK, 2022). A recent BEIS report predicts a similar hydrogen storage capacity requirement for their upper-bound scenario, estimating that between 0.2-3.1 TWh of salt cavern hydrogen storage will be required by 2030, rising to 0.6-13.2 TWh by 2035 (BEIS, 2022). The above-ground storage requirements were also estimated to be 0.02-0.9 TWh in 2030, rising to 0.04-2.3 TWh by 2035 (BEIS, 2022).

Fortunately, the UK possesses highly favourable geographical characteristics and access to depleted hydrocarbon fields, offering the potential to meet these storage requirements (DESNZ, 2021).

To further place these hydrogen production targets into perspective, the lower heating value of hydrogen[6] is 33 kWh/kg. **This means that the UK target of 10 GW of hydrogen production by 2030 would require the production of 303,030 kg of hydrogen every hour of 2030 to meet this target. The 3.4 TWh of large-scale hydrogen storage by 2030 relates to storage of 103 million Kg of hydrogen, increasing to 296 million Kg by 2035**. The storage target of 103 million Kg of hydrogen at a 10 GW production capacity would require the storage of 340 hours' (or two-weeks') worth of hydrogen production.

3.2 Deployment trajectories of hydrogen storage technologies

3.2.1 Current hydrogen storage capacity and sites

3.2.1.1 Above ground hydrogen storage

Small-scale hydrogen storage is common throughout UK industries for use as a chemical reagent and as a fuel. Pressurised gaseous hydrogen as well as liquid or cryogenic compressed hydrogen facilities are therefore already operational and store and supply small to moderate quantities of hydrogen (MWh) depending on the requirements. For example, hydrogen refuelling stations for hydrogen fuel cell vehicles are currently operational at various locations in England. Identified facilities include: London, Crawley, Birmingham, and Sheffield, which have capacity to store and deliver 80 to 3,000 kg (or 2.64 to 99.0 MWh) of hydrogen to fuel cell vehicles each day (Hydrogen Energy

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[6] A measure of the chemical potential energy held within one kilogram of hydrogen gas.

Association, n.d.). There are likely to be more such facilities since at the time of reporting, a manual review of data by the Environment Agency identified 16 permits for hydrogen electrolysis. Around half of these permits are associated with refuelling stations. Refuelling stations are, however, short-term facilities for transport infrastructure only, and are not a means of storing energy for the wider energy grid.

While no active facilities are currently in operation, large-scale above-ground hydrogen storage projects in England are being actively investigated and are currently in initial stages of research. These will be discussed in more detail in Section 3.2.2.

3.2.1.2 Underground hydrogen storage

England is home to one of the few large-scale underground facilities for pure hydrogen storage in the world. The Teesside hydrogen storage facility in north-east England is comprised of a cluster of three equally sized salt caverns (3 × 70,000 m^3) with a total hydrogen storage capacity of 30 GWh of 95% purity hydrogen at a pressure of 4.5 MPa (Gaffney Cline, 2022) (relating to a mass storage of approximately 3 × 250 tonnes of hydrogen[7]). The site currently operated by Sabic Petroleum has been operational since 1972 and has demonstrated the commercial feasibility for large-scale hydrogen storage in England. While this site has been influential in demonstrating the feasibility of large-scale hydrogen storage in England for over 30 years, the storage capacity at the Teesside facility is over two orders of magnitude lower than the estimated requirement of 3.4 TWh by 2030 – over one hundred more facilities of this size would need to be constructed within the next seven years to meet net zero hydrogen strategy targets.

Since construction of many new sites in a short timeframe is unlikely, new underground hydrogen storage facilities will need to provide significantly higher capacities. These higher capacity sites have not yet been demonstrated within the UK, and as such their feasibility is uncertain. One such high-capacity site is Clemens Dome located in Texas, USA which has a capacity of 892 GWh (0.9 TWh) of hydrogen. Since the stipulations defined by the USA competent authorities for the layout, equipment, and safety verifications for hydrogen storage are not as strict as the UK regulations, facilities which have demonstrated feasibility in the USA may not be equally feasible within the UK (Kruck et al., 2013).

Outside of England, there are a number of large-scale underground hydrogen storage facilities including salt caverns, aquifers, and depleted gas reservoirs. These facilities, their capacities and other measures such as date of first operation, operating pressure, and volume are summarised in Table 5 (based on Gaffney Cline, 2022).

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[7] Calculated by the study team based on the ideal gas law for a system at 298K.

Table 5: Global large-scale underground hydrogen storage facilities and their properties

Location	Type of Stor-age	Depth (m)	Since	Electricity Generation	Hydrogen Percent-age	Press ure (MPa)	Capacity (m3)
Teesside, UK	Salt Caverns	370	1972	30 GWh	95%	4.5	3 x 70,000
Moss Bluff, Praxair, US	Salt Caverns	850-1,400	2007	80 GWh	N/R	7.0-13.5	566,000
Spindletop, (Air Liquid), US	Salt Caverns	850-1,400	N/R	N/R	95%	Up to 15.0	600,000
Clemens Dome, (Conoco-Phillips), Texas, US	Salt caverns	850	1986	892 GWh	95%	15.0	580,000
Kiel, Germany	Salt caverns	1,335	1971	N/R	62%	8.0-10.0	32,000
Ketzin, Germany	Aquifer	200-250	1964	N/R	62%	N/R	N/R
Beynes (GDF), France	Aquifer	430	c.a. 2002	N/R	50-60%	N/R	1,185 $MMSm^3$
Lobodice, Czech	Aquifer	400-500	1960	N/R	45-50%	4.5-5.9	400 $MMsm^3$
Kasimovskoie, Russia	Aquifer	N/R	N/R	N/R	N/R	N/R	1,800 $MMSm^3$
Hychico Argentina	Depleted Gas Reservoir	600-800	2015	24.6 GWh	100%	25	N/R

Location	Type of Stor-age	Depth (m)	Since	Electricity Generation	Hydrogen Percent-age	Press ure (MPa)	Capacity (m3)

Source: Gaffney Cline, 2022

Notes:

N/R = Property not quantified within the literature

$MMsm^3$ = Million standard cubic metres

3.2.2 Planned hydrogen storage capacity and sites

3.2.2.1 Above ground hydrogen storage

In order to meet the above-ground hydrogen storage requirements estimated by the Department of Energy Security and Net Zero (DESNZ)[8], an upper-bound approximate of 2.3 TWh of new capacity must be integrated into the UK infrastructure[9]. This figure of 2.3 TWh translates to a mass capacity of 70 million kg of hydrogen[10].

No large-scale above ground hydrogen storage facilities currently exist within England, largely due to safety concerns of storing large quantities of hydrogen gas under pressure, and the low technical maturity (approximately TRL 3) of safer non-gaseous storage systems such as metal hydride storage and hydrogen carriers (Boretti, 2024). However, there are a number of projects testing the feasibility and further developing experience with these technologies. This section gives an overview of the most prominent above ground hydrogen storage projects and their current status.

The **HyDUS** (Hydrogen in Depleted Uranium Storage) project by a consortium involving EDF UK, The UK Atomic Energy Authority, Urenco, and Bristol University is evaluating the feasibility of storing hydrogen as a uranium hydride (UH_3). There are numerous benefits to using uranium. Firstly, the volumetric density of hydrogen in UH_3 is twice that of liquid hydrogen, and it also makes use of depleted uranium waste generated from nuclear power stations in the UK. In addition, the properties of UH_3 make it a favourable hydrogen storage medium as it can release its stored hydrogen by heating to around 250°C without the need for a catalyst. Due to UK activity in the nuclear sector for many decades, depleted uranium is abundantly available with no previously foreseen commercial uses. This project secured funding of £7.7 million from the Net Zero Innovation Portfolio from DESNZ in late 2022 (EDF, 2022). Beyond laboratory scale research, the HyDUS project is

[8] Previously BEIS.

[9] Based on the upper bound estimate for above ground energy storage for 2035.

[10] Based on the lower heating value of 33 kWh/kg for hydrogen.

aiming to build a pilot scale UH_3 hydrogen storage demonstration facility by 2024 (HyDUS, n.d.).

Similar to HyDUS, HESS (Hydrogen energy storage system, previously **HEOS**) by LAVO is investigating the commercial feasibility of long-term hydrogen storage in metal hydrides (LAVO, n.d.). However, information on the specific technology used or timelines for studies are not yet publicly available. Ten solar farms are currently being retrofitted with HEOS hydrogen production and storage technology in New South Wales, Australia. However, it is unclear whether the same technology will be adopted in England (FuelCellsWorks, 2021).

The **Corre Energy Consortium**, in collaboration with Carbon280, has secured funding from the UK government to explore the feasibility of creating a pilot hydrogen storage system (Corre Energy, 2022). The consortium will receive approximately £150,000 for a feasibility study under the Longer Duration Energy Storage Demonstration programme, which falls under the Net Zero Innovation Portfolio (NZIP) (DESNZ, 2024a). The project aims to develop a safe and non-toxic storage solution for hydrogen, which could have applications in long-term storage facilities and reduce transport emissions by replacing diesel. The main objective of this project is to assess the feasibility of a pilot hydrogen storage prototype that enables safe and efficient storage and transportation of hydrogen. The project will utilise Carbon280's patented hydrogen storage technology called Hydrilyte™. This technology stores hydrogen by binding it to metal dust suspended in a mineral oil as a metal hydride, providing a safe and cost-effective means of storage and transportation. The supply model for Hydrilyte™ would mimic the existing fossil fuel diesel market, with central hydrogen production hubs and conventional road tanker distribution to fuel stations.

The **SHyLO** (Storage of Hydrogen at Low pressure) project, spearheaded by H_2GO Power and in partnership with multiple institutions and organisations such as Autodesk, Ballard®, Climate-KIC, Imperial College London, and Innovate UK, endeavours to scale up a small-scale solid-state hydrogen storage system into a commercially viable solution (H2GO Power, n.d.). H2GO Power's technology uses solid-state materials, enabling hydrogen storage at near-ambient pressures and temperatures. This method eliminates the need for compression and cryogenic cooling, resulting in higher efficiency and lower costs. It offers enhanced safety through low-pressure requirements, an extended hydrogen storage lifetime, and a modular design. ShyLO secured funding of £4.3 million from the UK's BEIS' Net Zero Innovation Portfolio Low Carbon Hydrogen Supply 2 Competition and commenced on January 31, 2022. The project will run for two years, focusing on regulatory compliance, safety requirements, and efficient design for manufacturing (MTC, n.d.). It also includes an artificial intelligence platform (HyAI) for optimising energy use. The technology will undergo rigorous testing at the European Marine Energy Centre in the Orkney Isles, showcasing its capacity for large-scale power-to-gas applications and paving the way for commercialisation and high-volume manufacturing.

3.2.2.2 Underground hydrogen storage

In the public domain, in England there are currently three large-scale underground hydrogen storage sites proposed: Keuper Gas Storage Project, Rough, and Aldbrough Hydrogen Storage. Two of these proposed sites are located on the mainland at Aldbrough in Hull and Northwich in Cheshire, and the third is located off the East Yorkshire coast. If these projects were completed and operational by the late 2020s, the total underground hydrogen storage capacity would be up to 10.62 TWh, exceeding the 2030 and the 2035 hydrogen storage targets as proposed by Hydrogen UK.

The Cheshire project, known as the **Keuper Gas Storage Project (KGSP)** could potentially store up to 1.3 TWh of hydrogen gas in salt caverns[11](INEOS, n.d.a). In 2017, KGS Ltd were granted planning permission to store natural gas in salt caverns located at the Holford Brinefield and are seeking to amend this consent to provide the option of storing hydrogen gas as well as natural gas. The project proposes to reassign 19 of these salt caverns to the storage of hydrogen, equating to 1.3 TWh of hydrogen storage. The latest update on the acquisition of the amended planning permission was on 5th June 2023, and no further information on the decision by the Planning Inspectorate is known at the time of writing this section (November 2023) (Planning Inspectorate, 2023).

As planning permission to create these caverns for natural gas has been granted, and the amendment which is still being processed is a non-material change, construction works on the site are currently underway. Full construction was expected to have started as of 2023[12], with the works anticipated to take four to five years, and with an expected completion date of 2027 (INEOS, n.d.b). At this point the site will be fully operational.

The offshore natural gas storage facility, the **Rough** reservoir, operated by Centrica Storage Ltd was the UK's largest natural gas storage facility and was operational between 1985 and 2017, after which it was closed since it was no longer economically feasible. In light of the 2022 energy crisis, Rough was partially reopened in October 2022. Centrica has claimed that the Rough site will be repurposed to store up to 9 TWh of hydrogen, potentially supplying almost all of the Hydrogen UK target for 2035 (Centrica, n.d.). No publicly available information on the timeline of this conversion has been published to date. Centrica has stated that as soon as a regulatory and policy framework exists to enable the conversion of Rough, they will begin work on the £2 billion investment. As no rigid timeline is in place for this site, it is not possible to determine if or when hydrogen will be stored in Rough, and to what extent at this time.

The **Aldbrough Hydrogen Storage** project underway by SSE Thermal and Equinor aims to upgrade the existing Aldbrough Gas Storage facility in Humberside to accommodate the

[11] Note that salt caverns in Cheshire are currently being used for storage of natural gas, for example, Storengy UK's Stublach site and Uniper Energy Storage's Holford site (Storengy, n.d.) (Uniper, n.d.).

[12] Note that at the time of finalising this report, no further update was available.

storage of up to 320 GWh (0.32 TWh) of hydrogen in salt caverns which are proposed to be drilled close to the current site (Smith et al., 2023). The planning permission for this application is currently in the pre-application phase, however the details of the site have been provided to the Planning Inspectorate in the form of an Environmental Impact Scoping Report. It is estimated that the Aldbrough site could begin storing hydrogen as soon as 2028, though it is unclear if the full proposed capacity of 320 GWh will be operational at this date.

It is understood that aquifers are not being considered for hydrogen storage in England. While this may change in the future, due to England's large theoretical capacity for underground hydrogen storage in depleted gas fields and salt caverns, the use of aquifer storage is unlikely (Jahanbakhsh et al., 2024).

In conclusion, while exact timelines will be subject to granting of planning permission, construction, and generation of policy and regulatory frameworks, England is well placed to increase its underground hydrogen storage capacity considerably over the next decade. The three sites above, consisting of multiple individual salt caverns and oil fields, have the potential to increase the current underground storage capacity from 30 GWh (0.03 TWh) to over 10 TWh, almost three orders of magnitude.

3.2.3 Remaining capacity required for Net Zero and possible locations

The parameters for hydrogen storage have been mapped and are shown in Figure 2, with data sources provided below the figure. Based on the evidence for the deployment of hydrogen storage in England, it is likely that the majority of onshore underground hydrogen storage will be located in salt caverns for which England has a number of suitable salt deposits (see onshore salt deposits in the figure). Depleted Gas Field (DGF) and saline aquifer storage of hydrogen will most likely take place offshore as this is where environmental impacts will be minimised, and the largest volume of hydrogen can be stored. The map shows 'wells per field' as an indication of the level of activity within each field. While on-shore DGFs and saline aquifers may be used for smaller-scale hydrogen storage, these are not currently reported. Above-ground hydrogen storage is not constrained by geography, but will most likely take place close to hydrogen production facilities that have good electricity and gas connectivity. The map therefore includes both the gas network and electrical grid.

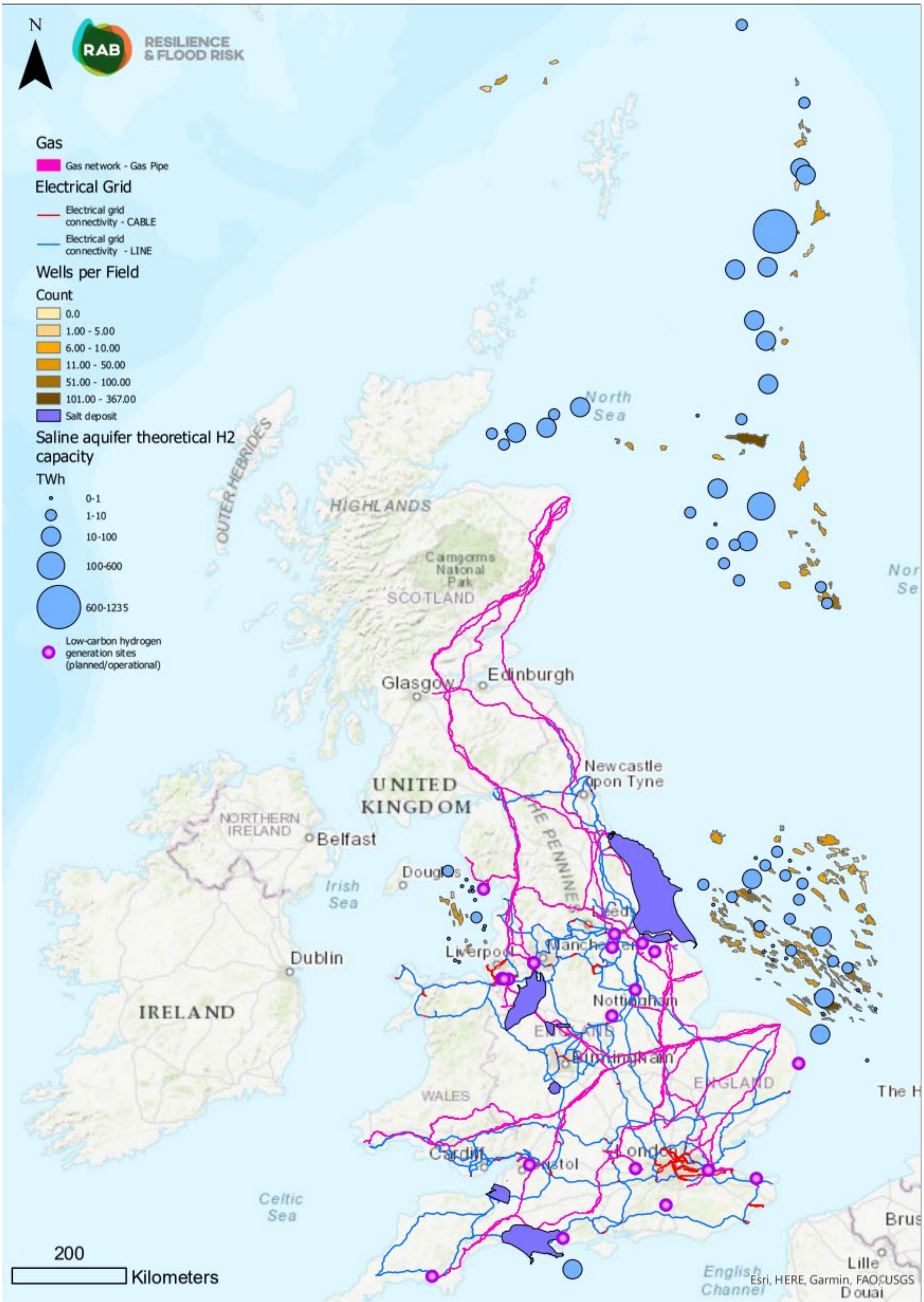

Figure 2: Locations with enabling conditions for the implementation of above and below ground hydrogen storage in England and sites where low-carbon hydrogen is currently or planned to be generated.

Basemap: Esri. "Topographic" [basemap]. Scale Not Given. "World Topographic Map". 26 October 2017.

https://www.arcgis.com/home/item.html?id=7dc6cea0b1764a1f9af2e679f642f0f5. (15 November 2023).

Other sources: Arcgis.com, 2024; mapapps2.bgs.ac.uk., n.d.; Scafidi et al., 2020; Thaysen et al., 2023; www.nationalgas.com., n.d.; www.nationalgrid.com., n.d.

3.3 Environmental impacts of hydrogen storage

3.3.1 Environmental impacts during construction

3.3.1.1 Above ground hydrogen storage

Above ground hydrogen storage technologies are more varied in their overall potential environmental impacts. Impacts during construction of these facilities will likely occur from sourcing of raw materials. For example, mining of minerals required for metal hydride storage such as lithium, titanium and manganese can result in groundwater pollution, air pollution as well as water resource usage for the processing of ores. The construction of pressure vessels and cryogenic vessels for compressed and liquid hydrogen respectively, as well as sourcing of large volumes of dehydrogenated hydrogen carriers such as polyunsaturated hydrocarbons for LOHC storage or metallic substances for metal hydride storage also apply their own environmental strain. However, these materials are typically produced in large volumes globally and their use for hydrogen storage in England is unlikely to significantly increase the impacts from sourcing these raw materials.

3.3.1.2 Underground hydrogen storage

3.3.1.2.1 Overview

A number of large-scale underground storage sites are planned as discussed in Section 3.2.2. The sites with the highest degree of certainty are the Aldbrough and KGSP salt cavern storage sites, which have already begun their planning process. As a part of this, both have undertaken detailed site-specific environmental impact assessments (EIA) which cover the potential environmental risks during construction, operation, and decommissioning. The storage of hydrogen in depleted hydrocarbon reservoirs is also expected to play a significant role in England’s hydrogen storage future. However, the only planned site for this is the Rough site operated by Centrica, and no environmental impact assessment has been submitted for this site to date. There are currently no planned aquifer storage sites, so environmental impacts are assessed using global aquifer hydrogen storage activities.

3.3.1.2.2 Salt cavern hydrogen storage

As identified from the academic literature and EIAs for the actual sites undergoing planning activities, during construction and implementation, the most likely environmental impacts of salt cavern construction are:

- Generation and use/disposal of brine from solution mining of salt caverns;

- Impacts on groundwater from well head drilling, installation of foundations and cofferdams;
- Impacts on air quality associated with dust raising activities;
- Noise and vibration from construction;
- Disruption of the ecosystem at the construction site of the facility and ancillary infrastructure;
- GHG emissions from construction activities

Brine generation arising from solution mining of salt caverns is a significant environmental consideration when constructing salt caverns for hydrogen storage. Brine is a highly concentrated sodium chloride solution formed when halite deposits are dissolved by pumping water into the deposit. Depending on the specific composition of the halite deposit, the brine generated may vary in the minerals dissolved. It is reported that the brine generated from the proposed Aldbrough site will have a salt concentration of approximately 185-230 g/l (ERM, 2023). As seawater (about 35 g/l) is typically used for solution mining, this constitutes an increase in salinity of 150-195 g/l following solution mining. For the Aldbrough site, the brine generated will be discharged back into the sea, with the potential for impacts on the ecology of the North Sea, though these are expected to be short-lived as the high hydrodynamic activity of this region results in the brine being rapidly diluted. It is suggested that a brine dilution factor of 5,000 is sufficient to reduce the contaminant levels from extreme at the site of discharge to benign (Dewar et al., 2022). The rate of dilution can be increased by releasing brine close to the sea surface rather than at the seabed, however, natural tidal flows are generally able to rapidly dilute the discharged brine effectively (Dewar et al., 2022).

Instead of discharging to the nearby sea, the KGSP has sufficient infrastructure and means to use the majority of generated brine as a feedstock for the production of other substances including chlorine which is used in water treatment. It is reported that, currently 98% of the chlorine used in drinking water treatment is produced from brine generated from solution mining activities at the Northwich site (INEOS, n.d.b).

Overall, while brine generation from solution mining activities is a significant factor when constructing salt caverns for hydrogen storage, the process is no different for hydrogen storage than it is for natural gas storage, which has been safely conducted for almost a century. Measures to reduce the environmental impact of brine generation are mature and already practiced within England. The additional environmental impacts from widescale construction of salt cavern storage for hydrogen gas are likely to be small compared to the mining of salt caverns for hydrocarbon storage. On the other hand, it is possible that the increased mining of salt caverns to meet England’s short-term hydrogen storage needs may result in an increase in brine generation over a short period of time.

Salt cavern mining, particularly through solution mining techniques, poses potential risks to **groundwater quality**. The injection of saline solutions to dissolve underground salt formations can result in the leaching of contaminants, such as heavy metals and hydrocarbons, into the groundwater. Additionally, the brine solutions produced themselves may contaminate aquifers if not properly managed. The presence of these contaminants can make groundwater unsuitable for consumption and agricultural use, posing health risks to both humans and wildlife (Aryafar et al., 2013). Moreover, changing subsurface pressures during mining could potentially cause the migration of pollutants to other rock formations or aquifers, exacerbating the risk of groundwater pollution (Lall et al., 2020).

Air quality is likely to be impacted during the construction phase of salt caverns due to dust raising activities and emissions from machinery and traffic such as carbon monoxide, nitrogen oxides (NO_x), sulphur oxides (SO_x) and fine particulate matter ($PM_{2.5}$). Air quality should be closely monitored during construction activities and a risk assessment should be undertaken in accordance with relevant standards including but not limited to:

- Air Quality Standards Regulations 2010 Limit Values and Target Values (Defra, n.d.);
- UK Air Quality Strategy Objectives (Defra, 2023); and
- Environmental Assessment Levels (Environment Agency, 2021a).

These standards set out limitations to the permitted emissions to air of a number of pollutants which may impact air quality, including carbon monoxide, NO_x, lead, sulphur dioxide, and particulates (Environment Agency, 2016). To mitigate the impacts on air quality during salt cavern creation, industrial best practices and guidance should be followed, such as the Institute of Air Quality Management's (IAQM) guidance in the assessment of dust from demolition and construction (Institute of Air Quality Management, 2014).

It is unlikely that salt cavern creation specifically for hydrogen will result in any additional impacts on air quality than generic salt cavern creation for hydrocarbon storage.

Noise and vibration occurring during the construction of salt cavern facilities can result in disturbance in quality of life for nearby populated areas, particularly residential areas. The Noise Policy Statement for England (NPSE) and the Government's planning guidance on noise sets out measures to avoid or mitigate significant adverse impacts on health and quality of life in potentially affected areas (Defra, 2010). Noise and vibration has been highlighted as a risk to the quality of life of residents close to the proposed Aldbrough site which is significant enough to require mitigation measures (ERM, 2023).

Examples of standards which are relevant to the monitoring and mitigation of noise and vibration and its impacts include BS 4142:2014+A1:2019[13] and ISO 9613-2:2024[14].

Specific construction activities that may generate significant noise and vibration and could require monitoring and control include:

- Construction equipment used to construct the hydrogen storage facility infrastructure including the central processing area, wellhead platforms, access roads and laydown areas;
- Continuous drilling activities to construct the well boreholes;
- Continuous solution mining of the halite deposits to form the salt caverns;

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[13] BS 4142:2014+A1:2019, Methods for rating and assessing industrial and commercial sound (BSI Knowledge, 2019).
[14] ISO 9613-2:2024, Attenuation of sound during propagation outdoors (ISO, 2024).

- Construction traffic for transport of the workforce and deliveries of materials;

Appropriate mitigation measures could include substitution of noisy activities, use of noise control enclosures, and ensuring equipment is properly maintained.

3.3.2 Environmental impacts during service

3.3.2.1 Above ground hydrogen storage

3.3.2.1.1 Compressed and liquid hydrogen storage

The main impacts of compressed and liquid hydrogen storage will arise from leakage of fugitive hydrogen from the vessel into the atmosphere. It is reported that due to the extremely low density and viscosity of hydrogen, the leakage rate from even the most secure pressure or cryogenic vessels can amount to 0.12 to 0.24 % of the contained mass each day for hydrogen cylinders, and 0.1 to 5% per day for liquid hydrogen due to rapid boil-off as discussed in Section 3.1.2.3 (Frazer-Nash Consultancy, 2022). The environmental impacts of these fugitive hydrogen emissions will be similar to those discussed in Section 3.3.2.1, where the indirect global warming potential of atmospheric hydrogen must be considered. In addition, since the emissions of hydrogen gas will be more localised, a risk of ignition or explosions is increased, which is an immediate risk to human health, but also involves a risk of knock-on effects such as the loss of containment of nearby stored ammonia. Appropriate measures should be taken to mitigate the risk of hydrogen accumulating beyond ignition limits in a given volume, as well as considerations as to what knock-on effects could occur should a hydrogen explosion take place.

3.3.2.1.2 Metal hydride hydrogen storage

Solid state storage of hydrogen largely mitigates the risks of leakage from the containment vessel, though there is still some risk of fugitive emissions when extracting hydrogen from its solid-state carrier into the gaseous state. While less flammable than hydrogen gas, many metal hydrides, and particularly $LiAlH_4$ are well known to be highly flammable solids. In addition, exposure of these solids to moisture (even moisture in the air) can liberate hydrogen in an exothermic reaction which can cause the mixture to auto-ignite. Mitigation measures for this risk include using a hydrophobic slurry of the solid carrier in mineral oil to prevent exposure of the carrier to moisture. Use of mineral oils for the safer storage of metal hydrides is commonly practiced and proven within laboratory settings, though care must still be taken to avoid sources of ignition.

3.3.2.1.3 Liquid organic hydrogen carriers

While LOHCs are also flammable, they do not liberate hydrogen in contact with moisture like metal hydrides, reducing the risk of explosions or generation of fugitive hydrogen. Depending on the specific LOHC used, and its properties such as volatility, viscosity, and human or environmental toxicity, persistence or bioaccumulation, appropriate risk management measures such as ventilation, personal protective equipment, and (bio)monitoring should be taken to limit risks of worker or environmental exposure.

Furthermore, the balance between hydrogen storage performance and risk profile should be considered when selecting an appropriate LOHC. For example, benzene is a known carcinogen but has been assessed as a potential hydrogen carrier, whereas toluene demonstrates similar performance with a much-reduced risk profile.

3.3.2.1.4 Physisorption hydrogen carriers

High-surface area materials for the physisorption of hydrogen such as zeolites, MOFs and particularly carbon allotropes such as expanded graphite, carbon nanotubes and graphene have significant risks of becoming aerosolised within the environment if not carefully handled. These aerosolised ultrafine carbon materials can have acute impacts on air quality if released and may impact the respiratory health of those exposed such as workers (Luanpitpong et al., 2014). As physisorption of hydrogen onto these materials is a physical process rather than a chemical process, an equilibrium between adsorbed hydrogen and liberated hydrogen gas can be expected and therefore leakage of hydrogen can occur from the containment vessel. This should be closely monitored to limit the effects of hydrogen emissions to the atmosphere and the risk of explosions.

3.3.2.2 Underground hydrogen storage

3.3.2.2.1 Overview

During service life, the large-scale underground storage of hydrogen may result in specific environmental impacts which must be understood, monitored, and mitigated. These hydrogen specific impacts arise from the low molecular size, viscosity, and density of hydrogen gas, as well as its capacity as a reducing agent and as an energy source for anaerobic microbes. Possible impacts will vary depending on the specific method of underground hydrogen storage, and will therefore be addressed for salt cavern storage, depleted hydrocarbon field storage and aquifer storage separately.

As reported in a previous Environment Agency publication, the main environmental risks of underground hydrogen storage are suggested to arise from increased microbial activity in the presence of hydrogen, geomechanical impacts of high-pressure underground gas storage and leakage of fugitive hydrogen into the atmosphere (Environment Agency, 2021b). These remain the most important environmental risks associated with underground hydrogen storage at this time.

3.3.2.2.2 Increased microbial activity

There could be increased microbial activity in underground hydrogen storage facilities due to hydrogenotrophic methanogens and sulphate reducing bacteria using hydrogen as an energy source and emitting environmentally harmful gases such as methane and hydrogen sulphide. A recent study compiled data from 75 depleted gas fields (DGFs) from the UK Continental Shelf and assessed the risk of microbial activity in the DGFs based on the critical conditions for hydrogenotrophic[15] bacteria (Thaysen et al., 2023):

- **Category 1: No risk –** DGF with a temperature above 122 °C were considered sterile as no activity of hydrogenotrophic microorganisms has been detected above this temperature;

- **Category 2: Low risk –** DGF with a temperature above 90 °C were considered paleosterile, based on previous reports of paleosterilization[16] of oil fields above 80–90 °C;

- **Category 3: Medium risk –** There is no documented evidence that cultivated hydrogenotrophic microorganisms can grow at temperatures equal to or above 55 °C combined with salinities above 1.7 M NaCl (equivalent to 99.35 g/l), indicating that fields with these characteristics are not at risk. However, non-cultivated hydrogenotrophic microorganisms, for which the growth conditions are unknown, may be present in DGF and that the threshold temperature and salinity for this DGF risk group are relatively low. This category is classified as medium risk.

- **Category 4: High risk –** DGF with a temperature below 55 °C, where the large majority of hydrogenotrophic microorganisms show optimum growth conditions and where extreme salinity tolerances may be found, can be considered at high risk for adverse microbial effects.

In addition to these risk categories, sulphate concentration within the DGF is another significant factor to consider. While methanogenic microbes will generate methane from reactions between molecular hydrogen (H_2) and CO_2, this could be used in heating applications (Thaysen et al., 2023). On the other hand, sulphate reducing bacteria will generate the highly toxic and corrosive gas hydrogen sulphide (H_2S) as a by-product. Therefore, DGFs with little to no sulphate content can be associated with a lower environmental risk than those with a high presence of sulphate (Thaysen et al., 2023). There is limited information on the sulphate concentration of DGFs, though for those where sulphate concentration is known, only one DGF has high enough concentrations that it is thought to potentially pose a secondary environmental risk due to generation of H_2S (Thaysen et al., 2023). The number of DGFs in each risk category and their regions are summarised in Table 6.

[15] Consume hydrogen as a source of energy.
[16] Prevention of oil biodegrading.

Table 6: Microbial growth risk of depleted gas fields and their locations

Risk Category	AM	CNS	IS	NNS	SNS	Total
High	0	1	6	0	2	9
Low	1	0	0	0	34	35
Medium	0	0	0	0	22	22
No risk	0	1	0	1	7	9
Total	**1**	**2**	**6**	**1**	**65**	**75**

Source: Thaysen et al., 2023

Key: NNS= Northern North Sea; SNS= Southern North Sea; CNS= Central North Sea; AM= Atlantic Margin; IS= Irish Sea.

The majority of DGFs with a high risk for hydrogenotrophic microbial activity lie within the Irish sea, and only two sites would be considered high risk in the Southern North Sea (SNS). The Rough DGF in the SNS is classified as low risk as it has an average temperature of 92°C and a salinity of 3.4 mol/L (NaCl; sodium chloride). Most of the DGFs in the SNS region are considered low, or no risk sites, and therefore this region may play host to a number of hydrogen storage facilities in the future. In addition, the offshore wind energy capacity in the SNS region is approximately 5 GW – the highest in the UK, therefore the viability of green hydrogen production and storage in the SNS is high with minimal risk of impairment by hydrogenotrophic microbe activity. Thaysen et al. (2023) also produced a geographic information system (GIS) map of available DGFs, their risk categories and the nearby wind or solar energy generation capacity. This map is reproduced in Figure 3.

The study also indicates that salt caverns demonstrate much reduced risk of increased hydrogenotrophic activity due to their high salinity, which causes osmotic stress to most microbial cells, reducing the risk of biofilm formation, clogging and by-product generation resulting from sulphate or CO_2 reducing bacteria. However, in the event of hydrogen leakage from the cavern through cavern defects or microcracks, hydrogenotrophic bacteria found in the rocks and groundwater between the cavern and the surface may be affected by the increased concentration of hydrogen.

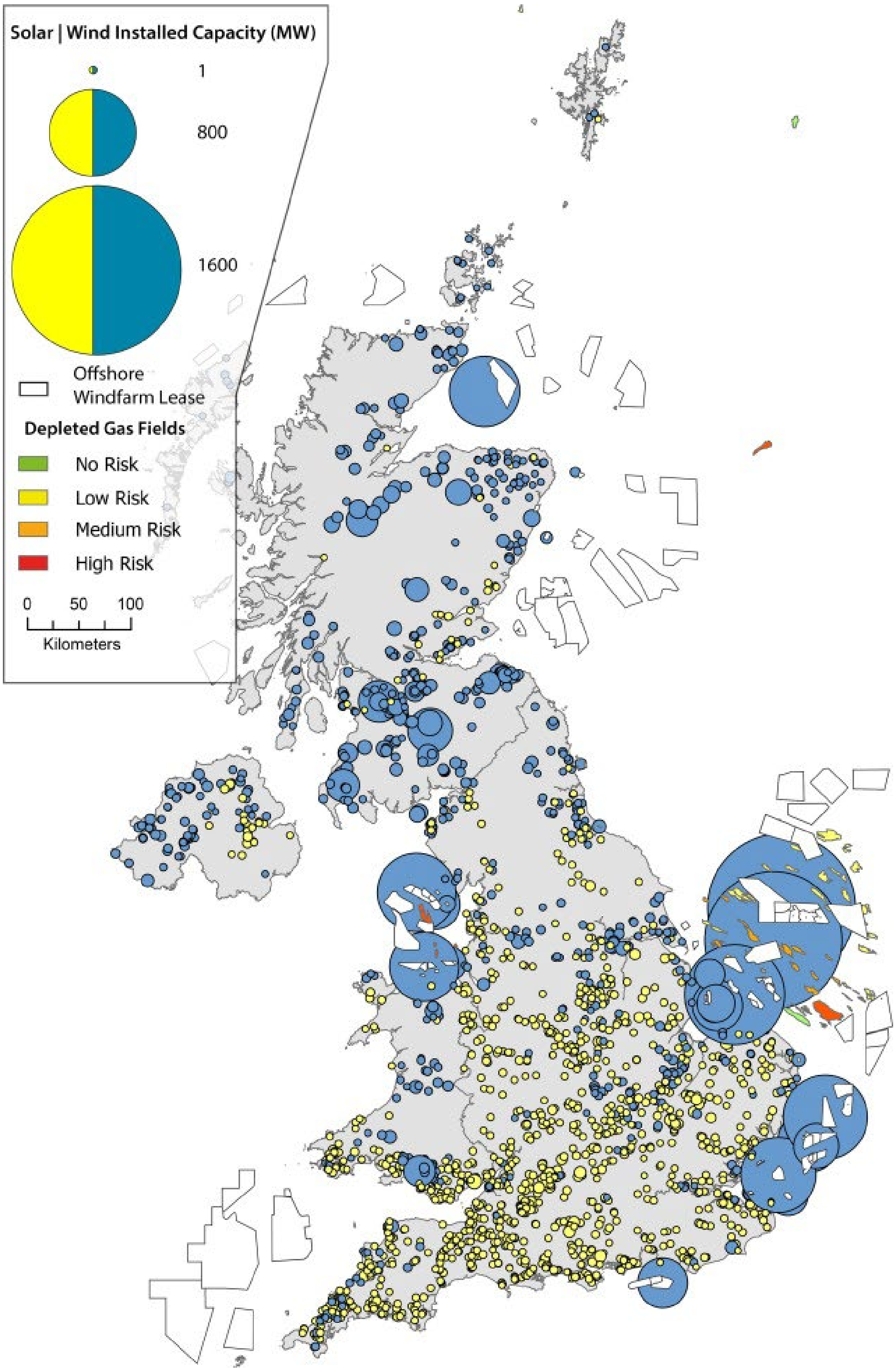

Figure 3 Map of DGFs on the UK Continental Shelf and their risk categories with respect to hydrotrophic microbial growth, overlain with wind or solar power generation capacity both on and offshore. ***Source:*** Map extracted from Thaysen et al., 2023

3.3.2.2.3 Underground geochemical and geomechanical impacts

The environmental impacts of underground hydrogen storage can also be influenced by a range of geochemical reactions that occur between the hydrogen, pore water, dissolved gases, and rock matrix (Heinemann et al., 2021). These reactions can lead to several outcomes, including significant loss of stored hydrogen, contamination of hydrogen by other gases like hydrogen sulphide (H_2S), and changes in the mineral composition of the reservoir and caprock (Heinemann et al., 2021). These alterations can affect the mechanical properties of the storage site, potentially compromising its integrity and efficiency (Osman et al., 2021).

Geochemical and geomechanical interactions with the caprock pose additional risks for underground hydrogen storage concerning the potential for hydrogen leakage into land, water, and air (Osman et al., 2021). Mineral dissolution in the caprock can create new migration pathways, compromising the integrity of the containment barrier and leading to the escape of stored hydrogen. For example, reactions with iron-bearing minerals or sulphur-bearing minerals like pyrite could weaken the caprock, making it more susceptible to fractures (Heinemann et al., 2021). These fractures could serve as conduits for hydrogen to migrate into surrounding environments. The formation of H_2S through reactions with dissolved sulphur species can exacerbate this issue. H_2S is not only corrosive but also poses risks of flammability and toxicity so such leakage could have far-reaching environmental consequences, including groundwater contamination and atmospheric release, which would not only defeat the purpose of using hydrogen as a low-carbon energy source but also pose health and safety risks. Therefore, understanding the geochemical and geomechanical interactions of hydrogen with the caprock is critical for ensuring the secure and efficient operation of underground hydrogen storage facilities.

3.3.2.2.4 Fugitive emissions of gaseous hydrogen

Due to its low viscosity and density and molecular size, hydrogen leakage from storage systems is possible, both through leakage associated with plant operation, including during maintenance, shutdown and emergencies; but also, from natural leakage through the subsurface. While hydrogen itself does not directly have an impact on global warming or air quality due to its infrared inactivity and lack of toxicity respectively, hydrogen is now thought to increase the lifetime of GHGs within the atmosphere by reducing the concentration of hydroxyl radicals in the atmosphere which are known to break down potent GHGs such as methane. It is estimated that the indirect global warming potential of hydrogen gas is approximately 11 ±5 times that of CO_2 (BEIS, 2018; Warwick et al., 2022).

No studies have been identified which expressly measure the rate of hydrogen leakage from underground hydrogen storage sites. However, it is reported that approximately 25 tonnes of hydrogen per year can be expected to leak from a typical surface plant that is linked to 15-20 caverns (Frazer-Nash Consultancy, 2022). Assuming a storage capacity of 2.6 TWh, this relates to an annual leakage rate of 0.04% (Frazer-Nash Consultancy, 2022). If the approximately 10 TWh underground hydrogen storage capacity target for 2035 is met, this could constitute an annual leakage of around 96 tonnes of hydrogen which would have the same global warming potential over a 20-year period as almost 2,000 tonnes of CO_2. While this annual figure may seem small in comparison to the estimated UK total of 308,000,000t in 2020, the indirect global warming potential of fugitive hydrogen may act to reduce the environmental benefits of net zero efforts if not closely monitored and controlled (Macrotrends, n.d.).

3.3.3 Environmental impacts at end-of-life

Above-ground hydrogen storage will have variable end-of-life impacts depending on the specific technology used. Pressure vessels and cryogenic vessels will most likely be disposed of as non-hazardous waste or recycled depending on their material when decommissioned. Hydrogen carriers on the other hand are often made from potentially hazardous waste such as flammable or water reactive solids, or liquid organics such as toluene. Metal-based hydrogen carriers are most likely to be recycled as typical hydrogen carrier metals, especially lithium, are also considered to be critical minerals and their sourcing and circular economy is of particular relevance to England's net zero efforts. LOHCs could be purified at their end-of-life and used as solvents or reagents in chemical feedstocks depending on the needs of the industry. For example, the hydrogen carrier toluene is routinely used as a solvent in numerous chemical processes. If LOHCs cannot be repurposed at their end-of-life, they will most likely be incinerated. This should take place at a facility with means to recover the energy and ideally at a site that is CCUS enabled to reduce the global warming potential of LOHC waste as organic materials, there is also a possibility of generating persistent organic pollutants (POPs) such as dioxins following incineration. The emissions should be carefully monitored and controlled as set out in the Waste Framework Directive. There is not currently a consensus on the lifetime of hydrogen carriers before they must be replaced, and therefore it is not possible to determine how much waste will be generated from the replacement of degraded hydrogen carriers during or at the end-of-life.

At end-of-life, the environmental impacts of decommissioning underground hydrogen storage facilities are likely to be similar to those encountered during the construction phases. Noise and local air pollution from machinery, including NO_x, SO_x, CO and particulate matter will be the most significant impacts during the decommissioning phase. Waste from the demolition of redundant infrastructure will be generated. However, there is a possibility that the site could be converted to a permanent underground CO_2 storage facility once the storage of hydrogen is no longer feasible. It is currently unknown whether there would be long-term stability issues from retaining caverns filled with only cushion gas if the sites are not decommissioned or repurposed for other gas storage applications. As shown in the Teesside hydrogen storage sites, salt caverns in particular will likely be operational for over 30 years before decommissioning, and likely much longer due to advances in hydrogen storage technology.

3.4 Social aspects of hydrogen storage technologies

3.4.1 Overview

Of all the ESTs, hydrogen has been studied most extensively, though research is far from conclusive. Studies show that there are low levels of familiarity with hydrogen energy technologies and research participants are often unclear about the differences between hydrogen production methods and their resultant carbon emissions. A 2021 systematic review of the social scientific literature on hydrogen technologies found just three articles on hydrogen storage. From this, the authors surmise that the public has low levels of knowledge about hydrogen as a storage technology but were supportive of its use as a potential solution for intermittency from renewable energy (Emodi et al., 2021; Vallejos-Romero et al., 2022). Given this paucity of data, research on public perceptions of hydrogen as a substance and hydrogen use in other contexts will be reviewed here, while bearing in mind the caveat about this lack of knowledge about hydrogen amongst the public. While hydrogen storage will of course raise specific issues, this broader literature is assumed to be relevant, not least because the evidence shows that knowledge and familiarity, including in different contexts, are very important factors in public perceptions and social acceptance of technologies (Stalker et al., 2022).

3.4.2 Public perceptions

3.4.2.1 Safety

A 2008 review of research on public perceptions of hydrogen as a fuel and energy carrier (Ricci et al., 2008) noted that, while even proponents of hydrogen have often assumed an association between hydrogen and explosivity in public perceptions, this is not commonly found in empirical research. While safety is a consideration (Emodi et al., 2021), it is not a key concern about hydrogen for laypeople across a range of locations (Häußermann et al., 2023; Vallejos-Romero et al., 2022). This may depend on the context in which hydrogen is being used (Vallejos-Romero et al., 2022), though members of the public and experts do still expect safety standards to be in place around hydrogen storage facilities (Emodi et al., 2021). One of the few studies of attitudes to hydrogen storage, from Germany, found that people viewed hydrogen as clean and modern, but also potentially dangerous, yet perceived its benefits to outweigh such risks (Zaunbrecher et al., 2016). However, this apparent lack of concern about safety could reflect widespread lack of knowledge about hydrogen.

3.4.2.2 Neutral, positive and negative perceptions

Existing research tends to find neutral or positive perceptions of hydrogen amongst the public, but also a great deal of uncertainty, including in comparison to renewable technologies such as wind and solar power (Carlisle et al., 2023; Häußermann et al., 2023). One of the main reasons that members of the public cite for positive perceptions of hydrogen is its (potential) lack of negative impact on the environment. This includes a German study of hydrogen storage, in which focus group participants identified the technology as ‘clean’ and a potential contributor to reducing carbon emissions (Zaunbrecher et al., 2016). This reflects general support for renewable energy technologies amongst people who have participated in research on hydrogen (Bentsen et al., 2023; Emodi et al., 2021; Häußermann et al., 2023; Scott and Powells, 2020). However, the widespread lack of knowledge about hydrogen and its potential role in decarbonisation, as well as public uncertainty about whether to use blue hydrogen or progress towards green hydrogen, should be borne in mind (Bentsen et al., 2023; Emodi et al., 2021). The main negative perception of hydrogen and hydrogen technologies that emerges from the existing literature is its current high cost to the consumer, which may become a barrier to acceptance (Emodi et al., 2021).

3.4.3 Acceptance and opposition

3.4.3.1 Overview

A systematic review of social science research on hydrogen energy technologies found that the most significant factors affecting acceptance across different countries were respondents' environmental knowledge, prior knowledge of hydrogen technologies, perceptions of costs and risks, educational level, gender (with males typically more positive), and attitudes to technology and the environment (Emodi et al., 2021). For studies within the UK, the most important of these factors were distributive benefits, cost, respondents' level of environmental awareness, their perceptions of infrastructure availability, and the siting of facilities close to consumers. Higher socio-political acceptance of hydrogen technologies has been found in energy-intensive countries like China, Japan, and South Korea, where they are associated with job creation, energy security, and expansion of business (Emodi et al., 2021).

Emodi et al.'s review (which covers all hydrogen technologies and data from across the world) found that men are more likely to support hydrogen technologies in general, as they tend to assume that they will be regulated before becoming available to the public, while women report more confidence in using hydrogen technologies due to a faith in technological advancement and a belief that hydrogen technologies could benefit the environment. Relatedly, women have a stronger preference for green hydrogen compared to men (Emodi et al., 2021). On the siting of hydrogen power plants, men were concerned about the scale of hydrogen production plants, sources of energy to power the plant and potential local pollution problems, while women tended to think of hydrogen production plants as like other industrial plants (Emodi et al., 2021). Younger people are more likely to support hydrogen energy technologies than older people but lack trust in local government (Emodi et al., 2021). The same study found that members of the public were concerned about security of supply, ensuring safety standards and regulation were established, and that hydrogen would not be more expensive than other sources of energy (Emodi et al., 2021).

A review of social scientific research on green hydrogen found that, while it is not as significant as some of the demographic factors outlined above, the existence of policies that support green hydrogen development and deployment is associated with greater awareness and acceptance of green hydrogen (Vallejos-Romero et al., 2022). Concern about the environment also seems to be an important factor (Bentsen et al., 2023).

3.4.3.2 Siting and local acceptance

Existing research suggests that there is support for the siting of hydrogen infrastructure near respondents' dwellings, though this is partly conditional on the provision of more information (Emodi et al., 2021). This local acceptance reflected assumptions that the industry would offer local job creation, perhaps especially in areas characterised by industrial decline or reconfiguration (Emodi et al., 2021; Ricci et al., 2008). However, this local acceptance is accompanied by concern about whether the benefits of this industry will be distributed locally and whether it will entail local capacity building and sustainable employment, as well as about the use of natural resources, especially amongst Indigenous communities in countries like Australia (Emodi et al., 2021). Similarly, in a mixed-methods study of perceptions of domestic hydrogen technologies in the UK, Scott and Powells (2020) point out that hydrogen transitions are likely to occur first in the North of England amongst relatively deprived communities already experiencing fuel poverty, so questions of cost and the distribution of jobs and other economic benefits are apt.

3.4.4 Knowledge and familiarity

Although the UK is the most frequent location for social scientific research on hydrogen (15% of the studies were located in the UK; Emodi et al., 2021), systematic reviews have found that levels of knowledge about hydrogen technologies and hydrogen as a substance amongst the British public are low (Emodi et al., 2021; Ricci et al., 2008; Vallejos-Romero et al., 2022). The latest (DESNZ, 2023b) public attitudes tracker found that 59% of people surveyed in the UK know ‘hardly anything or a little’ about hydrogen as a fuel; they did not ask about hydrogen as a storage technology, but it is likely this will be even higher. Hydrogen is more familiar in Germany, though even there, there is considerable unfamiliarity, especially in relation to hydrogen storage (Zaunbrecher et al., 2016). There is also substantial uncertainty: 'Only 37% of respondents feel able to form an opinion of hydrogen technologies, in contrast to other energy technologies, such as solar (62%) and wind power (60%)’ (Häußermann et al., 2023: 5). This German study also found that older people are more likely to be familiar with hydrogen, while familiarity with green hydrogen is higher amongst younger people and those with higher levels of educational attainment (Häußermann et al., 2023). Vallejos-Romero et al. (2022: 10) conclude: 'even though people have been gaining knowledge over time regarding green hydrogen, there is no change in the perception of its risks or benefits. … [C]oncerns prevail about on the one hand, its costs, impacts on the environment and efficiency and, on the other, safety appears as an important variable, but not a determining one, since it is assumed as given from the beginning of the projects'.

Several authors make an important observation, that the high levels of acceptance of hydrogen and green hydrogen may reflect a lack of detailed knowledge about hydrogen technologies, including any challenges that their implementation may pose, and can therefore indicate a general positivity towards science, technology, and ‘progress’ rather than enthusiasm for hydrogen per se. In the case of green hydrogen, this may be strengthened by its association with decarbonisation and environmental sustainability. For example, in Germany, 'Overall, it is possible to observe both a marked lack of knowledge and a large degree of openness towards green hydrogen and its local use, along with high expectations regarding environmental and climate protection' (Häußermann et al., 2023: 1). This is important since it could indicate that support for hydrogen technologies is thin and could easily shift with more information or if a different narrative about it emerged in public debate.

Similarly, giving people more information does not necessarily lead to greater support for hydrogen technologies, as people do not form opinions simply on objective knowledge, but also cultural predispositions, experiential knowledge, and affect (Stalker et al., 2022; Zaunbrecher et al., 2016). Relatedly, several researchers make the point that, while the positivity towards hydrogen may outweigh negativity, we should be careful not to overlook the large numbers of respondents who are undecided and uncertain about hydrogen technologies. Further, we cannot assume simple relationships between knowledge, positive perceptions, and acceptance of a technology, as was found in Germany in relation to green hydrogen: '87% of undecided respondents, along with 61% of those who foresee a negative impact on safety, nonetheless have a very or somewhat positive attitude towards local green hydrogen use' (Häußermann et al., 2023: 6).

3.4.5 Trust

Research in Germany found that trust in institutions implementing green hydrogen, and particularly their ability to ensure the fair distribution of its costs and benefits, was a significant factor in its acceptance. Similarly, they found a relatively strong positive correlation between acceptance of green hydrogen and trust in science (Häußermann et al., 2023). Another study of hydrogen storage in Germany found that people anticipated the technology might be risky but trusted public infrastructure to mitigate these risks (Zaunbrecher et al., 2016). These authors also note a decline in general trust in science and technology and point out that people who identify potential safety risks do not need more information, but more trust in the technology (Zaunbrecher et al., 2016). Emodi et al. (2021) note the need for improved public communication and awareness raising of hydrogen technologies to improve the public's engagement with the hydrogen industry. They also recommend that coordinated networks are built between science, industry, and local authorities to improve trust and therefore societal acceptance.

3.4.6 Gaps in the literature and future research

While hydrogen is the most studied aspect of ESTs within the social sciences, there is still room for further research and evidence-gathering about public perceptions and social acceptance of hydrogen storage in particular. Given that there is uncertainty about whether and how hydrogen will be used in the UK's progress towards net zero, tracking public opinion will be important in informing developers, regulators, and policymakers on how and where to implement hydrogen technologies. As noted, the high levels of unfamiliarity and uncertainty around hydrogen mean that acceptance might be quite precarious and therefore, if the narrative around hydrogen storage shifts, public opinion may change with it.

3.5 Remaining data gaps

The current understanding of hydrogen storage in England faces several key data gaps, particularly concerning the deployment trajectories and environmental impacts. Firstly, the exact volume of compressed and cryogenic hydrogen expected to be used in England over the coming years is unknown. This volume is essential for calculating storage capacity. Secondly, there is uncertainty regarding the specific above-ground hydrogen storage technologies that will be adopted to achieve short-term targets. This uncertainty complicates planning and infrastructure development. Thirdly, the durability of hydrogen carriers, specifically the number of cycles they can undergo before performance degrades to an unacceptable level necessitating replacement, is not clearly established. This impacts the long-term viability and cost-effectiveness of these storage solutions. Fourthly, it remains to be seen that there are any studies with quantifiable evidence of the rate of hydrogen leakage from underground storage; only theoretical predictions are readily available. Lastly, a comprehensive quantification of the environmental impacts arising from the sourcing and manufacturing of these various above-ground hydrogen storage technologies is not well understood, posing challenges in assessing their overall sustainability and environmental footprint.

3.6 Conclusions and summary

The evidence surrounding the deployment trajectories and environmental impacts of hydrogen is the most clear and complete of all technologies assessed in this work. The presence of numerous government, non-government, and academic estimations of the capacity of hydrogen storage needed over the coming years has allowed for an in-depth qualitative and quantitative assessment of the potential environmental impacts associated with a wide range of above-ground and underground hydrogen storage technologies.

The literature base detailing the potential environmental impacts is also diverse, particularly in underground hydrogen storage in geological formations, where geomechanical issues and microbiological issues have been researched in detail. However, for underground hydrogen storage significant gaps still remain, namely quantification of the rate of hydrogen leakage from these systems. The importance of this data gap is emphasised by recent studies highlighting the risk of hydrogen as an indirect GHG.

Explicit research on the environmental impacts of above-ground hydrogen storage is much more sparse, with the few exceptions mainly focussing on the environmental impacts of hydrogen transport, rather than stationary above-ground storage. However, due to the relative simplicity of above ground storage, the environmental impacts can largely be deduced from other literature which is not specific to above-ground hydrogen storage (i.e., explosion risks, chemical risks from LOHCs, global warming potential of hydrogen etc.)

A summary of the potential environmental issues associated with underground and above-ground hydrogen storage is shown in Table 7 and Table 8.

Table 7: Summary of the main environmental issues associated with different underground hydrogen storage solutions

Technology	Notes	Environmental Issues
Salt cavern storage	Where new salt caverns need to be created, this is done by pumping water into underground halite deposits, producing brine and a vacuous space suitable for the storage of gases.	Brine generation and disposal during cavern creation (c.a. 8 m3 per m3 cavern volume). Potential for leakage into groundwater. Emissions of fugitive hydrogen through leakage during pumping operations and through mechanical defects. Interruption of mechanical stability of the cavern.
Depleted Gas Field (DGF) storage	Porous media of natural gas reservoirs on the UK Continental Shelf can be repurposed to store hydrogen gas.	Reduced stability of caprock under elevated pressures. Hydrogenotrophic microbial activity leading to H_2S generation as well as pore clogging and equipment malfunction. Fugitive hydrogen emissions through caprock. Geochemical reactions with hydrogen leading to precipitation of solids.
Aquifer storage	Hydrogen can be injected into deep saline aquifers, displacing water for longer-term storage. Unlikely to deploy in England due to availability of more suitable options (Scafidi et al., 2020).	Similar impacts to DGFs but with fewer sterile sites leading to increased microbial activity risk (Thaysen et al., 2023).

Table 8: Summary of the main environmental issues associated with different above-ground hydrogen storage solutions

Technology	Notes	Environmental Issues
Compressed hydrogen storage	Hydrogen is stored as a gas in pressurised vessels. These vessels may vary in size depending on the application.	Hydrogen leakage from malfunction, operator error or equipment failure. Explosion risk.
Cryogenic liquid hydrogen storage	Hydrogen is cooled and compressed to induce liquefaction. Allows for lower pressure storage of hydrogen.	Risk of boil-off, releasing large quantities of hydrogen. Explosion risk. Emissions and waste generation from refrigeration and liquefaction activities.
Metal hydride storage	Hydrogen can be stored in the solid state as metal hydrides such as $LiAlH_4$ or MgH_2, removing the need for pressurisation and reducing the risk of hydrogen leakage.	Metal hydrides undergo exothermic reaction with moisture, liberating hydrogen leading to potential explosions or fire. Sourcing of raw minerals and manufacture of carriers. (Lifetime of carriers is unknown). Waste disposal.
Liquid organic hydrogen carriers	Aromatic or polyunsaturated organic compounds can be catalytically hydrogenated/dehydrogenated to store hydrogen as a liquid, allowing transit through pipelines with low explosion risk. Examples include the toluene/methylcyclohexane pair.	Risks associated with hazards of the specific LOHC pair used. Flammability and toxicity considerations. (Lifetime of carriers is unknown). Waste disposal. Volatile organic compound (VOC) emissions.
Adsorption storage	High-surface area porous materials can adsorb hydrogen via weak electrostatic interactions, increasing the volumetric storage density of hydrogen. Materials may include metal-organic frameworks, zeolites, or high-surface area carbon allotropes.	Sourcing of raw materials. Hydrogen leakage and explosion risk. Workplace exposure to high-surface area materials. Waste disposal.

4 Ammonia Storage

4.1 Introduction

This chapter aims to explore the role of ammonia as an energy storage medium, a subject that has garnered significant interest in the context of global decarbonisation efforts. Ammonia's journey as a commodity spans over a century, with its efficient synthesis achieved through the work of Fritz Haber and Carl Bosch in 1909. The industrial synthesis of ammonia, primarily through the Haber-Bosch process, has been a cornerstone in chemical production, combining hydrogen and nitrogen gas over an iron-based catalyst. Despite technological advancements, the core principles of this process have remained consistent, underpinning the production of approximately 150 million tonnes of ammonia globally in 2022 (Statista, 2024a).

Historically, ammonia's applications have been diverse, ranging from its use as a solvent, reagent, refrigerant, and cleansing agent to its critical role in agricultural fertilisers. However, its potential extends far beyond these traditional domains. In recent years, ammonia has emerged as a promising vector for energy storage and transport, contributing to the global decarbonisation agenda. Its ability to act as a carrier for hydrogen offers a solution to increase the volumetric energy density of hydrogen, facilitating more efficient storage and transportation. Moreover, ammonia can be used in electrofuels for fuel cells, including solid oxide fuel cells, and as a combustion fuel in internal combustion engines.

The attractiveness of ammonia as a hydrogen carrier lies in its established synthesis from green or blue[17] hydrogen, leveraging technically and economically mature methods. Additionally, ammonia can be stored and transported more safely and under far less stringent conditions than hydrogen gas, presenting a practical and scalable alternative for energy storage.

In the subsequent sections of this chapter, the deployment trajectories of ammonia as an energy storage medium in England are assessed, as well as the environmental impacts of ammonia storage, considering both the potential benefits and the challenges that need to be addressed.

4.1.1 Ammonia storage technologies

Large scale ammonia storage is a mature area of engineering, as ammonia vessel design has been constantly evolving over the past century. Historically, ammonia was stored

[17] Green and blue hydrogen refers to hydrogen which is produced from water electrolysis using zero-emissions fuels, and hydrogen which is produced by reforming natural gas, but with carbon capture in place respectively.

under elevated pressure in either bullets with a capacity of around 3,500 m^3 or Horton spheres with a capacity of around 9,000m^3. Modern vessels store 50,000 tonnes of ammonia at atmospheric pressure at a reduced temperature of -33 °C which allows for safer storage at a lower capital cost (AmmoniaKnowHow, n.d.). Ammonia storage facilities are being explored as part of integrated systems combining renewable energy generation, green hydrogen manufacture, green ammonia manufacture and storage as well as cracking facilities to regenerate green hydrogen. These sites are likely to be located at ports providing the option of importing green ammonia from other countries where production is more economically feasible due to greater access to solar energy.

4.1.2 The role of ammonia and its storage in achieving Net zero

Ammonia is continuing to gain traction as an attractive medium for the storage of energy, particularly low-carbon energy. Beyond its existing uses in fertilisers, refrigeration, explosives, cleaning, and as a chemical reagent, ammonia is currently in early stages of use in both the energy generation sector and as a transport fuel. Direct combustion of ammonia or use as an electrofuel in polymer electrolyte membranes, alkaline or solid oxide fuel cells, provides a carbon-free energy vector which could play a significant role in decarbonising energy and transport. Ammonia is of particular interest as a maritime fuel for low-carbon shipping, where existing vessels are undergoing early retrofitting as a proof of concept for the transition to ammonia fuel. In the aviation sector, research is currently underway to produce low-carbon fuels from partially cracked ammonia (ammonia which has been partially converted into hydrogen gas).

In its role as a hydrogen carrier, ammonia is seen as particularly unique in that upon discharging hydrogen gas from ammonia, the only by-product is nitrogen gas, which is environmentally benign and already makes up 79% of Earth’s atmosphere. Therefore, nitrogen can be sourced directly from the air during ammonia production and can be released directly into the atmosphere following hydrogen discharge. This means that complications arising from carrier sourcing and recycling are largely addressed in comparison to other hydrogen carriers such as metal hydrides or LOHCs. However, the widespread use of ammonia as a hydrogen carrier is hampered by the technical immaturity of efficient large-scale cracking processes.

There are no formal estimates for the required capacity of ammonia production or storage to meet England’s net zero targets. However, it is estimated that the demand for hydrogen-based fuels, which would be comprised principally of ammonia, could reach 75 to 95 TWh by 2050 (DESNZ, 2021). Globally it is estimated that an annual production capacity of 566 Mt of renewable ammonia will be required in 2050 to achieve the 1.5°C climate scenario. However, this includes the production of ammonia for fertiliser applications, and the demand for ammonia for shipping and as a hydrogen carrier under the 1.5°C scenario will be around 300 Mt in 2050.

4.2 Deployment trajectories of ammonia storage technologies

4.2.1 Current ammonia storage capacity and sites

It is challenging to determine the current operational capacity of ammonia storage in England due to the dynamic nature of the industry and lack of readily available and recent data. However, as a point of reference, the CF Fertilisers UK plant in Billingham was until recently the UK's largest production facility of ammonia and ammonia related fertilisers, producing around 230,000 tonnes of ammonia per year (CF Fertilisers UK, n.d.). It is proposed that this site will close due to economic infeasibility (CF Industries, 2023). However, the historical activity of this site highlights that the infrastructure for the storage and transport of large volumes of ammonia in England is mature.

4.2.2 Planned ammonia storage capacity and sites

There is no comprehensive strategy for the deployment of green ammonia production and storage technologies, however, two planned large-scale fully integrated green energy ports are currently in the planning stages. These sites aim to bolster England's hydrogen economy using green ammonia as an imported form of stored hydrogen.

Stanlow Terminals Ltd have announced that they are to develop a major new open access import terminal for green transport in the Port of Liverpool (Stanlow Terminals, 2023). This expansion of existing facilities will enable the import and storage of over one million tonnes of green ammonia annually, facilitating its distribution within the UK or its conversion to green hydrogen through cracking for industrial use in the Northwest of England. The proposed ammonia terminal is set to begin operations in 2027 and will comprise the following infrastructural features:

- Deep draft jetty for large vessels;
- Large-scale cryogenic ammonia storage tanks;
- Cracking facility for conversion of green ammonia to green hydrogen;
- Ammonia distribution pipeline and facilities;
- Connection to the hydrogen gas pipeline; and
- Connection to the hydrogen transport hub

Air Products and Associated British Ports announced in late 2022 their intentions to develop a green energy terminal at the Immingham port on the Humber estuary (Air Products, 2022). This would involve the production of green ammonia from a centralised site of renewable energy generation, green hydrogen generation through water electrolysis and green ammonia production at an onsite Haber-Bosch facility. Most of the green ammonia, however, is expected to be imported to the site by ship from Saudi Arabia. Cryogenically stored ammonia can then be distributed through pipeline or transport networks to the UK, or converted into hydrogen and nitrogen on-site, where the hydrogen would be utilised as a green fuel. This site is proposed to have a minimum import capacity in excess of 5.6 million tonnes of liquid, which would likely largely be comprised of ammonia.

4.3 Environmental impacts of ammonia storage

4.3.1 Environmental impacts during construction

During construction of ammonia storage sites, the main environmental impacts are expected to be on air quality from dust raising activities and operation of machinery. Noise emanating from the construction site to the surrounding area, particularly residential zones may have impacts on human quality of life and health if not carefully mitigated.

During the first-filling phase of ammonia tanks there may be additional risks of emissions of ammonia into the environment. The impacts of ammonia emissions will be addressed in detail in Section 4.3.2.

Aside from this, there are unlikely to be environmental impacts at the construction phase which are specific to the storage of ammonia, and general impacts of the construction of a large industrial facility are to be expected.

4.3.2 Environmental impacts during service

The primary environmental concern associated with the storage of ammonia is its potential release of ammonia into the atmosphere. Ammonia is classified under the Global Harmonised System for substance hazard classification as Skin Corrosion category 1B, Acute Aquatic Toxicity category 1, Flammable Gas category 2, and Acute Toxicity category 3, and ammonia emissions present significant risks to both ecological systems and human health.

In the event of a leakage, which could occur due to equipment malfunction or operator error, there is a possibility that ammonia could reach concentrations in the air that are harmful to individuals through inhalation. It is noteworthy, however, that ammonia has a distinct odour that is detectable at concentrations well below those that could cause long-term health effects, providing an early warning sign for corrective measures to be taken.

When in storage or during gas transmission or use activities, ammonia may leak through both preventable and unpreventable defects in the infrastructure. These are known as fugitive emissions and should be minimised through industrial best practices, including careful monitoring and regular servicing of equipment, as well as considering transport of emitted ammonia by wind and how ammonia emissions may be blown over populated areas or protected sites.

While ammonia storage for energy applications is still in its infancy, the historical use of large quantities of ammonia in agriculture and refrigeration has resulted in the rigorous study of the environmental impact of its emissions and its environmental fate. These studies on environmental impact and fate will be discussed in the remainder of this section.

4.3.2.1 Ammonia emissions in the UK

Ammonia emissions have been steadily falling over the past four decades due to better industry practices, particularly in the agricultural sector. However, ammonia emissions have been the slowest to decline over this period when compared to other pollutants such as sulphur dioxide, nitrogen oxides and non-methane volatile organic compounds (NMVOCs) due to the increased demand for fertiliser, and an increasing livestock population, where animal excretion contributes significantly to ammonia emissions (Defra, 2022a). The trends in various air pollutant emissions including ammonia can be seen in Figure 4.

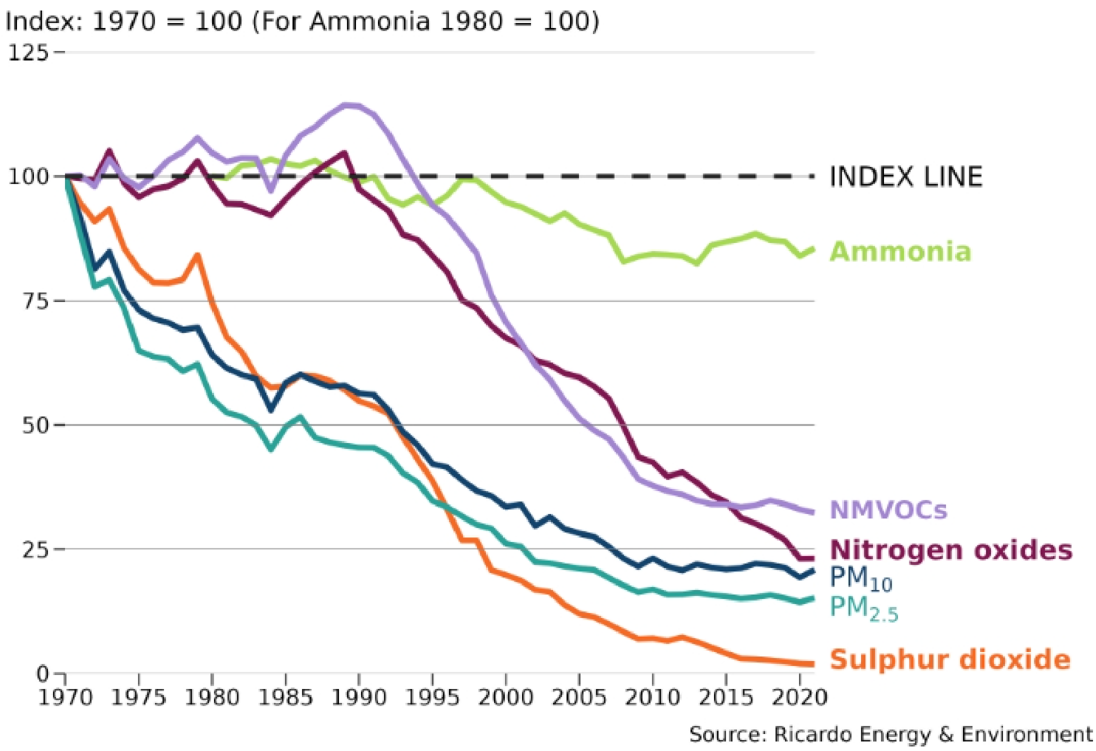

Figure 4: Long-term trends in emissions of air pollutants. ***Source:*** Defra, 2022b

In 2021, the total emissions of ammonia in the UK were 265 kt, and the emissions from the agricultural sector represented 230 kt, 87% of the total ammonia emissions in that year. Emissions from all other sources accounted for the remaining 35 kt, 13% of the total (Defra, 2024).

No data is currently available on the rate of ammonia leakage from storage tanks, though as ammonia is intentionally emitted into the environment as a fertiliser, it is expected that additional fugitive ammonia emissions from storage tanks will represent a relatively small proportion of overall emissions. To limit fugitive ammonia emissions from storage tanks as the deployment of ammonia for energy proceeds, regular inspections and repairs must be undertaken to limit the effects of tank corrosion, stress corrosion cracking, and other defects which may result in unwanted leakage of ammonia from the system (Fertilizers Europe, 2008). More research within the large-scale ammonia storage industries should be undertaken to better quantify the emissions of ammonia from storage vessels, which could then be put into the perspective of the well-documented impacts of ammonia on the environment.

4.3.2.2 Fine particulate matter generation

While ammonia itself is a gas at atmospheric pressure and temperature, it is a precursor to fine particulate matter ($PM_{2.5}$)[18] which can cause severe illnesses such as chronic obstructive pulmonary disorder (COPD), and cancer (Bauer et al., 2016). In atmospheric conditions, ammonia is transformed into ammonium salts such as ammonium sulphate, bisulphate and nitrate ($(NH_4)_2SO_4$, NH_4HSO_4, NH_4NO_3 respectively) (Wyer et al., 2022). These salts precipitate as fine particles and can enter human airways and penetrate the thoracic region of the respiratory system (Wyer et al., 2022).

It was found in 2017 that exposure to $PM_{2.5}$ was responsible for 4.58 million deaths globally, and therefore represents a significant risk to human health (Bu et al., 2021). It is suggested that a significant proportion of the global $PM_{2.5}$ levels arise from anthropogenic emissions of ammonia. In fact, within Europe, it is suggested that half of the atmospheric $PM_{2.5}$ results from agricultural use of ammonia (Wyer et al., 2022). The Department for Environment Food & Rural Affairs (Defra) has placed limits on the acceptable annual average levels of $PM_{2.5}$ in the atmosphere in which measurements taken at monitoring stations must not exceed 20 $\mu g/m^3$ on average[19]. These acceptable levels are set to decrease in 2028 and 2040 as a part of the Environmental Improvement Plan 2023 to 12 $\mu g/m^3$ and 10 $\mu g/m^3$ respectively.

It is important to note that non-agricultural anthropogenic uses of ammonia only contribute to 2% of current total ammonia emissions to air (Wyer et al., 2022). However, the increase in ammonia emissions from energy storage may negatively impact the Environmental Improvement Plan 2023 targets for atmospheric $PM_{2.5}$ levels.

4.3.2.3 Impact on terrestrial ecosystems

Increased ammonia emissions are expected to intensify global nitrogen cycles, exacerbating air pollution and stressing terrestrial ecosystems. Enhanced nitrogen deposition can boost primary production and alter vegetation characteristics, such as leaf area index and canopy height, which may, in turn, affect biosphere-atmosphere exchanges and impact air quality (Liu et al., 2021).

The deposition of nitrogen compounds, including ammonia, has been identified as a significant threat to species diversity in terrestrial ecosystems in north-west Europe. The

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[18] $PM_{2.5}$ refers to fine particulate matter with average particle diameter less than 2.5 microns.
[19] Air quality standards regulations 2010.

consequences of such deposition include eutrophication, acidification, loss of soil buffer capacity, leaching of base cations, and increased availability of metals, which can inhibit nitrification and affect the decomposition rate of organic matter (Aerts and Bobbink, 1999).

4.3.2.4 Eutrophication

Eutrophication of aquatic ecosystems occurs when an abundance of minerals such as nitrogen, which can be sourced from ammonia or phosphorus, is present in the body of water. This results in over-proliferation of plant species with a high affinity for nitrogen or phosphorus, such as algae. This over-proliferation itself results in a biodiversity loss in the ecosystem and can also prevent sub-surface species' access to sunlight. Moreover, as algae die, they are digested by aerobic bacteria resulting in a loss of dissolved oxygen within the waterbody. This can result in the waterbody becoming hypoxic and unable to support life (Guthrie et al., 2013).

4.3.2.5 Greenhouse gas generation

Ammonia itself is not considered a potent GHG, and its presence in the atmosphere does not contribute to radiative climate change. However, there is evidence that ammonia which has been assimilated into soil in the form of ammonium (NH_4^+) salts can be converted into nitrous oxide (N_2O) by certain aerobic bacteria (Huang et al., 2019). Nitrous oxide has a global warming potential 273 times greater than that of CO_2 over a 100-year timescale, and therefore ammonia emissions to the air may have a substantial yet indirect impact on global warming. However, it is not clear what proportion of anthropogenic nitrous oxide within the atmosphere is a result of conversion of deposited ammonium species from emissions of ammonia.

4.3.2.6 Ozone depletion

The ozone layer is a critical component of Earth's atmosphere, primarily located in the stratosphere, a region approximately 10 to 50 kilometres above the Earth's surface. This layer is composed of ozone (O_3), a molecule formed by three oxygen atoms. Its significance lies in its ability to absorb the majority of the sun's harmful ultraviolet (UV) radiation, specifically UV-B rays (World Meteorological Organization, 2023). Without this protective layer, these rays could directly reach the Earth's surface, leading to increased risks of skin cancer, cataracts, and other health issues, as well as detrimental effects on ecosystems, particularly in marine environments.

Global action taken by the UN Environment Programme (UNEP) under the Montreal Protocol has eliminated the most significant ozone depleting substances, such as chlorofluorocarbons (CFCs), from commercial use and the ozone layer is slowly recovering (UN Environment Programme, n.d.). However, accelerated nitrogen cycles from the anthropogenic emissions of ammonia into the environment cause secondary emissions of nitrous oxide, another ozone depleting substance (UN Environment Programme, n.d.). Though nitrous oxide is a less powerful ozone depletion agent than halogenated organic compounds, the release of ammonia into the environment may negatively impact the rate of ozone layer recovery (Bertagni et al., 2023).

4.3.3 Environmental impacts at end-of-life

At the end-of-life of ammonia storage facilities, the remaining ammonia within the tank must be emptied responsibly, minimising emissions to the atmosphere. Following this, decommissioning of the site would involve similar environmental impacts to the construction of the site, where noise and a reduction in air quality from decommissioning machinery and traffic would be the main drivers for environmental damage.

4.4 Social aspects of ammonia storage technologies

4.4.1 Overview

Social scientific research on ammonia as an energy storage technology is extremely scant. A study by Guati-Rojo et al. (2021) claims to be the first to study public attitudes to ammonia as an energy vector. Since it was published, another study of public perceptions of ammonia as a potential alternative shipping fuel has been conducted (Carlisle et al., 2023) as well as a study of consumer acceptance of ammonia in South Korea (Park et al., 2023). This review therefore largely summarises relevant findings from these studies. Given the close relationship between ammonia and hydrogen, it is also worth noting that some public perceptions of hydrogen and ammonia may be quite similar, so the research on hydrogen, which is more substantial, may be a useful complement.

4.4.2 Public perceptions

4.4.2.1 Popular associations

Guati-Rojo et al. (2021) performed a non-representative survey of members of the public in the UK and Mexico on their perceptions and acceptance of ammonia as a potential energy vector. They found that ammonia sparks a set of specific associations in people's minds:

> "When examining both samples [in the UK and Mexico] together, most of the participants (18.4%) answered with a single broad concept such as "chemical" or "chemical compound/substance" that does not have specific negative or positive connotations. However, 17.4% of the whole sample mentioned words that reflect a more negative opinion about ammonia, referring to it as "poison", "toxic", "corrosive" or "acid". A further 8.6% used the words "dangerous", "not safe" or "bad for humans" to describe their associations with ammonia. An interesting observation was that the association with "killing", "bomb" and "death" also came up, although in a low number of participants (1.4%). If we look at the data from each country separately, several differences between them were found. The results show that for the UK sample, the most popular answer was associated with smell (23.2%). This was followed by mentions of urine/manure (15.1%) and cleaning products (13.7%)". (Guati-Rojo et al., 2021: 7).

Carlisle et al., 2023 also found that words including ‘dangerous’, ‘toxic’, ‘hazardous’ and ‘poisonous’ came up in association with ammonia as a potential alternative shipping fuel in qualitative interviews. Park et al. (2023) also found that Korean survey participants associated ammonia with potential for explosion, toxicity, and odour.

4.4.2.2 Neutral, positive, and negative perceptions

In Guati-Rojo et al.’s study, participants were shown an infographic about green ammonia and asked to describe their thoughts or images about this technology. They found a change in perception, with nearly 40% of British respondents (compared to 30% of Mexican respondents) giving positive comments, using words like ‘promising’, ‘great idea’, ‘beneficial’ and ‘amazing’ (Guati-Rojo et al., 2021: 7). Most (64%) of the British respondents also perceived green ammonia to be definitely, or probably feasible (Guati-Rojo et al., 2021). By contrast, the study investigating people’s perceptions of ammonia as a potential alternative shipping fuel found that 'the UK public strongly dislike ammonia, perceiving it as unproven, risky, and lacking availability' (Carlisle et al., 2023). Similarly, Park et al. (2023) found that ammonia’s ‘green’ or ‘clean’ potential was insufficient to outweigh concerns about explosion, toxicity, and odour.

The study by Guati-Rojo et al. also probed people’s concerns about ammonia as an energy vector and found that, for UK participants, the main concern was about potential NOx emissions if ammonia was not burned properly, followed by concerns about the toxicity of the gas when inhaled, then intensive water use. For participants in both the UK and Mexico, the possible increase in electricity price that might accompany ammonia use did not seem to be a major concern, though this was before the energy crisis that started in 2022 (Guati-Rojo et al., 2021). Overall, more participants in both countries agreed that the benefits outweigh the risks (45% in the UK), though this still leaves nearly 16% who think the risks outweigh the benefits in the UK (Guati-Rojo et al., 2021).

4.4.3 Acceptance and opposition

Most of the participants in Guati-Rojo et al.’s (2021) study supported the development of green ammonia. In the UK, support for green ammonia is most strongly associated with gender (men are more likely than women to support green ammonia), perceptions about the threat from climate change and perceptions of risks and benefits (Guati-Rojo et al., 2021). Nearly three quarters of UK participants support the development of green ammonia in their country (28% strongly support, 44.9% somewhat support; Guati-Rojo et al., 2021). Park et al. (2023) found that emphasising ammonia’s positive attributes as ‘clean’ or ‘green’ did not outweigh the negative attributes of ammonia (explosivity, toxicity, and odour) and even instituting monetary incentives such as a carbon tax would not be enough to persuade people to accept ammonia in South Korea. They instead recommend that technological measures that can manage explosion potential and alert people to potential problems should be developed to address concerns about ammonia’s potential risks.

4.4.4 Knowledge and familiarity

Guati-Rojo et al. (2021) found that the public have good baseline knowledge about climate change, but high uncertainty about which fuels contribute to it. In both Mexico and the UK, most doubts were expressed in relation to hydrogen, which they point out could have knock-on effects for perceptions of ammonia since it is based on hydrogen (Guati-Rojo et al., 2021). Park et al. (2023) found that respondents who had more knowledge about ammonia were less sensitive to its potential for explosion and toxicity; they therefore recommend that governments enhance public understanding of ammonia and its safe management and design incentives that specifically target people who are more risk averse.

4.4.5 Trust

Trust in government is correlated with support for green ammonia technologies (Guati-Rojo et al., 2021). 'For participants from the UK, the most trustworthy institution to regulate this technology is a combination between government and industry (43.8%)' (Guati-Rojo et al., 2021: 9). Conversely, they found that support for this technology is considerably lower among participants who do not trust either government or industry (Guati-Rojo et al., 2021).

4.4.6 Gaps in the literature and future research

Given the lack of research on ammonia, especially as a storage technology, it is difficult to draw any conclusions about public perceptions or social acceptance, but the evidence suggests that developers and policymakers may need to work to counter the negative perceptions found so far. Therefore, there is simply a need for further quantitative and qualitative research, which could include efforts to measure the effect of further information on public perceptions and acceptance, given the specific concerns that people have about ammonia as a substance.

4.5 Remaining data gaps

During the compilation of evidence relating to the deployment and environmental impacts of ammonia storage for energy applications, the following key gaps in the evidence were identified by the authors of this report:

Ambiguity in Storage Capacity Data: A significant data gap exists in the accurate determination of ammonia storage capacities in England. This lack of clarity hinders comprehensive assessments of the historical environmental impacts associated with ammonia storage, especially when used for fertiliser production. The absence of precise data on production and storage capacities is a notable obstacle in understanding the full scale and environmental implications of ammonia-related activities in the region.

Limited Sectoral Detail in Ammonia Emission Reporting: While the volume of annual anthropogenic ammonia emissions is generally well-documented within the literature, there is a notable deficiency in sector-specific details. A large proportion of non-agricultural emissions are categorised under 'other,' which obscures the understanding of the specific sources and sectors contributing to these emissions. This limitation restricts the ability to accurately attribute and mitigate ammonia emissions from various industrial and non-agricultural sectors.

Unclear Reporting on Emissions from Ammonia Storage Tanks: The data on the volume of ammonia emitted annually from storage tanks is not explicitly reported in existing literature and sources. There is a general consensus that fugitive emissions from ammonia storage should be minimised. There are Best Available Techniques (BAT) for ammonia storage, and these are tied into COMAH regulations, but there is no specific information on storage from BAT reference documents (BREFs). This gap in data on fugitive emissions hampers efforts to effectively reduce emissions from ammonia storage facilities.

Lack of Evidence Linking Ammonia to Atmospheric Nitrous Oxide: While it is established that the conversion of ammonia to the potent GHG nitrous oxide occurs, there is an absence of evidence or research quantifying the proportion of atmospheric nitrous oxide that originates from anthropogenic ammonia emissions. This gap hinders the understanding of the broader environmental impact of ammonia, particularly its indirect contribution to GHG emissions and global warming.

4.6 Conclusions and summary

The deployment of ammonia storage as an energy storage vector (as a hydrogen carrier and as a standalone fuel) mainly for shipping is highlighted in a number of government and academic reports. However, there has yet to be a clear estimation of the volume of ammonia needed to be produced or imported and stored in England to achieve net zero goals. The literature made reference to two specific planned sites where large-scale ammonia storage facilities will be located, and both of these examples are planned to be a part of wider green hydrogen production, storage and transport sites.

The literature surrounding the environmental impacts of ammonia storage for energy is sparse, and as such the volume of ammonia expected to be leaked from storage facilities could not be quantified. On the other hand, the environmental impacts of ammonia emissions are very well understood both for England and globally, due to significant historical emissions from the agricultural sector. However, due to a lack of data on ammonia storage systems for energy applications, it is not possible to quantitatively compare the impacts of ammonia emissions from upcoming energy applications to those arising from agriculture.

A summary of the potential environmental issues associated with ammonia storage are given in Table 9.

Table 9: Summary of the potential environmental issues arising from ammonia storage for energy applications

Receptor	Notes	Environmental Issues
Air quality	Emissions of ammonia to air arising from loss of containment due to accident, operator error, equipment failure or passive leakage from equipment.	Generation of fine particulate matter ($PM_{2.5}$) from the reaction of atmospheric acids such as sulphuric acid, and ammonia, generating fine particulate ammonium sulphate. Exposure to $PM_{2.5}$ can lead to respiratory diseases including chronic obstructive pulmonary disorder (COPD) and cancer (Bauer et al., 2016). Increased indirect GHG emissions from the conversion of atmospheric ammonia (global warming potential (GWP) = 0 CO_2e) to N_2O (GWP = 273 CO_2e) in biological systems. N_2O emissions also contribute to slowing of ozone layer regeneration (Huang et al., 2019).
Terrestrial and aquatic ecosystems	Emissions of ammonia to air and subsequent deposition of NH_4^+ solids or solutions (rainfall) are assimilated into terrestrial ecosystems. Loss of containment of liquid ammonia, which is taken up by soil and groundwater, as well as surface waters.	Intensification of nitrogen cycles, leading to loss in species diversity and biosphere changes (Liu et al., 2021). Deposition of NH_4^+ can lead to soil and water acidification, loss of buffer capacity, and leaching of base cations and nutrients (Aerts and Bobbink, 1999). Eutrophication from deposition of NH_4^+ into water leading to proliferation of algae and biodiversity loss (Guthrie et al., 2013).
Acute human or environmental health	In the event of large-scale loss of containment of ammonia from storage tanks, ammonia concentrations in the air may increase locally to harmful levels.	Exposure of the skin, lungs or eyes to large quantities of ammonia can cause burns, swelling, blindness or potentially fatal breathing disorders (GOV.UK, n.d.).

5 Compressed Air Energy Storage (CAES)

5.1 Introduction

Compressed air energy storage (CAES) operates by storing high-pressure, compressed air in a large underground cavern during periods of low electricity demand or periods of high electricity production (due to generation fluctuations in renewable energy sources, such as wind or solar power). When energy demand is high, or supply from renewable sources is low, the compressed air is expanded and heated prior to being released into a gas-turbine chamber, which in turn drives a generator to send electricity to the grid (Wang et al., 2017).

A review completed in 2019 listed four categories of reservoirs that could, in theory, be used as a reservoir for CAES: solution-mined salt caverns; porous rock – saline aquifers and depleted hydrocarbon fields; abandoned mines and hard/competent rock caverns (unlined); and lined rock caverns (Evans et al., 2018).

Currently, there are only two operational commercial CAES plants worldwide: the Huntorf plant, constructed in Germany in 1978, and the McIntosh CAES plant in the USA, Alabama, constructed in 1991 (King et al., 2021). All other CAES sites to be found around the world are experimental facilities which are operational for testing purposes only.

The following sections investigate the various CAES technologies that have been proposed or are currently in-use. In particular, the discussion will focus on the use of underground rock formations in England as the air reservoir, while considering the impacts to the environment as well as any risks attributable to the emerging technology.

5.1.1 CAES technologies

A CAES system typically has three main components: compressors, a reservoir, and expanders. The compressors collect air from the atmosphere and convert the kinetic energy from a motor into potential energy stored in the high-pressure gas. This compressed air is channelled into an underground reservoir, which are typically pre-existing, man-made, subsurface networks such as salt caverns or decommissioned onshore oil and gas fields. When electricity generation is required, the high-pressure air is released and heated before being channelled into the turbine hall. The pressure differential subsequently turns the blades of the turbine, which in turn spins the generator rotor. This process schematic is presented in Figure 5.

The air must be heated before it is sent to the turbine because of the extreme loss of thermal energy during the expansion stage due to the relationship between temperature and pressure in gasses. The release of the pressurised gas leads to the expansion and subsequent cooling (to around -150°C) of the air (and the system it is operating within), thus increasing the chance of equipment damage. It should be noted that thermal energy is also produced at the compression stage (up to 650°C) due to this thermal principle. To mitigate thermal damage to the reservoir, this thermal energy is exhausted during compression (STORELECTRIC, n.d.; Evans et al., 2018).

CAES technologies tend to have a discharge time of, at most, 10 hours, but conversion time is no more than a few minutes (European Association for Storage of Energy, n.d.).

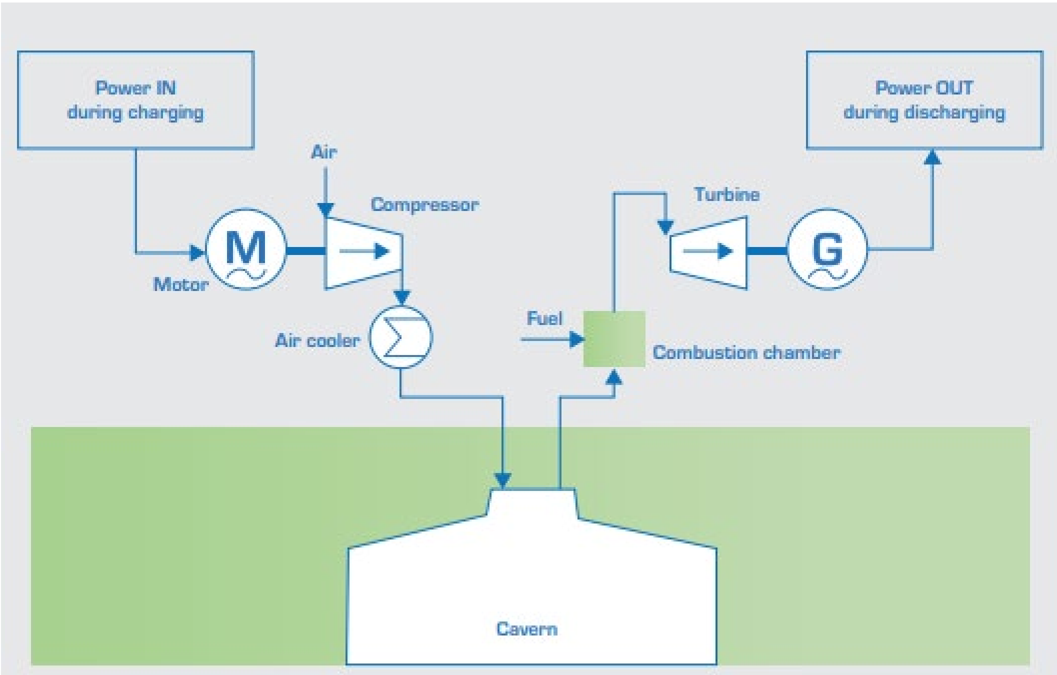

Figure 5: Schematic diagram of an CAES plant. *Source:* European Association for Storage of Energy, n.d

In general, CAES systems can be divided into 3 categories:

- Diabatic compressed air energy storage (D-CAES);
- Adiabatic compressed air energy storage (A-CAES); and
- Isothermal compressed air energy storage (I-CAES).

These categories use different methods to transfer energy, particularly in the compression and expansion stages.

5.1.1.1 Diabatic compressed air energy storage (D-CAES)

At the expansion phase, D-CAES systems heat the compressed air with an external fuel source, which is depicted in Figure 6. Typically, fossil fuels are used as the fuel during the heating phase, which in turn emit GHGs. With an efficiency of approximately 54% (Adib et al., 2023), the benefits of an operational D-CAES system may not outweigh the consequences, especially from an environmental perspective. It should be noted, however, that the only two currently operational large-scale commercial CAES plants, in Huntorf and McIntosh, are both diabatic systems that use natural gas as the fuel in the decompression phase.

5.1.1.2 Adiabatic compressed air energy storage (A-CAES)

In A-CAES systems, thermal energy released during compression is stored in an insulated thermal energy storage (TES) system, as presented in Figure 6. The stored energy is then used to heat the air during the expansion phase, rather than relying on an external fuel source. This reduces or removes the need for fossil fuels in the expansion stage. A-CAES systems tend to be a more efficient variation of the technology, with theoretical efficiencies of 70%; although, the thermal insulation efficiency of the TES system plays a significant role in the efficiency of the overall system (Adib et al., 2023).

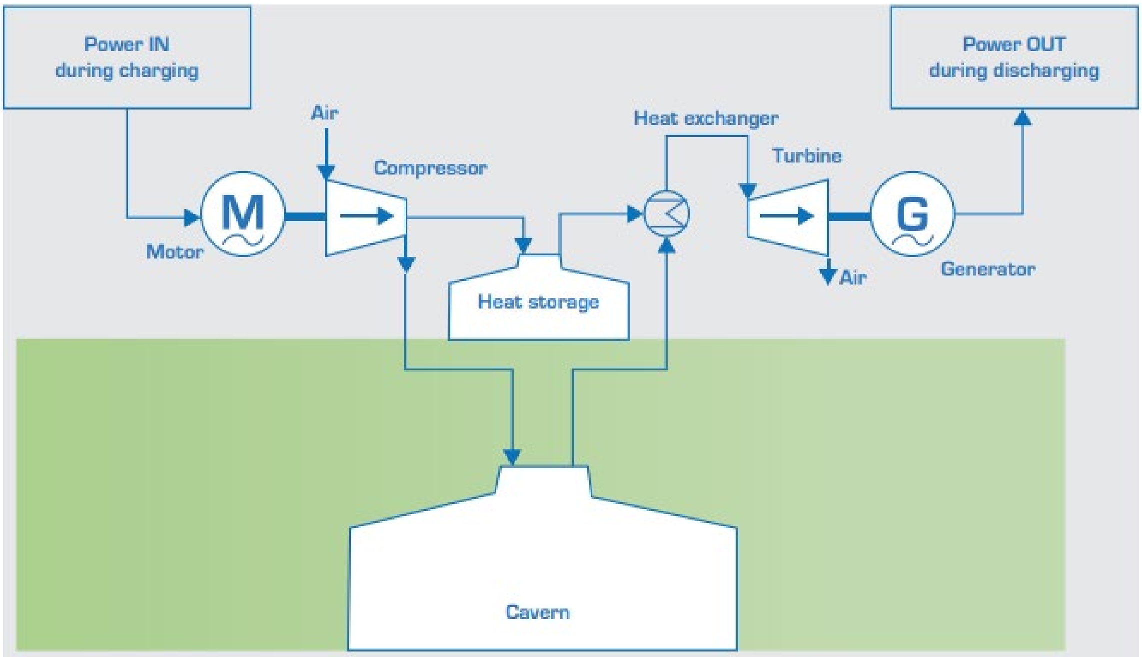

Figure 6: Schematic diagram of an A-CAES plant. *Source:* European Association for Storage of Energy, n.d.

It should be noted that A-CAES technology is still in its infancy, with only small-scale research or commercial facilities currently in operation. A review identified eight A-CAES projects between 2010-2021, of which three were for demonstration purposes and the remaining five were for commercial purposes (King et al., 2021).

5.1.1.3 Isothermal compressed air energy storage (I-CAES)

I-CAES systems aim to reduce the waste energy initially lost at the compression stage. Historically, the compressors raise the pressure of the air to 7MPa while also heating the air to around 600°C, as mentioned in Section 5.1.1. In the case of I-CAES systems, advanced compression and expansion equipment is used to keep the temperature at both stages constant. This is shown in Figure 7. A study from 2023 suggests that there was only one I-CAES research system operational, between 2013-2015, with a recorded efficiency of only 54% - more akin to the efficiency expected from a D-CAES system (Rabi et al., 2023).

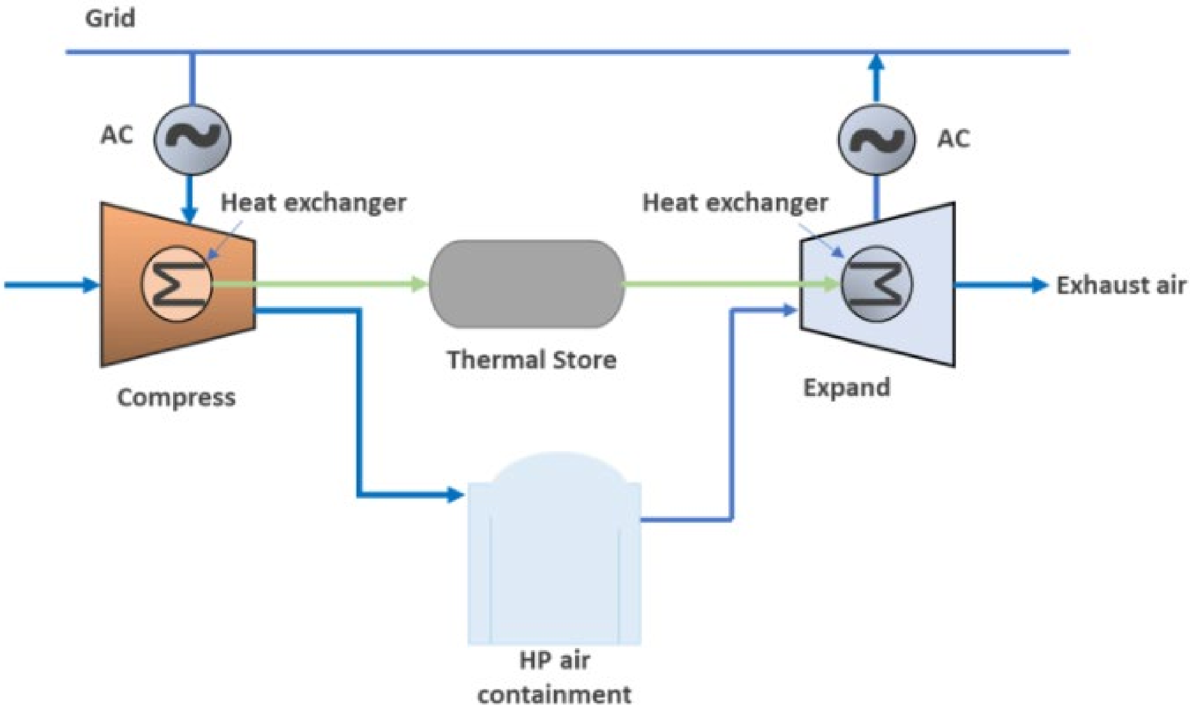

Figure 7: Schematic diagram of an I-CAES plant. ***Source:*** Rabi et al., 2023

It should be noted that the air in the I-CAES system reservoir is kept at a much lower pressure (approximately 1 MPa) compared to D-CAES or A-CAES systems, due to the reduction in thermal energy introduced into the system from the compression stage. As a result of this, I-CAES systems are typically less energy-dense than D-CAES and A-CAES systems and should only be considered for small-scale energy systems since the demand expected from grid-scale storage systems is, in most cases, too high (Rabi et al., 2023).

5.1.2 The role of CAES in achieving Net Zero

While traditional D-CAES systems have been in-use outside of the UK for several decades, they do not effectively contribute to the achievement of the Net Zero goals. This is primarily due to their low efficiency, which is a result of poor thermal performance in the compression and expansion stages. Moreover, the combustion of fossil fuels during the decompression phase further adds to the inefficiencies of the system, as well as emitting its own set of GHG. While measures to reduce or completely remove the use of fossil fuels in the expansion stage have been investigated using renewable energy technologies, implementation has been found to only be possible on the small scale (Adib et al., 2023).

In contrast to D-CAES systems, A-CAES is a more promising technology for providing low carbon grid-scale underground energy storage systems, providing a similar capacity, discharge time and long lifetime while reducing the need for an external fuel source in the expansion stage. A-CAES systems also tend to be much more efficient than traditional D-CAES systems; although, there are currently no grid-scale A-CAES systems to gauge the effectiveness of such systems in practice.

5.2 Deployment trajectories of CAES technologies

5.2.1 Current CAES capacity and sites

There are currently no commercially operational CAES sites in England or the wider UK. Globally, the landscape of CAES implementation is relatively limited, with only two operational facilities at a grid-scale, both utilising D-CAES technology. These facilities are located in Huntorf, Germany and Alabama, USA; these are summarised in Table 10. The Huntorf facility was the world's first commercial CAES plant and uses two solution-mined salt caverns to store air at a pressure of 48-66 bar. The site can discharge electricity for two hours (King et al., 2021). The Alabama site, operational since 1991, exhibits improvements in several areas of operation when compared to the site in Huntorf, such as a higher efficiency (36% compared to 29%) and a much longer discharge time (26 hours compared to 2 hours). It uses a single solution-mined salt cavern at a pressure of <76 bar (King et al., 2021).

Table 10: Current commercially operational CAES sites

Location	Operational year	Power rating (MW)	Efficiency (%)	Reservoir type	Capacity (m^3)	Depth (m)
Huntorf, Germany	1978	290	29	Salt cavern	310,000	600
Alabama, USA	1991	110	36	Salt cavern	500,000	450
Sources: King et al., 2021**, Chen et al., 2009**						

5.2.2 Planned CAES capacity and sites

A coalition of EDF, iO Consulting, and Hydrostor have been granted permission by the UK Department for Energy Security and Net Zero for the construction of CAES facility in Cheshire (StrataStore, n.d.). The project, called StrataStore, aims to use decommissioned salt caverns for an A-CAES system that aims to store more than 100 MW of power. While no technical information about the future A-CAES site has yet been released, Hydrostor, the planned facility constructors, have previously designed A-CAES systems that can store over 200MW of power for multiple days. EDF reported that the consortium had to plan the design and commercial aspects of the facility by January 2023 (EDF renewables, 2022), but no further information has been released regarding dates for site construction or operation.

5.2.3 Remaining capacity required for Net zero and possible locations

Based on the evidence for the deployment of CAES in England, it is apparent that the most suitable option for this technology is in salt caverns. England has favourable geological characteristics for these salt caverns and the majority of existing CAES sites across the globe are in salt caverns. Figure 8 maps the salt deposits that have been suggested as the most suitable for salt cavern formation and therefore could host CAES facilities. Since any CAES sites would require connection to the grid, the existing gas network and electrical grid are also included. Data sources are provided below the map.

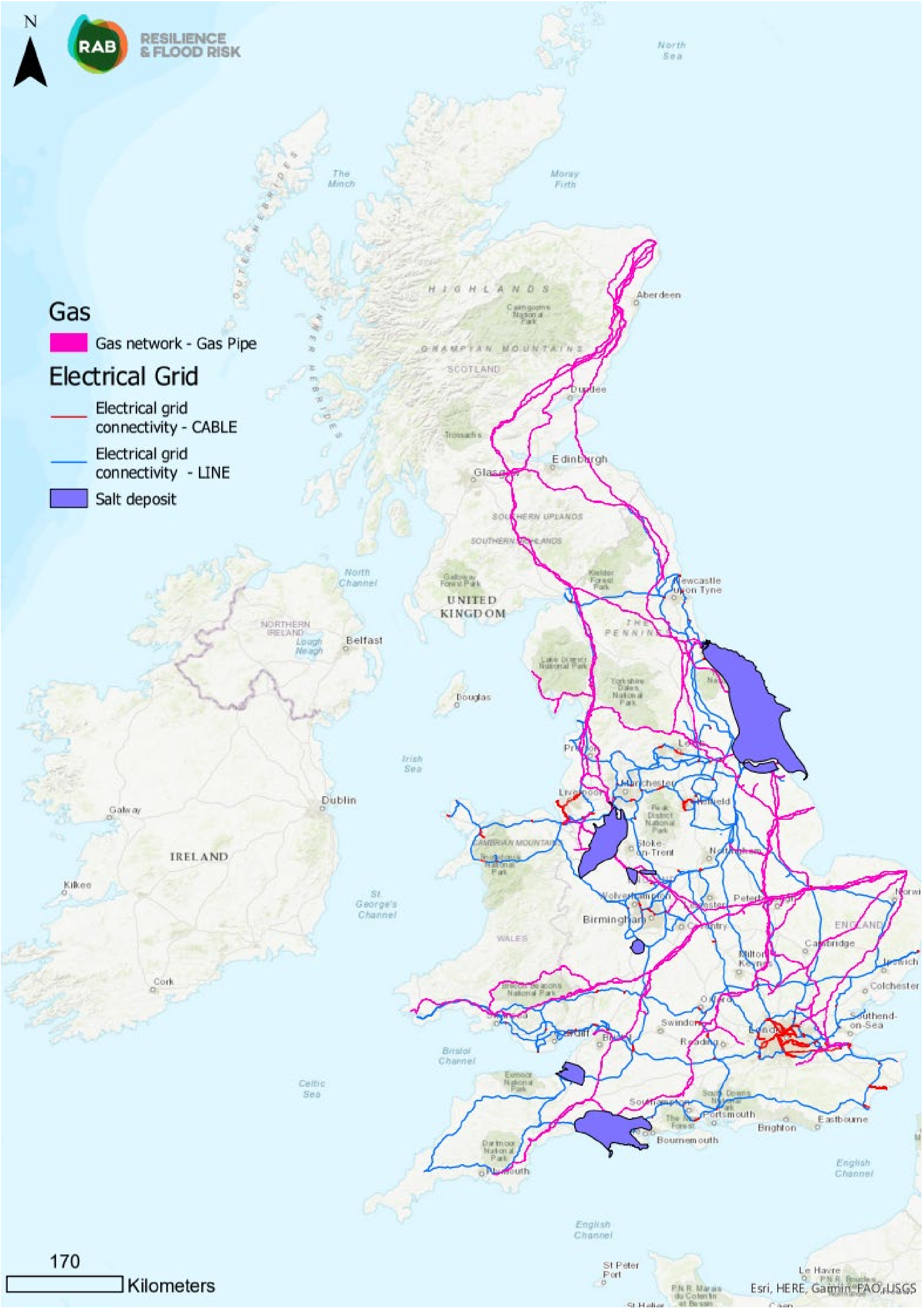

Figure 8: Locations of salt deposits which are thought to be suitable for the mining of salt caverns in England.

Basemap: Esri. "Topographic" [basemap]. Scale Not Given. "World Topographic Map". 26 October 2017.

https://www.arcgis.com/home/item.html?id=7dc6cea0b1764a1f9af2e679f642f0f5. (15 November 2023).

Other sources: mapapps2.bgs.ac.uk., n.d.; Scafidi et al., 2020; www.nationalgas.com, n.d.; www.nationalgrid.com, n.d.

5.3 Environmental impacts of CAES

5.3.1 Environmental impacts during construction

Among the recent major CAES projects undertaken globally, the majority use repurposed or specifically solution-mined salt caverns (King et al., 2021). The impacts of salt cavern construction are evaluated in more detail in section 3.3.1. In summary, the regulated and well-managed extraction of brine from salt cavern mining has been undertaken safely for many decades. Furthermore, the potential environmental effects stemming from the mining of salt caverns for application in CAES facilities are assumed to be comparatively minor when considered against the ongoing mining of salt caverns for hydrocarbon storage. There will be additional emissions released into the air due to dust raised from mining, as well as substantial brine generation. These are detailed further in section 3.3.1.2. It is expected that there are no environmental impacts at the construction phase that are specific to CAES facilities, and general impacts of the construction of a large industrial facility are to be expected.

5.3.2 Environmental impacts during service

5.3.2.1 Noise generation from compressor facilities

During the expansion phase of the CAES facility, a high enough turbine spin speed may cause extreme noise and vibrations if the turbine rotors first or second order critical speed is met, causing an exponential increase in resonance (Wang et al., 2017). Further noise will also be generated by the compressors during the intake and compression stage of CAES.

5.3.2.2 Emissions from operation

A-CAES and I-CAES facilities will have no gaseous emissions directly from the site area, as they recycle the thermal energy generated by the compressors during the compression stage for use during the expansion stage. As discussed in Section 5.1.1.1, D-CAES facilities use fossil fuels to raise the temperature of the expanded gas before it is channelled into the turbine hall as there is no heat recovery system during the compression stage. The magnitude of GHG emissions is contingent upon the type of fossil fuel used.

5.3.2.3 Coolant considerations

While water is typically used as a coolant in CAES systems, it may be possible that an organic liquid coolant would be required in some instances. If this is the case, then understanding the risks of the coolant used in the closed-loop cooling system will be an important aspect of determining the potential environmental impacts of CAES.

5.3.2.4 Geomechanical stability

As with hydrogen (Section 3.3.2.1), the storage of compressed gases underground can potentially impact the geomechanical integrity of the cavern and surrounding rock formations. This may result in long-term stability issues, including increased risk of land subsidence, landslides, and micro-seismicity.

5.3.2.5 Chemical reactions

Compressing air into an underground reservoir increases the partial pressure of oxygen within the system, effectively increasing its concentration. This not only has the potential to increase the reaction rate of oxidations which would occur under normal conditions, but also increases the effective oxidation potential of the system through Nernstian electrochemical behaviour (Jesudason and Bachrach, 2009). This means that reactions with oxygen that are not possible under atmospheric pressures could be enabled under these high-pressure conditions in a manner analogous to increasing the temperature of a system. This could result in the precipitation of new minerals which can clog the reservoir pores, leading to potential losses in efficiency, but also infrastructure damage and site failure.

Furthermore, the reaction of stored oxygen in D-CAES results in a lower partial pressure of oxygen in the air used for combustion of the fuel which drives the generator turbine, resulting in lower efficiency, response times and resulting in the release of incomplete combustion products (Wang and Bauer, 2019).

5.3.2.6 Microbial activity

Injection of air into CAES reservoirs could have an effect on microbial activity within the reservoir, potentially leading to dissolution of the cavity constituents or clogging of the reservoir (Sopher et al., 2019). As with underground hydrogen storage, CAES in salt caverns or high-temperature depleted hydrocarbon fields as discussed in Section 3.3.2.1 will likely be low risk for increased microbial activity as these reservoirs are seen as sterile. In addition, compressed air would not have the same nutrient properties as hydrogen gas in these sites, as air is a less effective nutrient than hydrogen, particularly for sulphate reducing bacteria. While more studies will be needed to fully understand the effects of CAES on microbial activity in gas reservoirs, the risks of microbial activity are likely to be less for CAES than for hydrogen storage (Sopher et al., 2019).

5.3.3 Environmental impacts at end-of-life

Upon reaching the end of their operational life, the decommissioning process for CAES facilities is anticipated to mirror the challenges encountered during their construction phases. Predominantly, noise and localised air pollution are expected to be the primary impacts during the decommissioning phase. The generation of waste from the demolition of obsolete infrastructure will also be a notable aspect of this process. In the case of D-CAES facilities, the fuel source used for heating the air during the expansion stage will need to be repurposed for other uses, otherwise there is risk of the release of harmful substances into the surrounding environment.

5.4 Social aspects of CAES technologies

Research on public perceptions and social acceptance of CAES is very limited, though of course findings about attitudes towards ESTs in general may be relevant. The available evidence seems to be limited to a survey comparing public attitudes to different ESTs in the UK and Canada (Jones et al., 2021) and the study by Thomas et al. (2019), which used deliberative workshops in the UK to assess people's knowledge, perceptions and acceptance of different ESTs, from which can be gleaned some specific information about CAES.

Thomas et al. (2019) found that CAES provoked some safety concerns, as a small number of participants interpreted it as using toxic materials which might cause damage through leakage. CAES, like UPHS and pumped hydroelectric storage (PHS), can, however, also prompt positive associations between these technologies' use of natural resources, as well as a sense that they may be more compatible with rural or natural locations. However, they also caution that such positive perceptions may be more compelling in the abstract and that people may feel differently if a CAES system is planned for development in their local area. Underground siting was viewed as a particular benefit of CAES, to save space above ground (Thomas et al., 2019). In fact, the participants in their workshop suggested that other ESTs might be more acceptable if they were also sited underground, as this could reduce spatial impacts and reduce risks to households.

Jones et al. (2021) measured the attitudes and preferences of people in the UK and Canada for four grid-scale ESTs. Respondents ranked PHS as their preferred technology, followed by BESS; UK participants ranked CAES as their third preference, before flywheels (for Canadian respondents, CAES was their lowest preference). Notably, the researchers included information about the different technologies in the survey, including a traffic light ranking system for their power quality, bridging power, and energy management. CAES had roughly the same ratings as PHS in this system (red for power quality, orange/yellow for bridging power, and green for energy management), yet PHS was viewed much more favourably. This indicates that people do not only judge technologies on these specific criteria, but that other factors play a part. According to their data, this includes levels of trust in developers and environmental worldviews, though they measured these in relation to general attitudes towards ESTs rather than for the specific technologies (Jones et al., 2021).

As well as a need simply for more research that is specifically focused on CAES, researchers could investigate further the findings of Thomas et al., following the indications from their research that CAES is seen as potentially risky but also one of the more ‘natural’ forms of EST, as well as probing the effects of socio-demographic factors including environmental views on acceptance of this technology.

5.5 Remaining data gaps

During the compilation of evidence relating to the deployment and environmental impacts of CAES for energy storage applications, the following key gaps in the evidence were identified by the authors of this report:

A-CAES knowledge gaps: One significant gap in our understanding pertains to the absence of commercially active A-CAES facilities in England. While A-CAES systems have demonstrated promise in theoretical models, their real-world application at a grid scale is yet to be realised. The lack of operational A-CAES sites on a commercial level hinders our ability to assess their effectiveness, efficiency, and potential contribution to achieving Net Zero goals. Despite this, grid-scale demonstration projects in China have proven successful in the past, so the validity of A-CAES at such scales has been exhibited (Yang et al., 2023).

I-CAES knowledge gaps: Similarly, I-CAES presents a promising alternative to traditional methods, yet there still remains a global absence of I-CAES facilities. Experimental sites for demonstrative purposes are scarce, and commercially active, grid-scale facilities are non-existent. The dearth of operational I-CAES sites limits our understanding of their scalability, performance, and environmental impact in practical applications. Investigating and addressing these knowledge gaps is crucial for informed decision-making in the integration of I-CAES into the national energy storage infrastructure.

5.6 Conclusions and summary

The literature surrounding the deployment of CAES technology in England is sparse and the technology does not receive the same attention in the energy sector literature as hydrogen or batteries. However, as CAES is primarily located in salt caverns, it has been identified that England has promising geological conditions for CAES implementation. While discussion of the environmental impacts of CAES is also particularly sparse, many parallels can be drawn with the storage of hydrogen gas in salt caverns. For the construction phase, the impacts between salt cavern hydrogen storage and CAES are essentially the same. During operation, the environmental issues of CAES likely diverge from hydrogen storage, particularly due to the differences in the chemical, physical and environmental properties of the stored gases. However, research explicitly comparing the two technologies has also been limited. As England appears to have a good degree of suitability for CAES implementation, the field would benefit from more research into potential environmental issues associated with it, particularly as much of the fundamental research into salt caverns has already been done for hydrogen storage.

A summary of the potential environmental issues associated with CAES is given below in Table 11.

Table 11: Summary of the potential environmental issues associated with compressed air energy storage

Receptor	Description	Environmental Issues
Air quality	Burning fossil fuels from the operation of D-CAES facilities.	GHG emissions and acceleration of climate warming. Photochemical oxidant formation.
Water quality and availability	Abstraction of large quantities of water from rivers, lakes or aquifers to source water for cavern dissolution and cooling.	Changes in water flows and reduction in water levels. Potential for groundwater depletion. Changes to water cycles.
Terrestrial and aquatic ecosystems	Salt caverns are created by pumping water into underground halite deposits, producing brine and vacuous space suitable for the storage of gases.	Brine generation and disposal during cavern creation (c.a. 8 m^3 per m^3 cavern volume).
Acute human or environmental health	Damages caused by thermal-mechanical and thermal-chemical stresses. Irreparable damage to reservoir caused by cavern instability.	Safety challenges during operation. Induced micro-seismicity. Increased risk of land subsidence and landslides. Infrastructure damage and ultimate failure (Environment Agency, 2021b)

6 Underground Pumped Hydroelectric Storage (UPHS)

6.1 Introduction

Underground pumped hydroelectric storage (UPHS) has been conceptually proposed as a promising innovation to make a substantial contribution to the reduction of carbon emissions and the realisation of net zero goals within the energy sector. However, the technology has yet to demonstrate feasibility in any real sites and has several uncertainties surrounding its operations and environmental impacts. The technology involves the transfer of water from a deep underground reservoir to a shallower reservoir during periods of low energy demand. These reservoirs are vertically separated by depths from hundreds of metres to around a thousand meters (EERA, 2016; Pickard, 2012), thereby generating gravitational potential energy that can be efficiently harnessed and deployed when required (Carneiro et al., 2019), see Section 6.1.1.

UPHS follows similar principles to traditional pumped hydroelectric storage. However, its distinguishing feature is the underground location of the lower reservoir reducing reliance on topographical features and mitigating some of the environmental repercussions and societal disturbances typically associated with conventional pumped hydroelectric storage technologies (Carneiro et al., 2019). Nevertheless, UPHS technology remains in its early stages, characterised by a low TRL, and currently there are no operational UPHS facilities.

The following sections assess the use of host rock formations and disused mine shafts as potential underground reservoirs, the identification of prospective locations within England for UPHS development, the environmental impacts associated with the technology, and the challenges and risks it may pose.

6.1.1 UPHS technologies

As described in an earlier Environment Agency publication (Environment Agency, 2021b), “UPHS is a large-scale energy storage facility, with power varying from 100 to 1,000 MW and energy capacity from 1 to 15 GWh depending on the size of the storage facilities”. Hydroelectric storage operates by capturing surplus energy or electricity generated from intermittent renewable sources like wind and solar when production surpasses demand, and subsequently discharging this stored energy during peak demand periods or when renewable energy generation is diminished (See Figure 9). When electricity generation surpasses immediate demand, water is actively transferred from the lower reservoir to the upper reservoir and subsequently released from the upper reservoir to drive a turbine situated in the powerhouse, ultimately replenishing the lower reservoir and providing energy as required.

The operation of this technology is more complex than implied in its description with several intricacies that arise during the processes of energy generation and pumping, including the accumulation of compressed air. During the pumping phase, air infiltrates the subsurface system, leading to the compression of air as the reservoir undergoes refilling. The presence of a pressurised subsurface system bears the potential for system inefficiencies attributed to back pressure. The oscillating temperature and pressure levels within the subsurface system were identified as sources of ground/mine instability in Environment Agency (2021b).

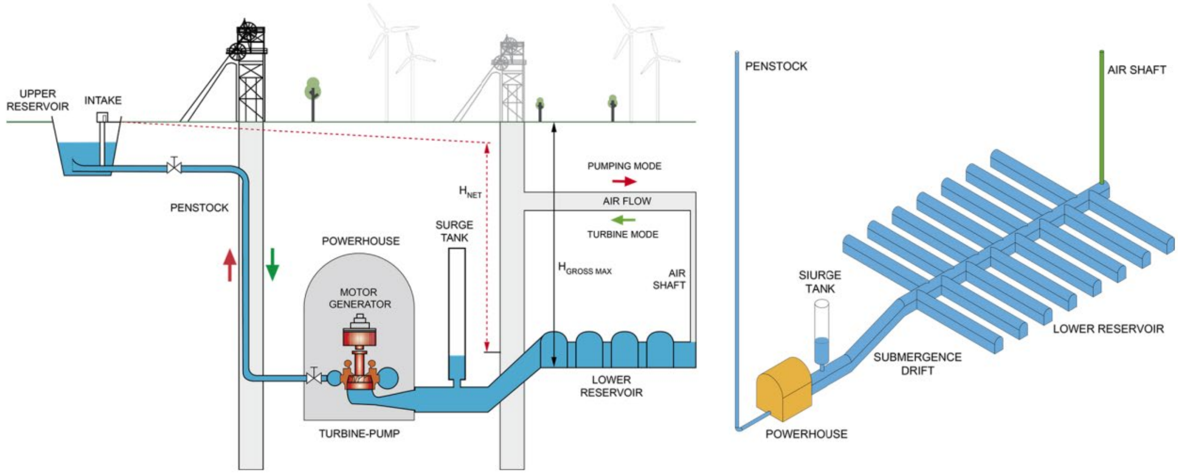

Figure 9: Scheme of UPHS in a disused underground mine: 3D detail of lower reservoir (right). ***Source:*** Menéndez et al., 2019c

In the majority of cases, pre-existing infrastructure suitable for the establishment of UPHS facilities may be lacking. Environment Agency (2021b) identified a number of proposed UPHS initiatives centred around repurposing disused mines. These projects often entail stringent site criteria and specific requirements, making the process of suitable site selection challenging. A more comprehensive examination of these criteria and specifications will be undertaken in subsequent sections.

6.1.1.1 Caverns hosted by rocks

Beyond considering abandoned mines as potential locations for UPHS facilities, porous rocks or purpose-built caverns in host rocks have also been suggested for hosting the lower reservoir (Carneiro et al., 2019). Caverns excavated in low permeability crystalline (igneous/metamorphic) and sedimentary (shale and siltstones) host rocks could be considered for large-scale UPHS facilities (0.5 to 3000 MW; Matos et al., 2019). Not all rock types are suitable for a UPHS plant, as soft sediments and friable rocks are susceptible to erosion (Morabito et al., 2020). General criteria to consider when selecting host rocks for potential caverns as a storage option are:

- Low permeability;
- Low porosity;
- Thermal stability (4 to 80°C);
- Level of fracturing; and
- Hydraulic conductivity (<10^{-8} m/s for water; Matos et al., 2019).

Although caverns hosted by rocks are a possibility for UPHS facilities, the literature favours disused mines as possible facility locations.

6.1.1.2 Disused mines

There remain a number of uncertainties with the use of disused mines. Moreover, the presence of flooding in many disused mine sites means they would not be viable as energy storage facilities (Menéndez et al., 2019c). However, due to the natural geothermal warming of flooded mine cavities, efforts are underway to repurpose these sites as low-carbon energy sources for heating residential and commercial properties (Menéndez et al., 2019b). To transform disused mines into functional UPHS facilities, it is likely that comprehensive excavation of the intricate tunnel networks and a thorough evaluation of the existing shafts, hoists, and ventilation systems will be required. The extent to which excavation would be needed will be dependent on the state of the mine (e.g., still open, collapsed, partially collapsed or flooded). The creation of a new access tunnel for transporting powerhouse equipment may be necessary, potentially triggering substantial geo-environmental challenges (Menéndez et al., 2019b; see Section 6.3).

A collaboration between the British Geological Survey (BGS) and the Coal Authority has yielded a comprehensive map (Figure 10) illustrating the geographical distribution of mines, along with the corresponding temperature elevations at various depths. This map could help identify prospective UPHS facility sites. The Coal Authority estimates that an extensive 25,000 square kilometres of disused subsurface coal mine workings and tunnels exist (Earth, Environmental & Geotechnical, 2023). It is unclear if these mines are suitable for the use of large-scale energy storage facilities with many being flooded.

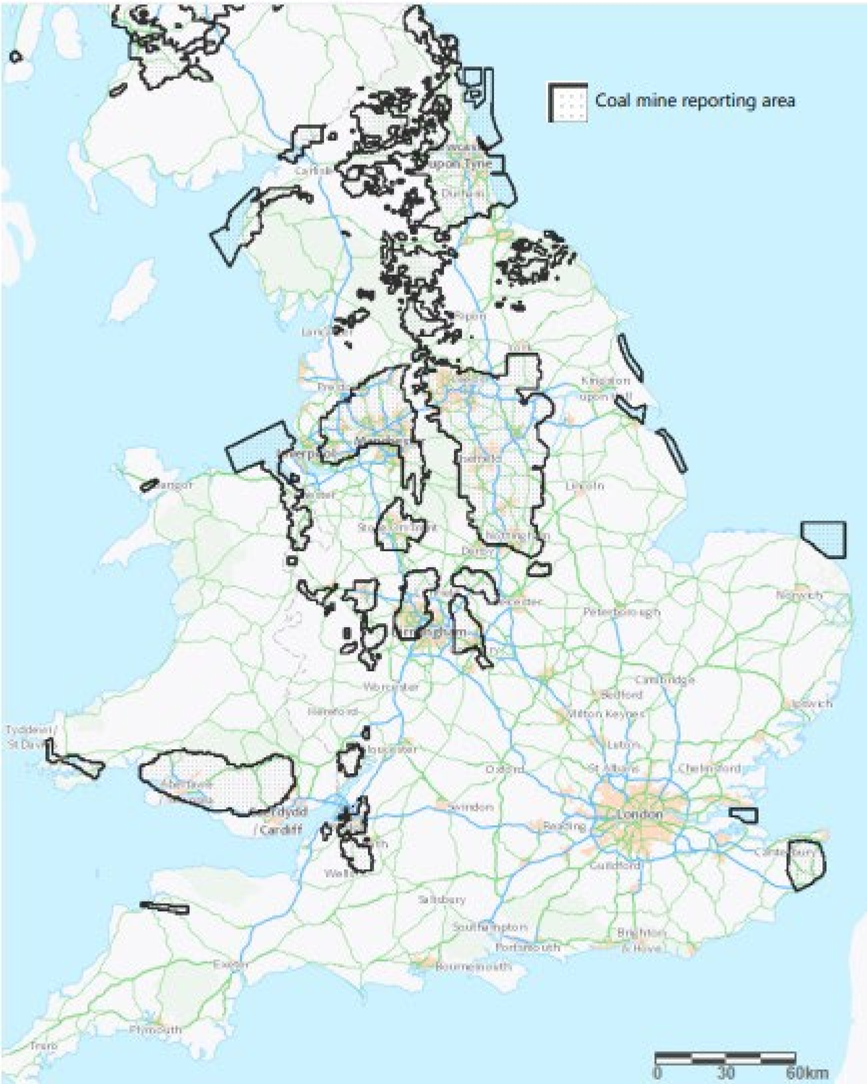

Figure 10: Map of coal mines in England. *Source*: Coal Authority, 2020

6.1.1.3 Considerations when assessing disused mines

The selection of sites for UPHS facilities can be complex. Ideally, the upper reservoir should be situated in remote areas and be separated vertically by several hundred metres (Environment Agency, 2021b). Data from the Coal Authority (BGS, 2020) reveals that roughly one-quarter of the UK's population resides above disused coal mines.

A study by Menéndez et al. (2019b) on energy and closed mines assessed the stability of disused coal mine infrastructure in northwestern Spain for UPHS plants. They established design parameters for general consideration. The disused coal mines assessed in the study reached a depth of 600m below the surface and consisted of a main vertical shaft (diameter: 6m), networks of horizontal drifts at different levels (cross section: 9 to 12m^2 supported by steel arches and wire mesh), and auxiliary shafts (diameter: 6m) for ventilation (Menéndez et al., 2019b).

A similar study (Menéndez et al., 2019a) assessing coal mines in Spain and their viability to be used as an underground water reservoir outlined similar design parameters.

6.1.2 The role of UPHS in achieving Net zero

UPHS shares parallels with conventional pumped hydro storage but holds the distinctive advantage of reduced reliance on topography, while also mitigating some adverse environmental and societal impacts.

The European Energy Storage Association projected that the European Union needs to increase power storage demand from 45 GW in 2018 to a range of 70 to 220 GW by 2050 (EASE, 2017), meaning an energy storage capacity of 1500 to 5500 GWh is required. A substantial portion of this demand is expected to be met through conventional pumped hydro storage, an already established technology. In the context of the UK, it is expected that 30 GW of energy storage capacity will be required by 2030 and up to 60 GW by 2050 (BEIS and Ofgem, 2021).

The role of pumped hydro storage is prominent in the current energy storage landscape and helping the UK meet its target. As of April 2023, the UK had a total of 4.8 GW of energy storage. Of this, 2.8 GW is in the form of pumped hydropower and 2 GW is in the form of battery storage (BEIS Committee, 2023).

With the increasing focus on porous media and underground caverns or disused mines for storage, it's worth noting that the size of disused mines in the UK varies. The suitability of these sites for UPHS depends on factors like geology, location, and environmental considerations. The coal mining industry was once a large part of the UK's economy providing jobs to over 1 million people in the 1930s (Statista, 2024b). However, since plans to phase out coal and reach carbon neutrality by 2050, the number of operating mines has reduced to 7 as of 2021, employing less than 1,000 people (Statista, 2024b). The start of the decline of the UK's coal mining began in the 1960s as coal powered railways were transitioning to diesel and electric power, there were 483 coal facilities at this time (Macalister et al., 2015).

6.2 Deployment trajectories of UPHS technologies

6.2.1 Overview

There are currently no operational UPHS facilities around the globe. The following sections discuss planned facilities and past projects that were never completed and their challenges.

6.2.2 Planned UPHS capacity and sites

Information from 2012 from National Infrastructure Planning (Planning Inspectorate, 2012) noted that there were no ongoing underground pumped hydroelectric storage projects in development or being planned in the UK. There are, however, a few conventional pumped hydroelectric storage initiatives in operation in the UK.

In Snowdonia, Wales, a pumped hydroelectric storage facility at Glyn Rhonwy is in the planning stages (Snowdonia Pumped Hydro, 2014). The project will utilise disused slate quarries as reservoirs with tunnels to connect the reservoirs and powerhouse. Upon completion, it is projected to offer a storage capacity of 700 MWh and reduce carbon emissions by an estimated 500,000 tonnes annually (Snowdonia Pumped Hydro, 2014)[20].

Drax Group, a prominent player in the renewable energy sector, recently secured funding from the Scottish Government to construct a £500 million underground pumped hydro storage plant adjacent to the Cruachan Power Station in a move to support the country's net zero plan (DRAX, 2021). The existing facility operates as a conventional pumped hydro storage system with both reservoirs above ground, offering 440 MW of capacity.

The expansion, while operating independently from the existing facility, will entail the construction of a new underground waterway system and powerhouse unit, but will use the same reservoirs as the existing facility (DRAX, 2022). This expansion will augment the existing Cruachan facility, adding an additional power generation capacity of up to 600 MW.

6.2.2.1 Planned UPHS facilities around the globe

In the Netherlands, the potential of UPHS has been contemplated for decades, the underground pumped hydro storage project known as the O-PAC[21] project is planning to establish a lower reservoir 1,400 metres below the surface in the Upper Carboniferous Limestone (Mearns, 2015). A feasibility study was conducted to address uncertainties. It was ascertained that these rocks could provide a stable rock formation at depths ranging from 1000 to 1700 m (Menéndez et al., 2019a), ideal for housing the lower reservoir and powerhouse, featuring largely undisturbed silicified limestones (Kramer et al., 2020). While the original project was temporarily suspended due to its scale and required investment, it has since been revived (Kramer et al., 2020). Currently in the conception phase, it is anticipated to advance to the development stage, which is expected to last three years, followed by a six-year construction phase (Kramer et al., 2020). This UPHS system is projected to generate 8.4 GWh per cycle, assuming 250 cycles per year, resulting in an annual output of 2.1 TWh.

The Kidston Pumped Storage Hydro Project in Queensland, Australia, is a pioneering venture set to become the world's first pumped storage facility situated within a disused mine site (Power Technology, 2022). It is designed to have a production capacity of 250 MW. Commencing in 2021, the project is expected to be completed in 2024. Notably, as per design specifications, the lower reservoir is expected to be positioned above ground (Genex, 2024).

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[20] Note that a blog published by one of the companies involved, Fichtner, provides a project update (Fichtner, 2023).
[21] Based on the Dutch for underground pump accumulation plant (Ondergrondse Pomp Accumulatie Centrale).

The Bendigo Mines Pumped Hydro Project in Victoria, Australia, with a planned capacity of 30 MW, is currently in the initial stages of investigation into the feasibility of repurposing old mines for a pumped hydro system. Preliminary assessments suggest that rock stability in the area is not a major concern (ARUP, 2024). However, a more in-depth study is scheduled to define the project's specifics, including its costs and benefits. Implementation faces legal obstacles, including the need for planning permissions and a new approvals process (Provis, 2019).

6.2.3 Past UPHS projects

Historically, there have been a number of UPHS projects envisioned on a global scale; nevertheless, none have advanced to operational facilities. Evaluating the setbacks and shortcomings of these previous global projects, which remained at the planning stage, might offer valuable insights to assess the suitability of this technology within the UK:

- **Elmhurst Quarry Pumped Storage Project in Chicago, USA (50-250 MW):** The Elmhurst Quarry project was conceptualised by DuPage County in 2012 and is currently being used as a critical flood storage resource using a disused limestone quarry (Charlton and Haag, 2012). This project would use traditional pumped hydroelectric storage technology, with both reservoirs above ground. The project's anticipated capacity is 50 to 250 MW with an annual generation of 708.5 GWh. Both the upper and lower reservoirs will have a minimum capacity of 9.2 million m^3. It was indicated that final evaluations of the site would need to be carried out to determine if these operations would affect rock stability. However, according to (DuPage County Stormwater Management (2021), the mines are still closed off and dry and this pumped hydroelectric storage project is still a concept. There are no formal plans to progress this project and it was not indicated if there was a specific reason for this.
- **Riverbank Wisacasset Energy Center in Maine, USA (1,000 MW):** This project was planned in 2009 when test results of rock samples carried out by Riverbank Power Corporation showed the site would be fit for development of a UPHS facility (Hydro Review, 2009). Further information on the project's development could not be found.
- **Prosper-Haniel coal mine in Germany (200 MW)**: Discussions around converting the mines into a pumped hydroelectric storage facility began in 2018 following the closure of the mine. The mine has 16 miles of mine shafts that reach 1,200 metres deep, which could produce 200 MW of hydroelectric power (Dalton, 2017). Further information on the project's development could not be found.
- **Mount Hope pumped storage in New Jersey, USA (2,000 MW):** This project was first proposed in 1975 and initiated in 1985 when a licence application for the project was submitted to the Federal Energy Regulatory Commission (FERC). However, construction never commenced due to market uncertainties and ownership changes of the licensee (Hydro Review, 2007). The FERC rescinded the licence in 2005 because construction did not commence (Hydro Review, 2007). A new licence application for the project was submitted in 2007 but with a reduced capacity to 1,000 MW (Hydro Review, 2007).

Unfortunately, the reasons behind the discontinuation of these previously envisioned UPHS storage facilities have been difficult to find. In certain instances, it seemed that the primary impediments to project realisation stemmed from financial considerations, the absence of demonstration or functional facilities as precedents, and substantial gaps in understanding the intricacies of the technology.

6.3 Environmental impacts of UPHS

The previous report published by the Environment Agency (Environment Agency, 2021b) examined possible environmental consequences related to the establishment of an UPHS facility, as well as areas in which knowledge is limited. The discussion primarily addressed operational aspects, and chemistry and contaminants associated with the construction phase, including the creation of subsurface caverns, reservoirs, and tunnels.

Given the absence of operational UPHS facilities, the understanding of their environmental impacts is constrained. Nevertheless, it is reasonable to anticipate that there may be similarities between UPHS facilities and traditional pumped hydro storage facilities. There are, however, some specific issues related to UPHS that are not covered by traditional pumped hydroelectric storage. These issues are covered in Environment Agency (2021b). Subsequent sections look into various impacts linked to the implementation and operation of such facilities, drawing insights from environmental impact assessments conducted during the development of pumped hydro projects such as:

- Landscape and visual appeal;
- Ecology;
- Geology and ground conditions;
- Water resources;
- Flood risk;
- Archaeology and cultural heritage;
- Noise and vibration; and
- Air quality.

Other areas for consideration include the existence of environmental protected areas, groundwater protection zones, proximity to urban areas or major infrastructures and seismic activity, and subsequent pollution.

6.3.1 Environmental impacts during construction

A site-specific environmental impact assessment is important to comprehensively address all potential impacts throughout the phases of implementation, operational service, and eventual decommissioning. As there are currently no UPHS facilities in operation there can only be generic assumptions made about the environmental impacts during the implementation phase. These impacts are expected to resemble those associated with the development of conventional pumped hydro storage facilities.

The construction of a UPHS facility will include temporary access tracks, working and lay-down areas, construction of permanent access roads, tunnelling, trenching, site dewatering, and land drainage.

There are certain similarities in environmental impacts between the implementation of UPHS and other storage technologies. For example, air quality and noise and vibration are discussed in Evans et al. (2018).

Water quality should be considered during the construction phase to determine if groundwater is an important contribution to regional or local water resources. Management plans including operation parameters to monitor changes in concentrations of dissolved solids, nutrients and heavy metals should be put in place to ensure there is no contaminated water run-off during construction. Another concern to consider when implementing future UPHS facilities are water pollution directives. A thorough investigation would need to be carried out to determine any potential impacts on groundwater quality (Pujades et al., 2017). Factors such as piezometric head oscillations and hydro chemical changes due to groundwater exposure could lead to environmental impacts (Pujades et al., 2017). Future UPHS facility developments need to consider a balance between efficiency and environmental impacts.

The process of filling the upper and lower reservoirs should also be meticulously planned, especially when there is no nearby natural water body. The transportation of substantial water volumes and the potential **flood risks** associated with these activities should be considered. The initial withdrawal of water from the environment to fill the reservoirs may have consequences for surrounding ecosystems, such as loss of fish and other aquatic species and migration delays of some species (Saulsbury, 2020). In addition, there could be impacts on protected species that are using the mines as their habitat such as bats.

Geology and ground conditions. A potentially significant impact when constructing UPHS facilities are those associated with tunnelling in disused mines and residual voids that may contain water, debris, and gas. Tunnelling would be necessary to excavate the existing mine workings or for the addition of new access and ventilation shafts (Menéndez et al., 2019c). It is important to select areas that are unaffected by past mining activities for tunnel construction (Menéndez et al., 2019c).

Ecological impacts could be observed during the construction of dams. This can alter the aquatic ecology of systems not just during the construction and filling of dams but with the initial withdrawal of water to fill the reservoirs. A habitat and pre-construction survey should be carried out prior to commencing activities. Consideration of mitigation activities would be likely. In addition, an Environmental Impact Assessment (EIA) would be required to evaluate potential effects of development on habitats, species, and ecosystems. This EIA would also consider **landscape and visual impacts**, as well as potential effects on **archaeological heritage**.

Hydrology concerns during construction include the impacts that trenches could have on the influence of preferential flow pathways for surface water drainage. In addition, if there are rivers in the area, they may need to be diverted during construction (Lockton, 2023).

6.3.2 Environmental impacts during service

Throughout their operational lifespan, large-scale UPHS facilities may have specific environmental impacts that require a comprehensive understanding, continuous monitoring, and effective mitigation. The nature of these impacts will vary based on the facility's location and the design of the lower reservoir.

Conventional pumped hydro storage facilities can have a diverse range of impacts, depending on the type of system (e.g., closed-loop, semi-open, or open-loop). Open-loop systems, in particular, tend to have more substantial environmental consequences, particularly affecting aquatic environments, while closed-loop systems have comparatively fewer impacts (Saulsbury 2020). UPHS facilities are likely to have similar characteristics to a closed loop pumped hydro system.

Closed-loop systems are discussed in Environment Agency (2021b). Where closed-loop systems use groundwater for the initial filling or replenishment of reservoirs, they might result in impacts on the geology, hydrogeology, and soil due to alterations in groundwater circulation patterns and chemistry. Impacts could occur, for example, due to changes in groundwater temperature, hydro chemical processes, chemical concentrations and mixing due to water/ore interactions (Saulsbury, 2020). When dealing with reservoirs that are not connected to naturally flowing water bodies, the overall environmental impact tends to be lower. Fluctuations in water levels stemming from continuous pumping operations can result in shoreline erosion and increased sedimentation in the reservoirs (Saulsbury, 2020). In addition, changes to concentrations of dissolved solids, nutrients, and heavy metals in the upper reservoir could be observed due to evaporation (Saulsbury, 2020). Notably, it has been observed that closed-loop projects featuring underground reservoirs located within former underground mining pits have the lowest operational impact on terrestrial resources (Saulsbury, 2020).

Most of these complications arise from the contamination of the water when pumped into the lower reservoir, which would likely be disused mines. Cycling these contaminated waters from the underground reservoir to the upper reservoir would be associated with significant risk of release of mine water contaminated with heavy metals and other polluting substances to nearby surface waters and land.

Overall, the principal areas of concern regarding environmental impacts during the service phase revolve around geology and contamination of soil, alongside the quality and quantity of groundwater.

6.3.3 Environmental impacts at end-of-life

Upon reaching the end-of-life stage, the decommissioning process for UPHS facilities is expected to have similar issues to those identified during their initial construction phases. Notably, noise, localised air pollution, groundwater and soil quality, terrestrial and ecological impacts.

It is difficult to predict the likely environmental impacts with the end-of-life stage of a UPHS facility due to uncertainty around the potential for its continued utilisation beyond the initial intended life span.

6.4 Social impacts of UPHS storage technologies

There is very little social scientific literature on UPHS, though what there is indicates that people are likely to draw on what they know about pumped hydro storage (PHS), as a much more established technology (it currently represents almost all grid-connected energy storage around the world), of which UPHS is a novel development. Tiwari et al. (2023) note that the limited development of PHS in the USA is likely due to social acceptance, though Steffen (2012) cites financial uncertainties as the main cause. Similarly, Steffen identifies lack of profitability as the limiting factor for PHS in Germany, which has changed with the turn towards renewables and the rejection of nuclear power by the German government following the Fukushima disaster.

Two fairly recent studies (Jones et al., 2018; Jones et al., 2021) which compare people's attitudes to different ESTs found a preference for PHS, which might be reasonably assumed to extend to UPHS; the QSR also identified Tiwari, Schelly and Sidortsov's study of social attitudes towards a potential UPHS site in Michigan. It would have been useful to complement this literature with further research on public perceptions and social acceptance of PHS, but somewhat surprisingly, there is a large gap in the research here. While some studies of ESTs and renewables mention public attitudes to PHS, Cohen et al. (2014) identify just one study of social acceptance of PHS: a study of the revival of the PHS sector in Germany (Steffen, 2012), though this is not based in empirical social science research. The only further evidence of public attitudes to PHS comes from Thomas et al. (2019)'s deliberative workshops in the UK.

6.4.1 Public perceptions

What little evidence there is of public perceptions of UPHS does not mention safety concerns – though this probably reflects a lack of data rather than a lack of public concern. Online surveys of 1,000 people in the UK (Jones et al., 2018) and in Canada (Jones et al., 2021) found them to be generally favourable to four grid-scale ESTs (CAES, flywheels, lithium-ion batteries, and PHS), with a slight preference for PHS in both countries. The researchers do not draw conclusions about why these results occurred, but suggest that it may reflect familiarity with PHS and a perception that it is more 'natural' than the other options (Jones et al., 2018). The importance of familiarity with hydroelectricity is reinforced by additional analysis on the Canadian data, which showed that preference for PHS was correlated with respondents' location in an area that relies on hydroelectricity (Jones et al., 2021). Thomas et al. (2019) similarly found that British research participants perceived PHS as 'more compatible with nature and rural landscapes'. Their qualitative study found that PHS was associated with positive, ambivalent or conditional perceptions, rather than negative ones. These included a sense that it was simple, long-term, uses existing (natural) resources, supports renewables and reduces carbon emissions and that it is preferable to, and safer than, alternative ESTs.

6.4.2 Acceptance and opposition

Steffen (2012) notes that local opposition has been a factor in delaying or even preventing PHS plants being established in Germany. Concerns include uncertainty about the effects on water, odour, mosquito plagues, and fears about dams bursting and increased risk of earthquakes. As Steffen notes, these concerns arise in areas that are unfamiliar with PHS, suggesting that this may be a factor in acceptance of UPHS – though some of these concerns may be allayed by the underground siting. Jones et al. (2021) found that attitudes towards ESTs in the UK and Canada were related to affect and perceptions of risks and benefits, and that trust in developers and environmental worldviews are significant predictors of attitudes towards ESTs. Specifically, participants with stronger environmental worldviews perceived ESTs to have greater benefits and so were more accepting of their implementation (Jones et al., 2021).

In their qualitative study of a proposed UPHS site in Michigan, USA, Tiwari et al. (2023) found that local people appreciated the potential environmental benefits of this technology compared to energy from fossil fuels. They also found that older community members were more sceptical of the project because of a concern about boom-and-bust cycles associated with extractive industries and the potential local impacts of that – presumably based on their experience of living in a former mining community (Tiwari et al., 2023).

6.4.2.1 Siting and local acceptance

Tiwari, Schelly and Sidortsov’s study in Michigan found that policymakers perceived local job creation and the rejuvenation of the community as an important potential benefit of the proposed UPHS site (2023). Amongst local people, they report, 'There was a clear interest in developing a local project that produces local benefit but concern that this could be a local project that provides more benefit to nonlocal actors' (Tiwari et al., 2023: 10). The researchers therefore emphasise the importance of developing the project in a way that would support community self-reliance in order to secure local support – a point which is likely to be relevant in the UK, too. Half of the interviewees were concerned about the proposed project disrupting their access to, or enjoyment of, nature, with many of them concerned about its effects on water quality. However, they argue that the fact that the site would be completely underground and would not use greenfield sites would be important in gaining community acceptance (Thomas et al., 2019; Tiwari et al., 2023).

6.4.3 Knowledge and familiarity

The evidence shows that, like other ESTs, public knowledge of UPHS is low (Jones et al., 2021), while Tiwari et al. (2023) found that even in a former mining community, 'There seemed to be consistently limited awareness among participants about redeveloping mines for energy storage'.

6.4.4 Trust

Jones et al. (2021) found that the more trust people had in developers, the more likely they were to support the roll-out of ESTs. In Michigan, Tiwari et al. (2023: 10) note that, 'a perceived lack of transparency in local government affairs and decision-making could negatively impact perceptions of future projects and suggest[s] that communities experiencing the consequences of postindustrialisation anchor their perceptions of new development to the sense of loss experienced as a result of previous development'. Steffen (2012) points out that monetary compensation for communities in which PHS sites are proposed may be counterproductive, as it can ‘crowd out civic virtue’ and result in stronger opposition – instead, it may be more important to address perceptions of procedural justice by involving communities early in the development process.

6.4.5 Gaps in the literature and future research

Given the lack of research on social acceptance of both UPHS and PHS, the most obvious need is simply for more evidence of both general and local acceptance of these technologies. The established nature of PHS means that it could provide a useful empirical comparator for more speculative research into perceptions of UPHS. If people have positive perceptions of PHS based in personal experience, this could also be very helpful for developers and promoters of UPHS, as they could share this with communities in prospective UPHS sites.

6.5 Remaining data gaps

As an evolving technology, there are a number of knowledge gaps associated with UPHS, many of those identified in Environment Agency (2021b) are still relevant. Notably, the suitability of sites for UPHS facilities, the precise operating conditions that are optimal, and the extent of possible environmental impacts during construction, operational service, and decommissioning.

6.6 Conclusions and summary

It is clear from the lack of real operational UPHS sites that the technical feasibility issues as well as the wide scope for significant environmental issues arising from the repurposing of disused mines that UPHS is highly unlikely to be deployed in England. The more likely scenario is that England and the wider UK will continue to use and implement conventional pumped hydroelectric storage, as this technology is much more mature and has real systems from which to learn.

In terms of environmental impacts associated with UPHS, there are significant environmental complications which are likely to severely limit its deployment in England. Most of these complications arise from the contamination of the water when pumped into the lower reservoir, which would likely be disused mines. Cycling these contaminated waters from the underground reservoir to the upper reservoir would be associated with significant risks of release of mine water contaminated with heavy metals and other polluting substances to nearby surface waters and land.

In summary, it is unlikely that England will implement any UPHS sites in the future, as its low technical feasibility and environmental risks are too high to consider the technology worthwhile to develop further. Indeed, this same perspective appears to be taken around the globe, as all planned UPHS projects have been disused for a number of undetermined reasons.

The main potential environmental issues associated with UPHS deployment, particularly for those utilising repurposed disused mines, are summarised below in Table 12.

Table 12: Summary of potential environmental issues associated with UPHS

Receptor	Notes	Environmental Issues
Geological instability	Excavation of tunnels and reservoirs as well as underground pressure changes can lead to fracturing of host rock formations, leading to geomechanical instability and increased permeability.	Host rock instability may lead to malfunction or total system failure due to tunnel collapse (Tong et al., 2013). Increased permeability may lead to greater exchange between groundwater and mine water. Geomechanical instability may also lead to fault (re-)activation, landslides and seismic activity (Menéndez et al., 2019c).
Water quality	Contamination of surface/groundwater with mine water and mine gases such as methane from mixing during cycling. Potentially exacerbated by increased host rock permeability from tunnelling and excavation.	Surface/ground water may become contaminated with toxic elements such as heavy metals commonly present in minewater, resulting in toxicity to terrestrial or aquatic ecosystems (Poulain et al., 2018).
Water quality	Abstraction of freshwater from water bodies to fill the upper reservoir during implementation.	Filling of the reservoirs could introduce flood risks and impact aquatic life from which the water was extracted (Saulsbury, 2020).
Land quality	Use of available land to build upper reservoir and potential destruction of natural ecosystems and habitats. Potential for soil contamination from construction activities, particularly where disused	Potential habitat loss and toxicity to wildlife. Assimilation of toxic elements by agricultural crops. Flooding after dike failure may result in larger scale contamination or acidification of soils (Poulain et al., 2018).

Receptor	Notes	Environmental Issues
	mines are used as lower reservoirs. Potential for flooding in the event of dike failure at the upper reservoir.	
Acute human and environmental health	Risks associated with flooding during operation and release of toxic, flammable or asphyxiant gases during construction.	Flooding may have acute impacts on human health of nearby populated areas. Release of toxic or asphyxiant gases during underground excavation of mines may result in fatalities or harm to health of workers (Tong et al., 2013).

7 Thermal Energy Storage (TES)

7.1 Introduction

Thermal Energy Storage (TES) may be used for heating, cooling or power generation. It provides a means of balancing energy demand with supply.

TES is often coupled with other renewable heating technologies to improve their efficiency and boost their thermal output, including Combined Heat and Power (CHP) systems that deliver space heating and electricity. Figure 11 gives examples of those applications and renewable heating technologies that can be used with TES.

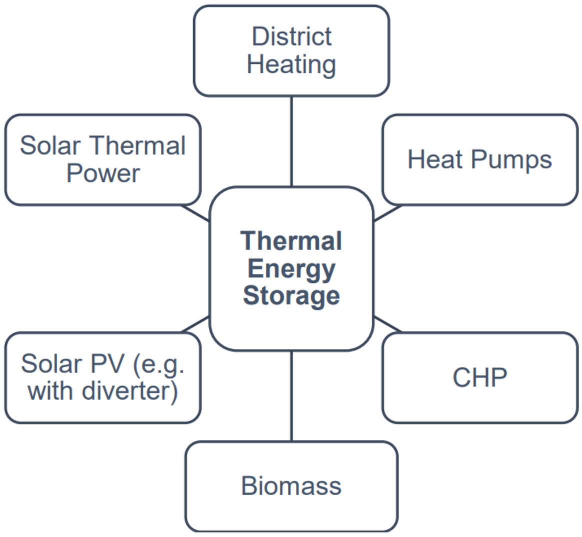

Figure 11: Examples of renewable heating technologies and applications coupled with TES. ***Source:*** BEIS, 2016

TES can be used for domestic schemes, e.g., hot water tanks, commercial/public buildings, and larger district heating schemes (BEIS, 2016).

There are three categories of TES, each with a number of sub-technologies including:

- Sensible: Heat stored in materials with a high specific heat capacity. Examples include tank thermal energy storage (TTES), and electric storage heaters;
- Latent: Phase change materials (PCM) store and release heat when transitioning between physical phases (e.g., solid to liquid). Examples include, aqueous salt solutions, water, gas hydrates, paraffins, salt hydrates, eutectic mixtures, sugar alcohols, nitrates, hydroxides, chlorides, carbonates, and fluorides
- Thermochemical: Heat stored and released through chemical reactions of a substance, including calcium sulphate, calcium carbonate, iron carbonate, and magnesium sulphate heptahydrate.

The release of energy from TES may be short-term diurnal (intra-day), spanning short charge and discharge cycles, or longer-term, with a long discharge cycle, such as inter-seasonal storage. Inter-seasonal energy storage is more suited to larger schemes for commercial buildings or district heating for example.

Intra-day storage encompasses technologies such as electric storage heaters and tank based thermal energy storage. In 2016 approximately 1.8 million dwelllings had electric storage heaters and 11 million included tank based hot water systems. Larger tank systems for commercial premises of greater than 500 litres were reported to number low thousands. District heating systems with tank capacities from hundreds to thousands of cubic metres represent the other end of the spectrum of use for tank systems in the UK (BEIS, 2016).

7.1.1 TES technologies

TES is divided into three categories, sensible, latent and thermochemical heat storage. Within these categories there are different methods of storage and retrieval.

7.1.1.1 Sensible

Sensible thermal energy storage uses solid or liquid materials that do not change phase and where no chemical reaction takes place. A thermal energy source heats the material, raising its temperature. This stored energy is ready to be exchanged or extracted at a later time to a lower temperature heat sink, for example space heating a room. Types of sensible thermal energy storage include:

- Tank (TTES): An above-ground or under-ground tank containing the thermal energy storage material and heat exchange apparatus to control the storage and release of heat;
- Borehole (BTES): An underground TES technology which involves heating the ground below the surface for seasonal heating;
- Pit (PTES): Similar to TTES but located underground in a dug-out pit; and
- Aquifer (ATES): Stores and recovers thermal energy in subsurface aquifers by extracting and injecting groundwater using wells[22].

[22] Aquifers can be used in low (<30°C), medium (30-60°C), and high (>60°C) temperature geothermal energy storage. High temperature geothermal storage is generally at a lower TRL than low and medium, and the geothermal resources with high temperature potential in the UK are somewhat restricted in comparison to other regions (Abesser et al., 2020).

Sensible heat storage in the form of PTES, BTES, and ATES, as well as larger underground water tanks (TTES) are categorised as underground thermal energy storage and are often employed to provide inter-seasonal TES (BEIS, 2016). Schematics of the four underground variants of sensible category of TES are shown in Figure 12**.**

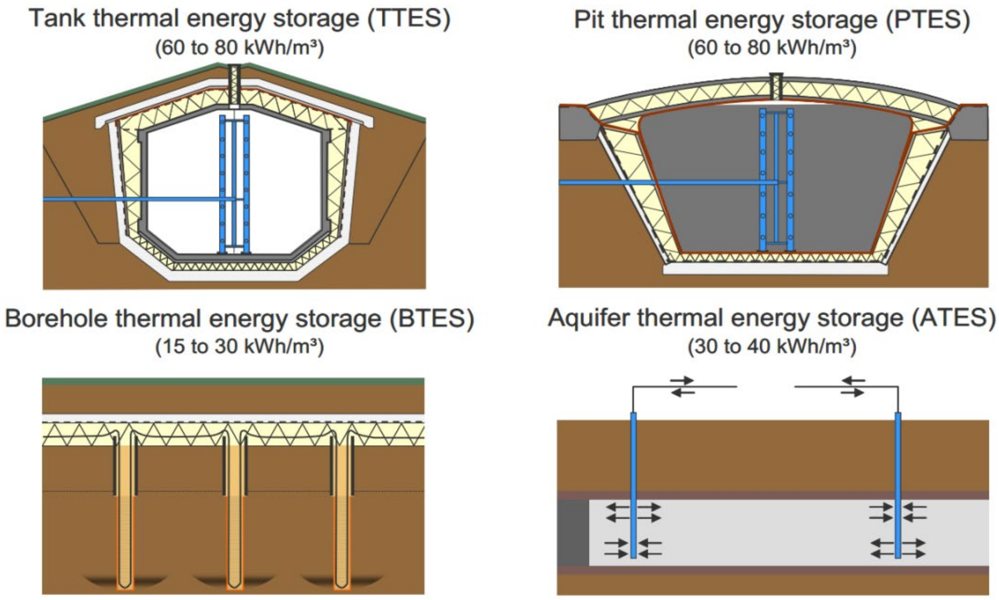

Figure 12: Types of underground TES. *Source:* BEIS, 2016

Materials exhibiting no phase change and high heat capacity used for sensible heat storage include glycols, concrete, and rock. However the most common material is water because it is relatively abundant, low cost and has a high heat capacity. Sensible thermal heat storage is often coupled with solar thermal systems as well as heat pumps. Pairing sensible TES with renewable energy sources such as solar thermal can help provide a significant proportion of a building's energy requirements (Cruickshank and Baldwin, 2022).

7.1.1.1.1 Tank Thermal Energy Storage

Tank (TTES), together with electric storage heaters, were reported to be the most prevalent form of sensible heating TES deployed in the UK in 2016 (BEIS, 2016). TTES installations can be adapted to service both residential, commercial, and district heating applications for both short term, intra-day storage but also longer-term inter-seasonal TES. Tank volumes vary from small residential hot water cylinders, a direct heating system, where water is heated by the domestic heating system, to very large thermal storage units, indirect systems, which can be used to balance Combined Heat and Power (CHP) or District Heating (DH) systems.

Materials that can be used for sensible thermal heat storage in TTES include water, heat transfer fluids, concrete, molten salts, rock, and other ground constituents such as sand. The losses of heat from a sensible TTES system, and therefore efficiency of the system, depend on the constant heat loss coefficient of the sensible heat storage, which is proportional to the surface area of the store and the temperature differential between it and the ambient temperature of the surrounding environment, as well as other factors, such as insulation between the store and the environment and specific materials used to store the thermal energy (Haines et al., 2014).

7.1.1.1.2 Borehole Thermal Energy Storage

Borehole arrays can provide inter-seasonal thermal storage which can be integrated with other renewable energy technologies, for example solar-thermal. The boreholes store heat within soil, rocks and pore water all of which have high volumetric heat capacities[23]. The borehole contains a single or double U-tube pipe typically ranging from 30 to 100 m depth, depending on the requirements of the heating or cooling system it supports and the geological conditions. Depending on the geological conditions, the borehole construction will include a casing pipe which may be filled by grout materials with high thermal conductivity (Wu et al., 2023). Typical grout materials include bentonite and cement though efforts are underway to increase the thermal conductivity of the grout to improve heat transfer from the surrounding environment, for example, by including up to 5% graphite (Mahmoud et al., 2021).

A diagram showing a grouted borehole construction is shown in Figure 13.

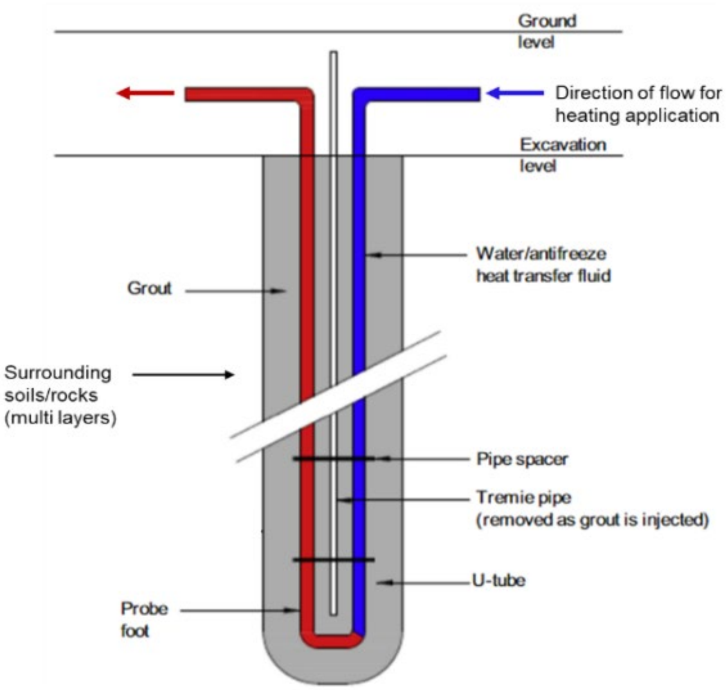

Figure 13: Grouted borehole construction. ***Source:*** Wu et al., 2023

Where geology and hydrology allow i.e., in locations of hard rock and high ground water levels, grouting materials may not be required for heat conduction to surrounding rocks.

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[23] Heat capacity per unit volume in J m^{-3} K^{-1} (Lockton, 2023).

Water, sometimes with added antifreeze such as ethylene glycol or propylene glycol, circulates in pipes as the heat carrier, removing heat previously stored in the ground via conduction. This transferred heat can then be utilised via a standalone application, or as part of an integrated network supplying heat in conjunction with other renewable technologies such as solar-thermal, as shown in Figure 14.

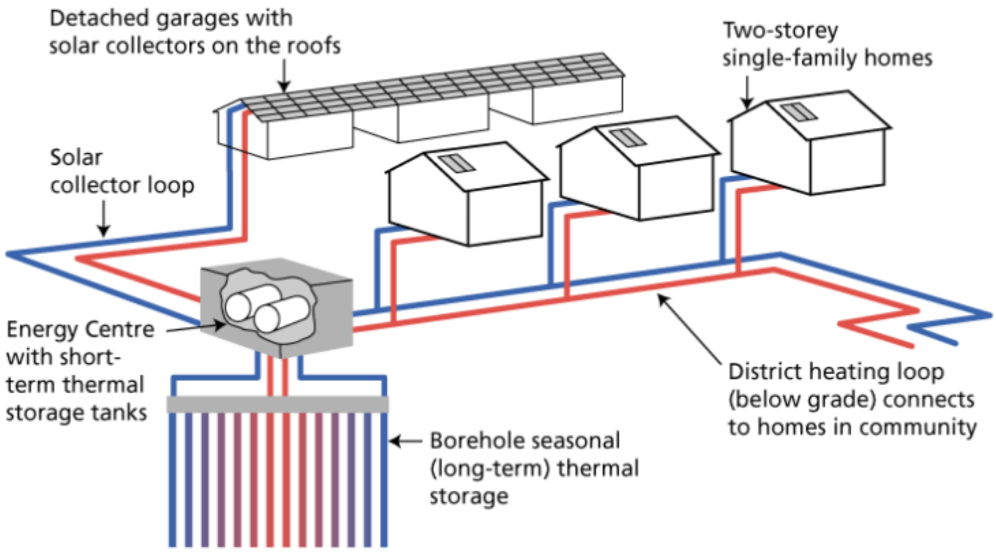

Figure 14: Schematic diagram of an integrated district heating system utilising BTES. *Source:* Mesquita et al. (2017)

7.1.1.1.3 Aquifer Thermal Energy Storage

Aquifer Thermal Energy Storage (ATES) is a method for the storage and recovery of thermal energy in subsurface aquifers. It functions by extracting and injecting groundwater using wells, allowing for both heating and cooling of buildings (Fleuchaus et al., 2018). In 2018, it was estimated that over 2,800 ATES systems were operational globally, and abstracting more than 2.5 TWh globally, demonstrating its feasibility on a moderate scale. 85% of ATES systems are operational within the Netherlands, and a further 10% are located in Sweden, Denmark, and Germany, though there is increasing interest in ATES technology in Great Britian (Fleuchaus et al., 2018); a good example being the recent ATESHAC project lead by Imperial College London in collaboration with the British Geological Survey and the University of Manchester (Imperial College London, 2021).

ATES utilises shallow groundwater as a seasonal storage medium for low-temperature (LT) thermal energy. In temperate climates with distinct seasons, ATES efficiently stores excess heat in summer and cooling capacity in winter, thereby balancing the availability and demand of thermal energy. The system consists of a warm and a cold storage volume in the subsurface, from which heated or cooled groundwater is extracted as needed. LT-ATES systems typically have maximum injection temperatures below 25 °C and are located in shallow depths. They are often used in residential buildings and larger complexes like office buildings or shopping centres. To ensure sustainable operation, a balanced thermal charging and discharging of the aquifer is crucial, as practiced in the Netherlands (Stemmle et al., 2022).

In contrast, high-temperature ATES (HT-ATES) systems store water at temperatures above 50 °C, typically in deeper aquifers. The heat sources for HT-ATES often include waste heat from industrial processes or excess solar thermal energy. These systems can be integrated into district heating networks operating at higher temperatures. HT-ATES systems face different challenges and requirements compared to LT-ATES, including aspects related to hydrogeological, hydrogeochemical, and technical conditions due to their greater storage depths and higher storage temperatures (Stemmle et al., 2022).

7.1.1.1.4 Thermal energy storage in disused mine water

Disused mines are potential sites for thermal storage. Water often reflects the geothermal gradient and is not affected by seasonal changes in temperature. This can be a stable source of renewable heat for space heating in local coal fields if managed sustainably (Coal Authority, 2023). Other potential applications include balancing intermittent electricity demand, capturing waste heat from other sources e.g., data centres and also for cooling (BGS, 2023).

The integration of mine water thermal storage with other renewable energy sources such as solar-thermal, is a developing area. Pilot examples of these integrated district heating and cooling networks include the council-owned Gateshead Energy Company which became operational in March 2023 and uses CHP and minewater thermal. This is one of the largest examples of this type of district heating system in Europe, supplying heat to municipal buildings and 350 council-owned houses with plans to add a further 270 privately-owned houses, conference centre, and hotel in the future. Another development in progress is Durham County Council Seaham Garden Village district heating scheme taking mine water from a treatment scheme owned by the Coal Authority to support heating needs for up to 1,500 houses (Coal Authority, 2023).

7.1.1.2 Latent – Phase change materials (PCM)

Phase change materials (PCM) are defined as a substance that undergoes a change of phase at a set temperature. The phase change is typically from solid to liquid, although systems can also be liquid to gas. A heat transfer fluid, which in most cases is different from the PCM due to the required phase change characteristic, flows over containers of the PCM, or alternatively a heat exchanger inserted into the PCM is used. Potential energy storage density and required storage volume from PCM is a benefit over sensible heating technologies if the required temperature range of the application receiving the heat is close to the phase change temperature of the PCM. Where a wider temperature range of operation is necessary for the serviced application, then it may be the case that a sensible heat storage solution is more cost effective (Haines et al., 2014).

Examples of PCMs which can be used in LTES include inorganic compounds, such as salts and salt hydrates; organic compounds, such as paraffins, fatty acids; and polymeric materials, such as polyethylene glycol (PEG) (Pielichowska and Pielichowski, 2014).

Important properties of PCMs include high latent heat of fusion (the latent heat associated with the melting of a substance), high thermal conductivity, high density, and high chemical stability. In addition, due to the large volume of PCM typically used, the materials should also be cheap and abundant (Streicher et al., 2005).

Examples of specific inorganic and organic PCMs are shown in Table 13.

Table 13: Non-exhaustive list of inorganic and organic PCMS used in LTES

Compound	CAS No.	Melting temperature	Latent heat of fusion	Principal hazards	Other comments
$KF \cdot 4H_2O$	13455-21-5	18	231	Toxic in contact with skin	Salt hydrate
$CaCl_2 \cdot 6H_2O$	7774-34-7	29-30	190.8	Causes serious eye irritation	Salt hydrate
$LiNO_3 \cdot 3H_2O$	13453-76-4	30	296	Oxidiser, harmful if swallowed	Salt hydrate
NaOH	1310-73-2	64.3	227.6	Causes serious eye damage, corrosive	Salt
Paraffin C_{20-33}	97722-14-0	48-50	189	Not reported	Organic (paraffin)
Caprylic acid	124-07-2	16	148	Causes skin burns and eye damage, toxic to aquatic life with long-lasting effects	Organic (fatty acid)
Palmitic acid	57-10-3	64	202.5	Not reported to be hazardous	Organic (fatty acid)
Source: Streicher et al., 2005; European Chemicals Agency Substance Database					

The choice between the use of organic or inorganic PCMs for LTES is dependent on a range of criteria. For example, organics are generally less corrosive and have a greater chemical and thermal stability than inorganics but generally demonstrate lower latent heat of fusion and can be flammable. On the other hand, inorganics have a greater latent heat of fusion but can be more corrosive to the storage container and demonstrate phase separation and lack of thermal stability to a greater extent (Streicher et al., 2005).

7.1.1.3 Thermochemical heat storage (THS)

The concept of THS is to utilise reversible chemical reactions to store large quantities of heat in a compact volume (BEIS, 2016).

Application of heat to the material causes it to breakdown into its constituent parts, referred to as charging. The constituents are stored separately until required, at which point they are combined together in a reactor which releases heat; discharging. The process benefits from high energy density of the reactive material, and the ability to store the material in the ‘charged’ state indefinitely, as the heat is stored as chemical potential energy rather than thermal energy which can be dissipated to its surroundings.

However, while THS can fundamentally store energy for longer periods of time than STES or LTES, THS is more often used for intra-hour or intra-day thermal energy storage (Ali et al., 2024).

This process is represented in the schematic illustrated in Figure 15.

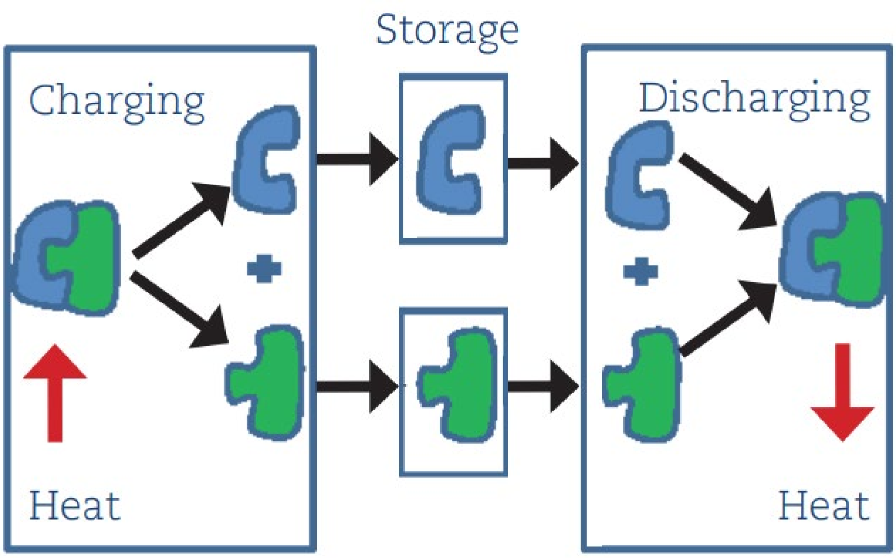

Figure 15: Schematic diagram illustrating thermochemical heat storage process (THS). ***Source:*** Haines et al., 2014

Examples of THS materials are given in Table 14, which is reproduced from Haines et al. (2014).

Table 14: Examples of materials identified as potential THS candidates

Thermochemical material	Reactant A	Reactant B	Approximate Energy Storage Density of thermochemical material (kWh/m^3)	Charging Reaction Temperature (°C)
Calcium sulphate	$CaSO_4$	H_2O	389	89
Magnesium sulphate heptahydrate	$MgSO_4$	H_2O	778	122
Iron (II) hydroxide	FeO	H_2O	611	150
Iron (II) carbonate	FeO	CO_2	722	180
Calcium hydroxide	CaO	H_2O	528	479
Calcium carbonate	CaO	CO_2	916	827
Source: Haines et al., 2014				

7.1.2 The role of TES in achieving Net zero

Seasonal variability of demand can drastically change the output requirements of the UK's gas, electricity, and petroleum energy sources. As an example, daily demand for gas in winter was recorded to be about four times that for summer (Birmingham Energy Institute, 2020). In order to meet these requirements coupled with a transition from fossil fuels, it will be necessary to build an integrated TES system that can supplement peak energy demand when necessary.

Heat pumps and zero emissions vehicles are key elements of the UK Government's Net Zero by 2050 commitment. A target to install 600,000 heat pumps per year by 2028[24] has been set (DESNZ, 2022). The majority of zero emissions vehicles use electric motors and therefore will add to the electricity demand on the UK grid.

Adding to the variability in demand currently experienced due to seasonal variability, is the impact from electric vehicle (EV) charging as EVs become more prevalent. There is scope for this change in behaviour to increase daily demand and also to move the peak period to later in the evening. Heat pumps, for example air-source and ground-source, are reliant on electricity to operate and therefore their progressive roll out into residential and commercial properties over the next decade will add to the electricity demand on the UK power grid. Daily heat demand profile does not mirror that for electricity so a change in the heat generation technologies reliant on electricity in their operation, could also affect the demand profile for energy. It is likely that the above demand drivers will increase demand for electricity in the following decade, accelerating into the 2030s (Birmingham Energy Institute, 2020).

As introduced in Section 7.1, TES provides a means for balancing demand for heating despite the unpredictability of renewable energy generation. It can still be utilised to supply energy into the grid, reacting swiftly to changes in demand as required.

7.2 Deployment trajectories of TES technologies

7.2.1 Current TES capacity and sites

Thermal energy storage projects across the UK, excluding Northern Ireland, are shown in a map from Barns et al. (2021), which is provided as Figure 16. The purpose of the study by Barns et al. was to research the sociotechnical factors influencing the development, application, and carbon reduction impact of thermal energy storage in the UK. This covered the current status of thermal storage deployment in terms of technology types, geographical distribution, and involved organisations, the sociotechnical characteristics shaping the current deployment of TES, and exploring how understanding the diverse values sought by project developers can inform the potential future deployment of TES technology. The location of certain types of TES is influenced by geological features present in the local area, for example natural features such as aquifers. Examples include those located in the London chalk basin and also the Birmingham sandstone aquifer. Additional potential sites for aquifer TES with suitable geological conditions are to be found in East Anglia, Liverpool, and the Southeast. Another sub-category of TES are anthropogenic aquifers formed from flooded abandoned mine shafts as part of former worked coal seams.

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[24] Point 7: Greener Buildings.

In recent years technologies have been developed to harness stored heat within mine-water. The Coal Authority has been working with partners to develop a network of old flooded mine workings to deliver heat to a district heating network. An example of this is the Gateshead Energy Company which supplies heat and hot water to buildings in the town. This is one of the largest examples of its type in Europe. It incorporates a 6-megawatt water source heat pump fed by boreholes accessing the flooded mine works 150m underground (Coal Authority, 2023; see Figure 17).

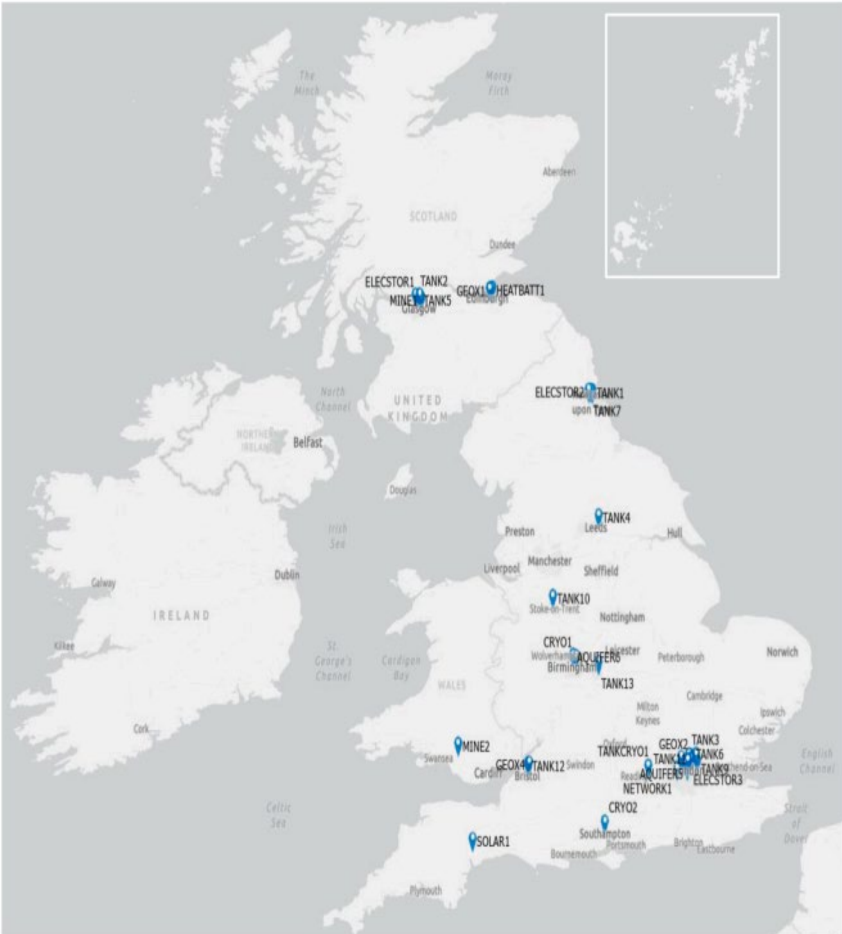

Figure 16: Distribution of TES project in the UK. ***Source:*** extracted from Barns et al., 2021

Figure 17: Borehole used to abstract mine water for Gateshead district heating scheme. *Source:* Coal Authority, 2023

Table 15 contains a list of projects linked to TES applications as described in this section.

Table 15: Projects linked to TES applications

Project Identifier	Description
SOLAR1	Large heat network serving new housing and commercial development, powered from solar thermal array with high temperature heat pump and central thermal storage tank for evening heat.
GEOX1	Geoexchange approach employed at several supermarket sites across the UK to balance heating and refrigeration needs. Directional drilling to achieve large storage volume from car park borehole site.
TANK1	Large town centre heat network with integrated tank thermal storage serving civic and commercial buildings and social housing dwellings.
AQUIFER1	Aquifer thermal storage used to provide heating and cooling to new housing development.
MINE1	Demonstrator project exploring the use of abandoned coal mines under city for heat source and potential thermal storage.
TANK2	Demonstrator project featuring energy recovery from sewage water to provide heating and cooling to a museum and art gallery, with tank storage for pre-heat hot water supply.

Project Identifier	Description
TANK3	Large mixed development as part of city regeneration scheme served by trigeneration heating, cooling and electricity networks from central combined heat and power (CHP) plant with thermal storage tanks.
TANK4	City-scale high temperature district heat network serving local authority dwellings and municipal buildings. Powered by energy from waste (EfW) CHP plant with thermal storage tanks to maximise heat recovery.
GEOX2	University development of geoexchange[1] using boreholes and shared heating and cooling between university buildings through ambient network.
TANK6	Waste heat recovered from underground rail network with air source heat pump. Part of expansion of large established heat network with thermal storage tank integrated to support system operation.
GEOX3	Large local authority community facility using geoexchange[1] approach through 'thermal bank' ground storage recharged with waste heat from summer cooling demand.
AQUIFER2	Aquifer thermal storage for new wing of national museum with active seasonal recharge through waste heat and cooling.
TANK7	CHP district heat network with thermal storage tanks serving new science and research hub along with commercial and residential buildings.
AQUIFER4	Aquifer storage providing heating and cooling to new residential development and commercial spaces.
TANK8	Oldest district heat network in the UK with large tank thermal storage serving 3,256 dwellings, 50 commercial premises and 3 schools.
TANK9	Large scale district heat network covering legacy Olympic site, residential developments, and shopping complex. Powered by trigeneration CHP and biomass boilers with thermal storage tanks.
TANK10	New deep geothermal powered city heat network incorporating thermal storage tanks in energy centre housing directional drill site.

Project Identifier	Description
AQUIFER5	Large mixed residential and commercial development using underlying aquifer storage and CHP.
MINE2	Demonstrator district heat scheme serving 700 dwellings, school, and church connected to abandoned mine working thermal energy store.
AQUIFER6	City centre hotel development employing aquifer thermal storage for summer cooling and winter heating.
TANK11	Trigeneration CHP with large thermal storage tank serving extensive mixed district heat network.
TANK12	City centre heat network with biomass boiler, gas CHP, and thermal storage tank serving thirteen social housing blocks. Long-term aim to connect to city-wide heat network.
TANK13	City scale district heat network fired from EfW plant initially serving range of civic buildings and cathedral. Prominent thermal storage tank seen as landmark feature with mounted carbon saving counter.

1. Geoexchange: collective term for different approaches to thermal storage

Source: **Adapted from Barns et al., 2021**

7.2.2 Planned TES capacity and sites

As a part of the DESNZ Longer Duration Energy Storage Demonstration Programme, two thermal energy storage projects have received funding to further develop and demonstrate longer term thermal energy technologies in England.

Stream 2 of the energy storage initiative focuses on accelerating the commercialization of longer-duration energy storage technologies by advancing projects from initial feasibility studies to the development of first-of-a-kind full-system prototypes. Within this initiative, two notable projects, **EXTEND** (aiming to extend the storage duration and capacity of thermal batteries) and **ADSorB** (Advanced Distributed Storage for Grid Benefit), have been awarded significant funding and are particularly focused on advancements in thermal energy storage.

The EXTEND project, led by Sunamp Ltd and funded with £9,245,261, seeks to enhance the storage duration and capacity of Sunamp's thermal batteries. This initiative integrates these advanced batteries with a smart heating controller and household energy systems, targeting the challenge of periods with low renewable energy generation on the grid. In Phase 2 of the project, the focus will shift towards the development, construction, and trial of the EXTEND solution in 100 dwellings across the UK. This phase is critical for assessing the potential impact of deploying a large fleet of these thermal storage systems in a specific network area. The R&D phase of the EXTEND project is set to conclude in late 2023, with a field trial running until July 2024, followed by a report of the project findings (Sunamp, n.d.).

In parallel, the ADSorB project, spearheaded by The University of Sheffield with funding of £2,595,571, is centred on developing innovative long-duration thermal storage technologies coupled with intelligent control systems. The project's aim is to create modular systems using thermochemical (TCS) and phase change material (PCM) technologies that allow for optimised and flexible heat storage within dwellings, providing benefits to both the residents and the grid. The next phase involves continuing the development of these modular thermal energy stores, along with the control software and hardware. The project plans to manufacture and deploy prototype energy systems at the Creative Energy Homes campus at the University of Nottingham, enabling practical demonstrations in actual living environments (ADSorB, n.d.).

7.2.3 Remaining capacity required for Net zero and possible locations

Beyond the TES projects highlighted above, no database of planned TES locations has been identified. However, as noted earlier, sites that have potential for aquifer TES can be found in East Anglia, the Northwest, and Southeast. Data deficiencies (including information on specific aquifer suitability across England) have prevented potential locations from being mapped.

7.3 Environmental impacts of TES

7.3.1 Environmental impacts during construction

The construction phase of thermal energy storage systems, particularly Borehole Thermal Energy Storage (BTES), pit TES, ATES, minewater TES, involves activities such as excavating pits or drilling boreholes and installing pipes underground, which can cause disturbances to local ecosystems. The extent of the impact depends on the scale of the drilling and the sensitivity of the surrounding environment, potentially leading to habitat destruction, alteration of groundwater flow patterns, or disturbance to soil structure, affecting local flora and fauna, as well as local noise and vibration generation and air pollution from construction activities similar to those previously discussed in this report.

Additionally, the use of alkaline cement in constructing underground thermal energy storage systems can lead to an increase in local soil pH (Richman et al., 2006). This change in soil chemistry can affect the growth and health of plants, microorganisms, and other soil-dwelling organisms. It can also lead to changes in nutrient availability and mobility of heavy metals, potentially causing broader ecological impacts (Cho et al., 2016).

Another aspect to consider is the use of phase change materials (PCMs) in Latent Thermal Energy Storage (LTES) systems. While some PCMs, such as fatty acids, are environmentally benign, other PCMs can pose environmental risks. Compounds like chromate salts, borates, and naphthalene used in some PCMs are toxic and can be harmful if released into the environment through loss of containment in the event of accidents or corrosion of the storage container over time (Streicher et al., 2005). Although PCMs in LTES are typically used in closed systems, which reduces the risk of environmental exposure, the production and handling of these materials still pose potential hazards.

Given the vast range of potential PCMs for LTES applications, careful selection and management are crucial to minimise environmental risks. Understanding the properties and impacts of each PCM is essential to ensure that the more hazardous materials are handled appropriately, and their use is justified based on performance and safety criteria. The selection process should prioritise environmentally friendly options where feasible, and rigorous containment measures such as regular inspections, system redundancies, and risk assessments should be implemented for toxic PCMs to prevent accidental releases.

7.3.2 Environmental impacts during service

For water-based underground thermal energy storage facilities, such as ATES and BTES, there is a concern that water with a significant temperature differential from its surroundings could disrupt the chemical environment and local ecosystems through altered reaction kinetics and mixing processes. These reactions and processes could result in changes in salinity, and the presence of inorganic and organic micropollutants (Matthijs Bonte, 2011). The introduction of thermally altered water into the environment could affect temperature-sensitive species and ecological redox processes (Possemiers et al., 2014), as well as enhancing the transport and volatisation of groundwater contaminants (Meng et al., 2021).

For underground TES systems like BTES or ATES, thermal energy is transferred to natural underground systems (ground or groundwater). Many geochemical processes are catalysed by microbes found in subsurface water bodies by consuming high redox potential substances like Fe(II) and other nutrients. This plays a crucial role in the prevention of harmful pathogens proliferating in drinking water sources by lowering the concentration of available nutrients. Disrupting this delicate balance through anthropogenic temperature changes may increase the nutrient content of the water body, allowing the potentially harmful pathogens or sulphate reducing bacteria (Lienen et al., 2017) to thrive and negatively impact water quality (Matthijs Bonte, 2011)

During service, ATES and BTES may also be incompatible with other subsurface functions including water supply, infrastructure, and water storage (Matthijs Bonte, 2011).

7.3.2.1 Impacts from ATES use in the Netherlands

Over the past 40 years, the use of ATES in the Netherlands has grown significantly from only 10 systems in 1990 to approximately 3,000 operational systems in 2024. The Netherlands has the largest use of ATES of any country worldwide, and it is estimated that only 500 systems are found outside of the Netherlands. As a result of this rapid and large-scale adoption, the research into the environmental impacts of ATES in the Netherlands has been vast, and is based on both laboratory studies and monitoring of real installations.

ATES stands out as one of the more challenging technologies from an environmental perspective, as it takes place in an ‘open’ system, meaning that its operation can have knock-on effects to the surrounding geological environment. For this reason, specific impacts of ATES are highlighted in this section. A comprehensive study conducted by the Dutch research programme, Meer Met Bodermenergie, summarises the potential and historical impacts of underground TES technologies in the Netherlands (Godschalk et al., 2019). The study mainly focuses on ATES, though other underground TES technologies such as BTES are also considered. The potential impacts covered in this study include:

- Hydrological effects;
- Soil mechanical impacts;
- Salinisation;
- Impacts from temperature changes in the aquifer.

In addition, the study describes several other aspects including regional groundwater management and methods of combining ATES with other technologies. While this study was published at a date outside of the desirable window for this report, underground TES technology has been implemented in the Netherlands for a longer period than in England, and therefore these learnings from the Netherlands should be considered. Furthermore, due to the close geographic proximity of England and the Netherlands, impacts resulting from specific geological conditions discussed in this report are assumed to be reasonably applicable to England.

The following section gives a summary of the key environmental issues discussed in the Meer Met Bodermenergie report.

7.3.2.1.1 Hydrological effects

The extraction of, and infiltration to groundwater during operation of ATES has several effects on underground hydrogeology, including effects on the hydraulic head of the aquifer, and groundwater level changes.

Hydraulic head changes may result in temporary dewatering of the aquifer, potentially limiting the volume of water which is available for drinking, industrial extraction, or nearby infrastructure which has been designed based on the hydraulic properties of the aquifer. Reduction in groundwater levels can also result in droughts for agriculture or desiccation of ecosystems which are dependent on the aquifer. Conversely, infiltration of water into an aquifer may raise the groundwater level, potentially resulting in flooding or watering of nearby residential sites, farms and habitats. However, it was reported that these impacts can be minimised as the degree of groundwater extraction and infiltration can be similar and effectively cancel each other out, particularly when the sites for extraction and infiltration are separated by only a short distance (a few hundred metres). Furthermore, the hydrological effects can be reasonably predicted if sufficient hydrological data is available.

7.3.2.1.2 Soil mechanical impacts

It has been reported that settlement and subsidence of soil can potentially result from the use of ATES, where the changes of the hydraulic head of the aquifer can cause loads and stresses on the soil layer which result in settling or subsidence. However, the degree at which settling or subsidence takes place is also dependent on a number of other factors. For example, clay and peat soils are reported to be more sensitive to subsidence than gravel and sand soils. Also, the sensitivity of an area of soil will depend on its degree of compression from historical loads. While in the Netherlands it was determined that the use of ATES had not resulted in any settlement which has led to environmental or structural damage, there were at least ten reported programmes for which ground level monitoring for settlement has been a requirement of the ATES sites.

7.3.2.1.3 Salinisation

Salinisation of an aquifer typically occurs when freshwater is extracted and higher salinity water diffuses into the aquifer. Saline waters could originate from deeper groundwaters, or diffused seawater for coastal aquifers. Salinisation of aquifers can have significant impacts on the chemical composition of natural water sources, resulting in potential knock-on effects to drinking water quality, agriculture and ecosystems.

While salinisation as a result of ATES usage is expected to be lower than that of typical groundwater extractions (as the extracted water is balanced with an equal volume of infiltrated water), it has been reported that salinisation can also occur as a result of mixing of the saline-brackish-freshwater phases from cyclical extraction and infiltration arising from ATES operation.

The extent of aquifer salinisation is expected to depend heavily on the specific detail of the ATES site, including, but by no means limited to the depth of the aquifer itself, the salinity of deeper groundwater and the temperatures at which water is extracted and infiltrated.

It is also important to note that aquifer salinisation is regarded as an almost irreversible process, and once mixing of freshwater and saline water has taken place, it could take decades to return to its original state. So, while the risk for ATES to cause salinisation of an aquifer is relatively low, the potential impacts are severe. Therefore, before implementing ATES at a specific site, careful and scrupulous considerations of the hydrogeological situation is necessary. During operation, regular water quality measurements of the system are desirable to assess the rate at which (if at all) salinisation of the aquifer is taking place as a result of ATES usage.

7.3.2.1.4 Changes in groundwater temperature

In the Netherlands, there are strict regulations on the temperature at which warm water can be infiltrated into groundwater. In most cases, this limit is 25°C, though in some instances (ATES in South Holland) a limit of 30°C is permitted. The basis of these infiltration temperature limits is multifaceted, where key concerns with infiltration of water exceeding these temperatures include, but are not limited to:

- Mobilisation of substances which have a negative impact on local groundwater quality such as organic compounds and arsenic;
- Increasing the rate of sulphate reduction by bacteria; and
- Precipitation of iron carbonate in the porous underground media, resulting in malfunction of the ATES system.

Sulphate reducing bacteria (SRB) growth is supported by the presence of organic carbon compounds such as alcohols and carboxylic acids. SRB use these carbon sources in combination with high-valence sulphur sources such as SO_4^{2-} (which is a common mineral found in aquifers) to gain energy for growth. The microbial sulphate reduction reactions result in the production of hydrogen sulphide (H_2S) and bicarbonate ions (HCO_3^-). In addition to these sulphate reduction reactions, the microbial reduction of iron-based minerals can also lead to the repartitioning of arsenic compounds held in the mineral phase to being dissolved in the groundwater, thereby increasing the arsenic content of the groundwater which may be used as a source of drinking water.

While the specific mechanism of the microbial redox reactions and subsequent generation and mobilisation of polluting substances is under debate, it is generally accepted that an increase in groundwater temperature can increase the rate of these redox reactions and therefore increase the risk and extent of groundwater contamination. Furthermore, cyclical abstraction and infiltration of water, particularly warm water, and when there is significant vertical variation in the composition of the original groundwater, can increase the degree of contamination through mixing between the pre-existing groundwater and the infiltrated water.

As well as the generation or mobilisation of specific pollutants such as arsenic, organic compounds, and hydrogen sulphide, the increased rate of microbial redox reactions can also influence the pH of the water body, as acidic hydrogen ions are consumed by the reducing microbial transformations, and basic bicarbonate ions are produced.

7.3.3 Environmental impacts at end-of-life

As discussed in Section 7.3.1, LTES can use a wide range of phase change materials which are potentially harmful to human health or the environment. At end-of-life stages, and during PCM replacement, the waste PCM must be disposed of responsibly to avoid exposure to people, or the environment, based on the hazard profile of the substance. In addition, some inorganic PCMs such as sodium hydroxide are highly corrosive, and regular inspections of the systems should be in place to limit the risks of loss of containment from the system due to corrosion damage (Streicher et al., 2005). The extent to which PCMs can be cycled before degradation is not well reported and is likely dependent on the specific PCM used. The same can be said for recycling of the PCM at the end-of-life, where degraded PCMs may be repurposed in other industries or refined to be used in new secondary materials. However, evidence for this point on circular economy and recycling of PCMs could not be found at this time.

7.4 Social impacts of TES technologies

No literature that investigates the public perceptions or social acceptance of TES was found, so this is clearly an area that would benefit from research. The environmental and health impacts of TES are limited and, along with the fact that the evidence about the other ESTs considered in this project finds largely positive or neutral attitudes towards these technologies, it may be reasonable to assume a similar lack of major concern about TES amongst the public. However, as with all technologies, this will depend on the information about TES that is or becomes available, where it comes from, and how it is framed.

Potential sites of public concern could be around environmental and biodiversity impacts of constructing TES plants and sourcing materials, as well as problems with heat and methane leakage, which would likely be particularly salient in communities closer to TES sites. More generally, there may be concern amongst people who have higher levels of environmental concern about the use of crude oil or palm oil in phase change materials. This might not translate to strong opposition but could be a relevant factor when individuals are weighing up support for one EST over another. More positive perceptions might include a sense that TES is more ‘natural’, in its use of natural resources, than other ESTs.

7.5 Remaining data gaps

The environmental impacts of TES appear to be reasonably well understood due to the relative simplicity of TES systems. However, it was noted that there was a lack of evidence specifically relating to the environmental impacts of TES systems, and much of the evidence base related to impacts which could be applicable to TES through extrapolation.

Specific knowledge gaps which were not clear at the time of writing this report included the pathways which substances, such as PCMs and heat transfer fluids, may enter the environment, and the rate at which leakage and loss of containment of these substances can be expected.

7.6 Conclusions and summary

The literature surrounding the deployment and environmental impacts of TES is surprisingly sparse, particularly considering the volume of technical information and diverse range of TES technologies available as well as the growing expectation of the role that TES will play in the future of England's heating solutions at dwelling and district levels.

For TES systems which make use of underground geological features such as rock formations or shallow aquifers for BTES and ATES respectively, it is foreseen that environmental implications will arise from the anthropogenic warming of underground natural systems. This could potentially disturb chemical reactions and microbial life which may result in proliferation of harmful pathogens which may be transferred to drinking water.

For above-ground systems such as LTES and THS, the type of material used to store the thermal energy plays a big role in determining its potential impacts. Due to the vast range of materials which can be used in these technologies, the impacts associated with their loss to the environment can range from relatively benign (in the case of paraffin waxes and fatty acids) to severe (in the case of caustic substances such as sodium hydroxide). It is also noted that many phase change materials are sold as proprietary products and the details of the substances used are not typically disclosed publicly. It would be a benefit if the substances used in real commercial LTES systems were known as this would help determine the specific environmental impacts resulting from their leakage to the environment.

In almost all cases of TES, a heat transfer fluid is required to charge and discharge the store. This is typically water but can also be mixed with ethylene or propylene glycol as an antifreeze agent. The spillage or leakage of this antifreeze into nearby land or groundwater would also pose significant environmental issues.

8 Battery Energy Storage Systems (BESS)

8.1 Introduction

The pursuit of a sustainable and environmentally responsible future has led to an unprecedented global commitment to achieve net zero emissions. Central to this transformative journey is the development and integration of innovative technologies that can store and manage renewable energy efficiently. Battery Energy Storage Systems (BESS) have emerged as a linchpin in this endeavour, offering a compelling solution to harness, store, and distribute clean energy effectively. This part of the report explores the critical role that BESS plays in the context of Net zero goals.

Battery storage technologies have evolved significantly over recent years, showcasing their adaptability and versatility. From lithium-ion to flow batteries, these technologies encompass a range of solutions, each tailored to specific applications and grid requirements. Lithium-ion batteries, for instance, are well-suited for short-term energy storage, such as smoothing out intermittent renewable energy sources. In contrast, flow batteries excel in long-duration energy storage, making them ideal for grid stability and backup power.

This report will investigate seven types of BESS technologies:

- Lithium-ion
- Lead-acid
- Nickel-cadmium
- Alkaline
- Sodium-ion
- Redox flow
- Organic redox flow

In order to understand the expected deployment timelines and environmental impacts of these technologies, it is important to first understand their mode of action and implementation requirements. Therefore, this section presents a brief overview of each of these BESS technologies and factors of their operation which have an impact on their deployment and environmental impact. The information provided should be considered in the context of the batteries being used in grid-scale applications, whereby the battery systems are directly connected to the grid for storing excess energy to be discharged during peak-hours. Batteries in this application need:

- A high energy density, so as to keep the footprint of the site to a minimum;
- A high efficiency, so energy is not ‘wasted’ during charge and discharge cycles;
- A low self-discharge rate to reduce energy ‘wasted’ during storage; and
- A long service life of the battery cell, so battery pack replacement can occur less frequently to maintain sustainability.

BESS facilities will also require high storage capacities when dealing with energy directly from the grid, although this parameter is not dependent on the technology deployed. It is important to note that BESS can be deployed in smaller applications and are not exclusive to being a part of the grid.

8.1.1.1 Lithium-ion

Lithium-ion batteries operate based on the movement of lithium ions between the cathode and anode. During charging, lithium ions move from the cathode to the anode through an electrolyte, which is typically a lithium salt dissolved in a solvent. This movement creates a potential difference, storing electrical energy. During discharge, the lithium ions flow from the anode back to the cathode, releasing electrical energy for use.

Lithium-ion batteries are the favoured choice for grid-scale storage, due to their favourable characteristics. These systems typically exhibit high energy density, often ranging from 120 to 260 watt-hours per kilogram (Wh/kg), making them well-suited for applications where a large amount of energy needs to be stored efficiently (International Energy Agency, 2023). In terms of efficiency, lithium-ion batteries report a round-trip efficiency of approximately 85-90%, which means they can effectively convert and retrieve a significant portion of the stored energy (Kebede et al., 2022). Additionally, their service life typically ranges from five to fifteen years. Their self-discharge rates are relatively low, with a typical self-discharge rate of 0.1-0.3% per day. This combination of high energy density, good efficiency, long cycle life, and low self-discharge rates makes lithium-ion batteries a compelling choice for grid-scale storage systems.

8.1.1.2 Lead-acid

Lead-acid batteries function using a chemical reaction between lead dioxide (PbO_2) at the positive plate and sponge lead (Pb) at the negative plate in a sulphuric acid (H_2SO_4) solution. During discharge, this reaction results in the release of electrical energy and the formation of lead sulphate ($PbSO_4$) and water (H_2O). Charging reverses this process, converting lead sulphate and water back into lead dioxide and sponge lead.

Lead-acid batteries, while not as prominent or popular as lithium-ion batteries, possess distinctive characteristics that render them valuable in certain applications. One of their notable attributes is their robust round-trip efficiency, generally averaging 70-80% (Kebede et al., 2022). This moderately high efficiency allows lead-acid batteries to effectively convert and retrieve a significant portion of the stored energy, which is particularly advantageous in applications where energy conservation is critical. However, they exhibit lower energy density, typically ranging from 30 to 50 Wh/kg (Kebede et al., 2022), compared to lithium-ion batteries, making them bulkier and heavier for the same energy storage capacity. Lead-acid batteries are also characterised by a moderate self-discharge rate, typically around 0.1-0.3% per day, depending on the design. Their service life spans from five to fifteen years, depending on factors such as depth of discharge[25] and maintenance (Kebede et al., 2022).

While lead-acid batteries may not match the energy density of lithium-ion batteries, they still find use in applications where their high efficiency, cost-effectiveness, and reliability are prioritised, such as in backup power systems or uninterruptible power supplies (UPS). However, they face competition from newer technologies like sodium-ion, redox-flow, and organic redox-flow batteries, which offer improved energy density and cycle life, potentially relegating lead-acid batteries to more niche applications away from grid-scale energy storage techniques. Moreover, lead's inclusion on the Candidate List for its toxicity to reproduction means lead-acid battery manufacturers will have to apply for an authorisation after the sunset date, inherently complicating the manufacture and trade processes.

8.1.1.3 Nickel-cadmium

Nickel-cadmium (Ni-Cd) batteries use nickel oxide-hydroxide at the positive electrode and cadmium at the negative electrode. During discharge, cadmium undergoes oxidation, releasing electrons and creating electrical energy, and the nickel oxide-hydroxide electrode experiences reduction. Recharging the battery reverses these reactions, restoring the original materials.

Nickel-cadmium batteries have faced a decline in popularity due to advances in battery technology. These batteries are notable for their competitive round-trip efficiency, typically measuring around 70%, which allows for effective energy conversion and retrieval. However, they exhibit relatively low energy density, typically ranging from 50-75 Wh/kg (Kebede et al., 2022). Additionally, nickel-cadmium batteries suffer from a memory defect from inefficient charge-discharge cycles (Bergmann et al., 2015) which can cause the battery to reduce in capacity. Despite this, nickel-cadmium batteries are reported to have a self-discharge rate of 0.03-0.6% per day (Kebede et al., 2022) which can be a limiting factor in applications with extended periods of inactivity. However, given the nature of grid-scale energy storage techniques and their frequency of use (typically no more than 24 hours of stored energy) this should not be a significant issue. Service life varies, but nickel-cadmium batteries can last between 10 and 20 years (Kebede et al., 2022) under regular use, although it is important to reiterate the effect that inefficient charging and discharging can have on maximum capacity.

While they may not measure up to the energy density and environmental concerns of lithium-ion batteries, nickel-cadmium batteries are still employed in certain situations where their technical maturity and commercial availability are important. However, they face competition from newer technologies like sodium-ion, redox-flow, and organic redox-flow batteries that offer improved energy density, cycle life, and environmental sustainability.

[25] Depth of discharge refers to the extent to which energy is cycled into and out of the battery. A high depth of discharge can accelerate battery aging (Kim & Shin, 2023).

8.1.1.4 Alkaline

Alkaline batteries employ an electrochemical reaction, typically with zinc as the anode and manganese dioxide as the cathode. The electrolyte is an alkaline (basic) solution. During discharge, zinc reacts with manganese dioxide, releasing electrical energy and forming zinc oxide and manganese hydroxide. Charging is not practical for most alkaline batteries, and they are considered non-rechargeable.

While alkaline batteries are suitable for many portable and low-capacity applications, they face significant limitations when it comes to grid-scale energy storage. The fundamental constraint lies in their non-rechargeable nature. Unlike technologies such as lithium-ion or redox flow batteries, which are designed for repeated charge and discharge cycles, alkaline batteries are not economically viable for large-scale energy storage systems. Their single-use design not only results in higher long-term costs but also generates substantial waste in applications demanding frequent maintenance and replacement of batteries. Furthermore, their energy density is comparatively lower, and they are less adept at handling the variable and extended energy storage requirements typical of grid-scale operations. These factors collectively render alkaline batteries ill-suited for the rigorous demands of grid-scale energy storage, where efficiency, longevity, and sustainability are paramount. Considering these limitations, alkaline batteries will not be evaluated further.

8.1.1.5 Sodium-ion

Sodium-ion batteries use sodium ions in lieu of lithium ions for charge and discharge. They operate in a similar manner to lithium-ion batteries but with different electrode materials. During charging, sodium ions move from the cathode to the anode, and the reverse happens during discharge. Sodium-ion batteries frequently employ carbon-based materials, such as hard or soft carbons, as anodes, while a variety of sodium transition metal oxides, such as NaCoO2 and Na2/3Fe1/2Mn1/2O2 (Li et al., 2020), are commonly used for cathodes. These materials accommodate sodium ions within their crystal structures during charging and discharge.

In the context of grid-scale energy storage, sodium-ion batteries offer specific attributes that make them a noteworthy technology. These batteries have been recorded to demonstrate a round-trip efficiency of up to 93% (Rudola et al., 2021), ensuring effective energy conversion. However, their energy density, usually in the range of 100-150 Wh/kg (Abraham, 2020), is lower than lithium-ion batteries, potentially leading to larger storage systems. While specific values for the daily self-discharge rate could not be obtained during the literature review, one study reported that sodium-ion batteries tend to “suffer from higher self-discharge rates compared to their lithium-ion counterparts” (Tesfamhret, 2017). Moreover, rapid degradation stems from the substantial mass disparity between sodium ions, which are three times heavier than lithium ions. This weight differential imposes significantly greater mechanical stress on the dynamic interaction between the anode and cathode, leading to the detrimental impact on the integrity of the anode material (Flash Battery, 2023).

Despite these considerations, the abundance of sodium as a resource is integral to its assessment as a relevant battery technology for grid-scale energy storage, as well as its superior environmental sustainability compared to older battery technologies like lead-acid and nickel-cadmium. Furthermore, recent advances in sodium-ion battery technology have accelerated its popularity amongst battery manufacturers, such as Contemporary Amperex Technology Co., Ltd. (CATL), who have advertised investment into the technology to compete with the robust lithium-ion battery (Contemporary Amperex Technology Co., 2021).

8.1.1.6 Redox flow

Redox-flow batteries (RFBs), available in various types such as polysulphide bromine, vanadium redox flow, and zinc bromine, employ a straightforward operational mechanism. RFBs consist of two distinct electrolyte tanks, one housing a positive electrolyte and the other a negative one. A selectively permeable membrane separates these electrolyte solutions, allowing for ion transfer while preventing intermixing. During the charging process, an external energy source induces redox reactions in these solutions, causing one electrolyte to undergo oxidation and become positively charged, while the other experiences reduction, acquiring a negative charge (Luo et al., 2015). These charged electrolytes are preserved until energy is required. In the discharging phase, the charged electrolytes are conveyed through an array of electrochemical cells, where reversible redox reactions are initiated, releasing electrical energy. The specific chemistry of each RFB type, such as the use of vanadium, polysulphide bromine, or zinc bromine, influences the redox reactions and overall performance characteristics (Kebede et al., 2022).

Flow batteries constitute an intriguing category of electrochemical energy storage systems with notable characteristics that distinguish them from other battery technologies. Flow batteries are known for their commendable round-trip efficiency, which typically falls in the range of 65% to 85% (Kebede et al., 2022). However, their energy density is relatively low compared to lithium-ion batteries, with values typically ranging from 10 to 35 Wh/kg (Kebede et al., 2022). This lower energy density results in larger and heavier system designs. Flow batteries exhibit a favourable self-discharge rate, retaining energy efficiently over extended periods; although, they can experience self-discharge if the liquid electrolyte is replaced[26] (Kebede et al., 2022). They also have competitive service life, reaching approximately 15 years following consistent continued use, as well as a near-zero daily self-discharge rate (Kebede et al., 2022).

The durability and longevity of redox flow batteries are supported by their ability to withstand a high number of charge and discharge cycles (Sun et al., 2021). In contrast, technologies like lead-acid batteries may exhibit a relatively shorter service life, making redox flow batteries a more cost-effective, long-term option for grid-scale energy storage.

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[26] The replacement of the electrolyte solutions is another method of ‘charging’ the battery (Cecchetti et al., 2023).

8.1.1.7 Organic redox flow

Building upon the principles of redox flow batteries, organic redox flow batteries share a similar operational mechanism. Organic redox flow batteries, like their redox flow counterparts, comprise two separate tanks containing liquid electrolyte solutions, one with a positive and the other with a negative electrolyte. These electrolyte solutions consist of organic molecules, often featuring redox-active groups capable of reversible oxidation and reduction reactions. During charging, an external power source initiates the oxidation of the organic molecules in the positive electrolyte, leading to the accumulation of electrons and ions. In the subsequent discharge phase, the oxidised organic molecules are reduced back to their initial state, releasing stored energy, and yielding electrons and ions, which migrate to the negative electrolyte tank.

The key contrast lies in the materials employed. In organic redox flow batteries, organic molecules, such as quinones, viologens, or phenazines, serve as the active components in the electrolytes (Kwabi, 2021). These molecules play a central role in the redox reactions that store and release electrical energy. In redox flow batteries, on the other hand, inorganic materials like zinc bromine or vanadium-based solutions are typically used. Conversely, one study reported on the popular use of quinones as the active reactants in organic redox flow batteries and their high daily self-discharge rate caused by the high rate of decomposition (Kwabi, 2021).

Given their emerging status, organic redox flow batteries are subject to ongoing research and development efforts to address challenges, optimise performance, and enhance their durability and safety. While the potential advantages of organic redox flow batteries are promising, it is important to acknowledge that they have not yet undergone the extensive testing and real-world application that more established battery technologies have experienced. As such, their future development and integration into various energy storage applications, including grid-scale use, remain areas of active exploration and innovation.

8.1.1.8 Summary

Table 16 presents a summary of the characteristics of each battery type. Lithium-ion batteries showcase superior energy density and efficiency, making them a favoured choice for grid-scale storage, with round-trip efficiencies averaging 85-95% and energy densities ranging from 120 to 260 Wh/kg. Lead-acid batteries offer competitive round-trip efficiencies of 70-80%, albeit with lower energy densities of 30-50 Wh/kg, making them suitable for specific applications such as backup power systems. Nickel-cadmium batteries, while efficient, suffer from memory defects and comparatively lower energy densities of 50-75 Wh/kg. Sodium-ion batteries present high efficiencies of up to 93%, yet lower energy densities of 100-150 Wh/kg and potential degradation due to higher self-discharge rates. Redox-flow batteries exhibit moderate efficiencies ranging from 65% to 85% and low energy densities of 10 to 35 Wh/kg, compensated by a favourable service life of approximately 15 years. Organic redox-flow batteries, although promising, necessitate further development to address challenges like high self-discharge rates. While lithium-ion batteries currently lead in grid-scale energy storage, emerging technologies like sodium-ion and redox-flow batteries offer viable alternatives with potential for further innovation and adoption in the future.

Table 16: Summary of battery technology parameters

Battery Type	Energy density (Wh/kg)	Round trip efficiency (%)	Service life (years)	Self-discharge rate (%/day)
Lithium-ion	120-260	85-95	5-15	0.1-0.3
Lead-acid	30-50	70-80	5-15	0.1-0.3
Nickel-cadmium	50-75	~70	10-20	0.03-0.6
Alkaline	-	-	-	-
Sodium-ion	100-150	Up to 93	-	-
Redox flow	10-35	65-85	15	~0
Organic redox flow	-	-	-	-
Source: **Abraham, 2020; Bergmann et al., 2015; International Energy Agency, 2023; Kebede et al., 2022; Luo et al., 2015; Rudola et al., 2021; Tesfamhret, 2017**				

8.1.2 The role of BESS in achieving Net zero

BESS play a pivotal role in addressing the global imperative of achieving net zero goals. The field of battery technology has witnessed remarkable growth, characterised by iterative improvements in battery design and performance year-on-year. This continual innovation contributes significantly to the progress toward net zero emissions by enhancing the efficiency and sustainability of energy storage. The versatile application of batteries in the broader community, ranging from portable electronic devices to the burgeoning electric vehicle market, has accelerated the advancement of battery technology. As these industries expand, they drive the demand for better-performing batteries with higher energy density, more efficient charging capabilities, and improved cycle life. This ongoing demand spurs innovation and research in the battery sector, fostering the development of more efficient and sustainable energy storage solutions for grid-scale applications.

BESS also offers an array of parameters that render them ideal for grid-scale energy storage. Their fast charge and discharge times, long duration storage capabilities, and capacity for large-scale energy storage make them indispensable assets. Additionally, BESS exhibits resilience to the somewhat unpredictable nature of periods of low electricity demand and intermittent energy generation from renewable sources, such as wind or solar power, due to their reduced charging time and shorter response time (milliseconds to seconds; Castillo and Gayme, 2014).

On the 6th of December 2023, the UK Department for Business & Trade published the UK battery strategy, which outlines the government's plans for the UK to accomplish a robust battery supply chain by 2030. Following consultation via a Call for Evidence from businesses and stakeholders, the UK will initiate their "DESIGN-BUILD-SUSTAIN" approach to achieve a net zero transition (UK Department for Business & Trade, 2023). The initiative will aim to support innovation throughout the battery supply chain and maintain a robust and future-proof battery market, all while improving the sector's sustainability. Over £2 billion will be invested into the UK's battery sector for the purposes of research and innovation activities (UK Department for Business & Trade, 2023).

The Faraday Institution published a report in June 2022 analysing the potential demand, capacity, and production of batteries for use in various sectors, including grid storage (The Faraday Institution, 2022). Figure 18 shows that the predicted demand of battery energy in the UK is set to reach nearly 200 GWh per annum in 2040, of which approximately 3% will be used for grid storage. This equates to a demand of roughly 6 GWh per annum of BESS, upon the assumption that all battery cells are manufactured inside the UK and that none are exported overseas.

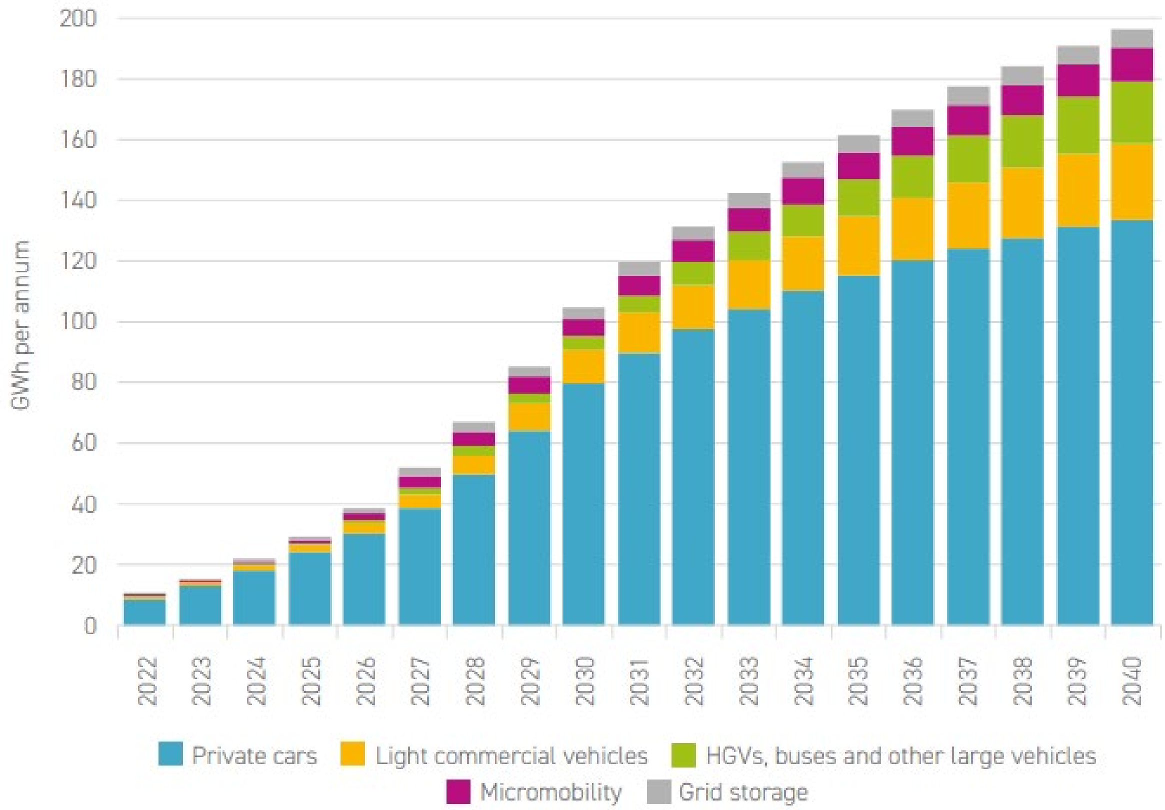

Figure 18: Potential demand for UK-produced batteries by end use. *Source:* The Faraday Institution, 2022

8.2 Deployment trajectories of BESS technologies

8.2.1 Current BESS capacity and sites

England has already seen the successful deployment of a notable number of BESS facilities, representing a significant step towards advancing energy storage capabilities in a dynamic energy infrastructure. A concrete assessment of both the quantity of operational BESS and their overall capacity within the UK currently lacks definitive data. The BESS facilities in England use predominantly lithium-ion battery technology, aligning with the prevailing trend observed across diverse sectors. This strategic choice reflects the widespread adoption of lithium-ion batteries due to their high energy density, efficiency, and competitive pricing. According to a report published by the electricity system operator (ESO) for Great Britain[27] regarding the Future Energy Scenarios (FES), the UK currently has an operational BESS capacity of 2.8 GW, with a further 1.6 GW currently under construction (Electricity System Operator, 2023).

[27] https://www.nationalgrideso.com/ [Accessed November 2023].

The US Department of Energy's (DOE) global energy storage database (US Department of Energy, 2023) has recorded the operation of 23 BESSs in the UK, of which 14 are located across England (Sandia National Laboratories, 2023). These sites, and accompanying information, can be seen in Table 17. A study of this database concludes that the preferred battery technology at these facilities is lithium-ion; although lead-acid, sodium-nickel, and flow batteries were reported to also be in use across the UK. The total power provided by these energy systems sum to 12.3 MW, although it should be recognised that the primary function of several of these sites is not to provide electricity during periods of low demand, but rather assist in the operation of the grid, i.e., voltage smoothing, frequency regulation. It is important to acknowledge that the database does not have a clearly defined timeframe; however, the last reported newly operational BESS facility was August 2016, so it can be assumed that this is the latest entry into the database. After this period, there have been advances in BESS technology with facilities constructed during the timeframe spanning from 2016 to 2023. The UK's Department for Energy Security and Net Zero renewable planning database (updated January 2024) shows that, since 2018, 14 BESS sites with a capacity of ~50 MW and above became operational in England[28], as shown in Table 18. The database does not record what technology the BESS facilities deploy.

Table 17: Operational BESS sites in England up to 2016 according to the US Department of Energy's global energy storage database (US Department of Energy, 2023).

Location	County	Battery technology	Rated Power (kW)	Year Constructed
Leighton Buzzard	Bedfordshire	Lithium-ion	6,000	U
Darlington	Durham	Lithium-ion	2,500	U
Wolverhampton	West Midlands	Lithium-ion	2,000	2016
U	Dorset	Lithium-ion	598	U
Butleigh	Somerset	Lithium-ion	300	2016
U	Berkshire	U	250	2015

[28] 74 BESS sites between 0.1 MW and 100 MW in total.

Location	County	Battery technology	Rated Power (kW)	Year Constructed
Milton Keynes	Buckinghamshire	Sodium-nickel	250	U
Darlington	Durham	Lithium-ion	100	2013
Denwick	Northumberland	Lithium-ion	100	U
Slough	Berkshire	Lithium-ion	75	2012
Maltby	South Yorkshire	Lithium-ion	50	U
Darlington	Durham	Lithium-ion	50	U
Wooler	Northumberland	Lithium-ion	50	U
Wokingham	Berkshire	Flow	5	2015

U – Undetermined

Source: Sandia National Laboratories, 2023

Table 18: Operational BESS sites in England post- 2018 according to the UK Department for Energy Security and Net Zero's Renewable Energy Planning Database

Location	County	Rated Power (kW)	Year Constructed
Capenhurst	Cheshire	100,000	2023
Wickford	Essex	99,980	U
Richborough	Kent	50,100	2022
Melksham	Wiltshire	50,000	2021
Malmesbury	Wiltshire	50,000	2022

Location	County	Rated Power (kW)	Year Constructed
Minety	Wiltshire	49,990	2023
Sale	Greater Manchester	49,900	2020
Rotherham	South Yorkshire	49,900	2021
Swindon	Wiltshire	49,900	2018
Cottingham	Humberside	49,900	2022
Liverpool	Merseyside	49,900	2022
Liverpool	Merseyside	49,900	U
Walsall	West Midlands	49,900	U
U – Undetermined			
Source: DESNZ (2024b)			

EDF, the largest generator of carbon-free electricity in Britain, currently has three operational BESS sites in England (Kent, Oxfordshire, Cambridgeshire) with a total capacity of 155 MW. A further four sites (Bedfordshire, Suffolk, West Midlands, Merseyside) are reported to be currently under construction (Table 19). All four sites will have a capacity of 50 MW and are estimated to be fully operational by the end of 2024 – increasing England's BESS capacity by 200 MW[29].

[29] Note that information has not been identified on the specific technology that will be used at these sites.

Table 19: EDF operational and under construction BESS sites

Location	County	Rated Power (MW)	Year Constructed
Bramford	Suffolk	57	Under construction, complete Spring 2024
Oxford	Oxfordshire	55	July 2022
Kemsley	Kent	50	October 2021
Sundon	Bedfordshire	50	Under construction, complete Spring 2024
Burwell	Cambridgeshire	50	January 2022
Coventry	West Midlands	50	Under construction, complete early 2024
Kirkby	Merseyside	50	Under construction
Source: EDF renewables, n.d.			

In early 2023, InterGen were awarded a 15-year agreement by the UK government to supply the UK with power from its Gateway battery storage project on the Thames Estuary, with construction estimated to be complete by 2025. The new site is reported to provide 450 MW of power to 450,000 dwellings once operational (InterGen, n.d.a), and will cost an estimated £300 m to construct. The site is reported to be one of the world's largest BESS facilities, and "more than ten times the size of the UK's largest operational battery project" (International Trade Administration, 2021).

8.2.2 Planned BESS capacity and sites

8.2.2.1 Potential pathways

The ESO for Great Britain produced a 2023 report concerning FES to provide a visualisation of how the UK can meet the requirements of net zero, as well as the predictions of what state the energy sector will be in upon full, partial, or non-completion of the net zero goals (Electricity System Operator, 2023). Moreover, this report is the basis for the scoping information of the UK's Department for Business & Trade's UK Battery Strategy call for evidence (Department for Business & Trade, 2023), which closed on 28th September 2023.

The ESO report considers four scenarios regarding the future of energy in GB Electricity System Operator (2023):

- Falling Short (Net zero targets not met);

- System Transformation (Net zero targets met through zero-emissions technology);
- Consumer Transformation (Net zero targets met through carbon capture technology);
- Leading the Way (Net zero targets met through zero-emissions technology and carbon capture technology).

With these considerations and scenarios in mind, an evaluation of Figure 19 reveals that the ESO predict that the capacity of BESS will more than triple by 2030 regardless of the UK's progression towards the net zero goals. Moreover, despite the stagnant nature of the Fall Short scenario, by 2050 there is expected to be over six times the capacity of BESS than in 2022.

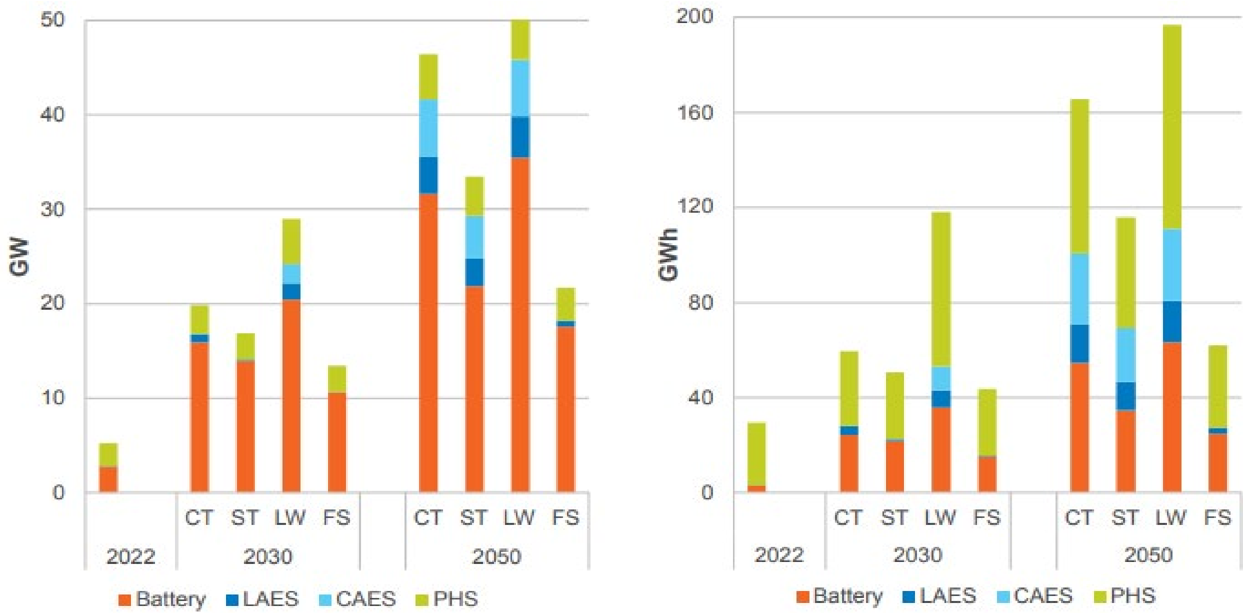

Figure 19: Electricity storage installed capacity (left) and output (right) prediction
Source: Electricity System Operator, 2023

8.2.2.2 Planned sites

Energy specialists from InterGen plan to combine their open cycle gas plant in Lincolnshire with a BESS facility in order to provide up to 1.1 GWh to 500,000 dwellings (InterGen, n.d.b). The site received Town and County Planning Permission in June 2023.

EDF have planned the implementation of 20 sites across England, all with a capacity of up to 50 MW. These are detailed in Table 20. Should all of these sites be granted consent by their local authorities, and construction is successful, EDFs total battery energy storage capacity will increase by 400 MW.

Table 20: EDF planned BESS sites

Location	County	Planning application date
Indian Queens	Cornwall	February 2022
Landulph	Cornwall	U
Alverdiscott	Devon	U
Exeter	Devon	U
Tauton	Somerset	U
Barewood Copse	Dorset	September 2023
Bolney	West Sussex	U
Laleham	Surrey	U
Iver	Buckinghamshire	U
Seabank	Bristol	U
Wymondley	Herfordshire	U
Braintree	West Sussex	U
Oldburry	West Midlands	U
Willington	Derbyshire	U
Bredbury	Greater Manchester	U
Carrington	Greater Manchester	U
Kirkby	Merseyside	Summer 2024
Kearsley	Greater Manchester	U
Spennymoor	County Durham	U

Location	County	Planning application date
Harker	Cumbria	U
Source: **EDF renewables (n.d.)**		

8.2.2.3 Consented sites

EDF Energy has received consent to build two BESS sites in Sellindge, Kent, and Norwich, Norfolk. The former will have a capacity of 49.9 MW, will utilise Lithium-ion battery technology, and will be operational in early 2025. The Norwich site will have a capacity of 114 MW in a 1.2-hectare area. Planning was consented by South Norfolk Council on 20th August 2023, although there is no publicly available estimate on when the site will be operational.

8.2.3 Remaining capacity required for Net zero and possible locations

It is clear that the deployment of BESS technology is set to rapidly increase over the coming years. It is not possible, and not the aim of this report, to predict exactly where these sites will be as BESS do not have specific geographical constraints like many other technologies evaluated in this report; one of the only necessities regarding location of the site is the ability for the facility to be connected to the grid. However, the Department of Business and Trade publishes the locations and life-cycle status of battery projects in the UK on a quarterly basis. Figure 20 is an extract from this database, showing the locations, size and status of planned and operational BESS projects in England at the time of writing this report (April 2024).

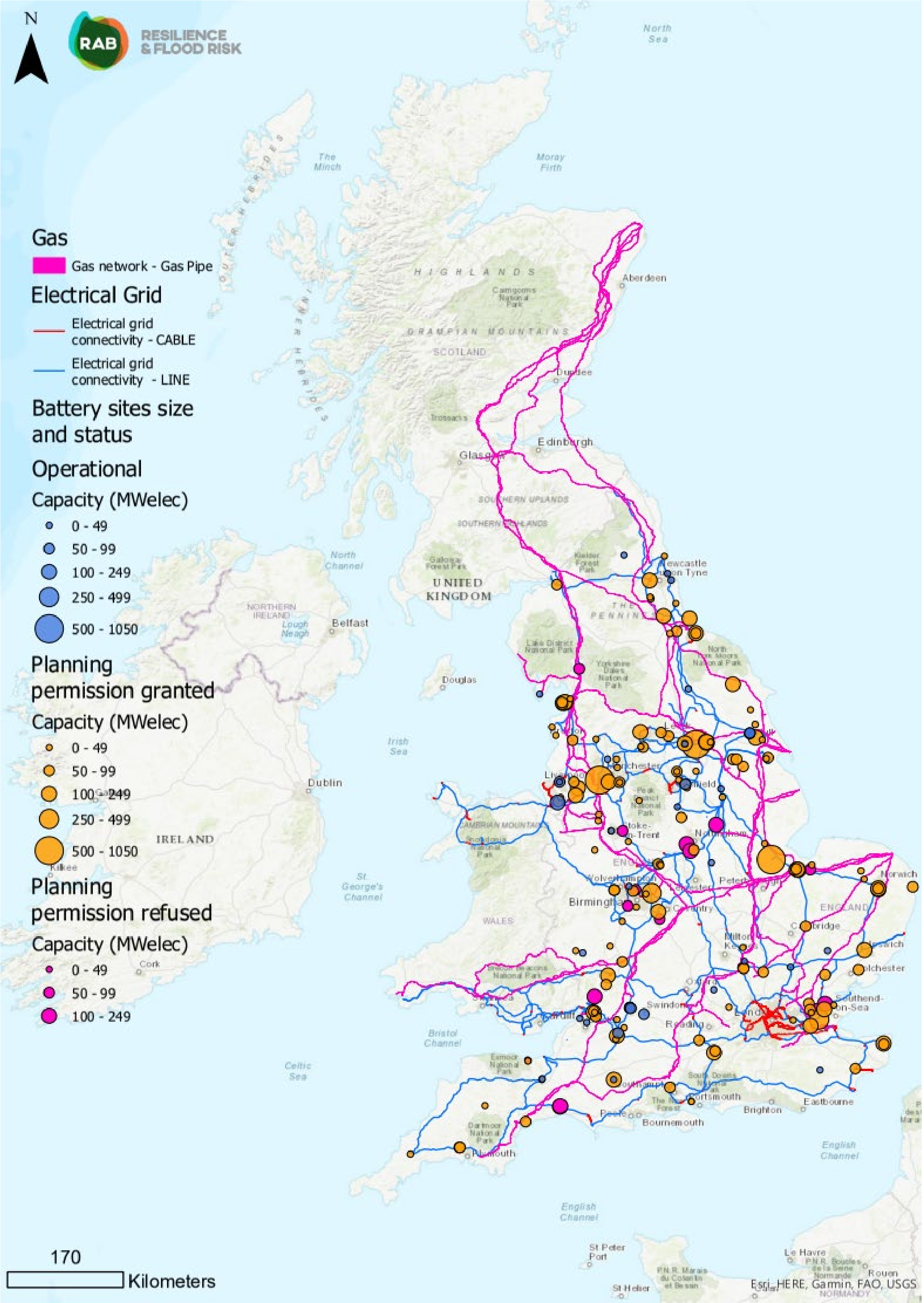

Figure 20 Map of operational, planning permission granted, and planning permission refused BESS sites in England with their planned or installed power capacity.

Basemap: Esri. "Topographic" [basemap]. Scale Not Given. "World Topographic Map". 26 October 2017. https://www.arcgis.com/home/item.html?id=7dc6cea0b1764a1f9af2e679f642f0f5. (15 November 2023).

Other sources: DESNZ, 2023c; www.nationalgrid.com, n.d.; www.nationalgas.com, n.d..

8.3 Environmental impacts of BESS

8.3.1 Environmental impacts during construction

Many of the battery technologies discussed previously contain a multitude of components manufactured from materials which exhibit hazardous properties. The components which typically contain the highest mass of hazardous materials are as follows:

- Electrode;
- Binder;
- Electrolyte; and
- Membrane.

Exposure to these components during the manufacturing stage of the battery life cycle may prove harmful to the workers constructing the batteries. Moreover, in the event of damage to the battery or battery casing, workers of BESS sites may also be exposed to the hazardous materials and their associated health risks. In most battery technologies, parts of the electrode may contain instances of cobalt or nickel, which are identified as carcinogenic substances, while the binder and electrolytes commonly contain per- and polyfluoroalkyl substances (PFAS), which are also highly hazardous (WSP, 2023).

The manufacture of lithium-ion batteries in England for the use of grid-scale storage applications is not a common practice; the relatively small amount of lithium processed within the UK tends to be used in the manufacturing of electric vehicle batteries or consumer goods. Historically, lithium-ion batteries are imported from other countries with a much larger capacity for the processing of lithium, such as China (Da et al., 2021).

Considering these factors, it is likely that England will remain reliant on imported critical raw minerals from other countries in their manufacture of batteries. This is reflected in a trade deal between the UK and seven other countries to “help diversify supply chains and increase the UK’s security of supply”, despite multiple firms providing funding for projects relating to the extraction or refining of lithium in the south-west of England (UK Department for Business & Trade, 2023). Therefore, it can be assumed that the mining of lithium in the UK for the use of utility-scale batteries is unlikely for the foreseeable future. Consequently, the environmental damages caused by the mining of lithium, such as land degradation, water contamination, and air pollution, can be considered offshored.

Much like the lithium used in battery cells, the raw materials used in the manufacture of the supporting structure of the BESS are expected to be sourced internationally. This is primarily attributed to the incorporation of electrical circuits used in various auxiliary systems in the BESS such as an HVAC system, battery management system, and safety systems. These circuits often originate from overseas manufacturers due to their assembly requiring minerals not available/abundant in the UK, such as cobalt, gold, and nickel.

The location of the BESS site is also a necessary consideration. Independent of the technology of battery cell used, the site will undoubtedly present a large mechanical strain on the underlying geology upon which it is situated. An impermeable surface would be a requirement not only to facilitate the operation of heavy machinery during construction, but to also mitigate the risk of mechanical instability of the ground in the event of firefighting fluids or extreme weather conditions altering the permeability of the underlying geology. During the construction phase, adequate containment and drainage plans are a necessity to mitigate the likelihood of the aforementioned effect of firefighting fluid run-off.

8.3.2 Environmental impacts during service

The stationary, non-mechanical nature of BESS facilities leads to different environmental impacts to be considered compared to other storage systems. Another unique factor to be considerate of is the potential hazards caused by facility failure contingencies, e.g., the impact of using specialised firefighting techniques to combat thermal runaway. The nature of these impacts will vary depending on the location/surrounding environment of the site.

BESS is not currently regulated by the Environmental Permitting Regulations (EPR), although Defra has plans to introduce the technology into the regulation. Likewise, the storage technology is not regulated by the COMAH Regulations; although, it was raised a potential Bill by conservative MP Dame Maria Miller in September 2023 (Dame Maria Miller, 2022).

8.3.2.1 Energy consumption

To operate as efficiently and as safely as possible batteries within the BESS need constant thermal stability provided by an HVAC system managed by a thermal control system (Immendoerfer et al., 2017). This is the case for all battery technologies since thermal runaway is possible in each system, albeit from different causes. This thermal control system, vital for ensuring the safe and efficient functioning of the BESS, requires electricity to operate. The generation and transfer of this electricity will add to the environmental burden typical to that of standard grid operations, such as air pollution[30], contributing to the overall environmental footprint of the BESS. There is currently no standardised system in place to achieve ideal thermal performance within the BESS (Lin et al., 2023), as each system will have different requirements due to a multitude of factors including, but not limited to, energy capacity, battery technology, and containment size. Moreover, HVAC refrigerants can contain perfluoroalkyl substances (PFAS) which are

[30] If a traditional method of electricity generation is used, such as the combustion of natural gas or oil.

persistent and potentially toxic to human health and the environment. PFAS refrigerants typically decompose to trifluoroacetic acid which is known to be harmful to the environment (David et al., 2021). These refrigerants can leak into the surrounding area during the service life of the HVAC system, affecting the local soil and groundwater.

8.3.2.2 Thermal runaway risk

Thermal runaway in a BESS is a critical concern that can occur due to factors such as overheating, external damage, or internal defects within the battery cells. This phenomenon triggers a self-sustaining increase in temperature, leading to a cascading series of events with severe consequences (Marsh, 2021).

For lithium-ion batteries, thermal runaway can result in the release of hazardous materials. The electrolyte, typically composed of lithium salts in organic solvents, can vaporise, potentially leading to chemical fires and toxic fume emissions (Klein et al., 2021). Lithium contamination of the ground may occur if these substances leak into the environment, posing risks to soil and water quality.

In the context of sodium-ion batteries undergoing thermal runaway, several hazardous materials may be released, posing risks to human health and the environment. Specific materials include toxic gases like hydrogen fluoride (HF) and hydrogen chloride (HCl), both corrosive and harmful to respiratory health (Kishida, 2020). The combustion of flammable electrolyte components, mainly organic solvents, can generate volatile organic compounds, contributing to air pollution. Additionally, the breakdown of materials during thermal runaway can release particulate matter, including metal oxides, presenting respiratory hazards and environmental contamination risks (Eshetu et al., 2020). The intense heat generated in such incidents can further exacerbate dangers, potentially causing secondary fires and material damage.

Lead-acid batteries, if subjected to thermal runaway, can release sulphuric acid, posing a significant risk to the environment. This acid can contaminate the ground and any nearby groundwater aquifers, affecting soil quality and potentially leaching into water sources, impacting aquatic ecosystems.

Nickel-cadmium batteries undergoing thermal runaway can release toxic cadmium fumes and nickel oxide particulates (Chung and Manthiram, 2019). Cadmium, being a heavy metal, poses a risk of soil and water contamination, while nickel oxide may contribute to air pollution.

When applying for the planning permission of a grid-scale BESS site, applicants are encouraged to liaise with local fire and rescue services before submission.

Up to 6 micrograms/litre of PFAS was measured in firewater from battery firefighting, and approximately 3,600 litres of water are used over 30 minutes to extinguish a battery fire (Quant et al., 2023a). These PFAS incumbent fluids will transfer into the surrounding ground and have the potential to contaminate local groundwater supplies, affecting both human and ecological health detrimentally, if there are no containment or drainage systems in place.

In response to a fire at a BESS site, firefighting crews may use PFAS incumbent foams to combat the fire; although, the use of PFAS firefighting foams is set to change. Until the 4th July 2025, PFAS firefighting foams may only be used in cases where they are fully contained upon use. After the aforementioned date, they have no permitted use and alternative solutions will have to be deployed instead.

8.3.2.3 Replacement batteries

The environmental impact of replacing batteries in a BESS is largely derived from the production and transportation of new batteries. The manufacturing of lithium-ion batteries involves resource-intensive processes, including the extraction and processing of lithium, cobalt, and nickel, contributing to habitat disruption and potential soil and water contamination – an example of which being the leaching of sulphuric acid into the surrounding site during certain methods of lithium extraction (Rioyo et al., 2022). Sodium-ion batteries, while less reliant on scarce resources, still involve energy-intensive manufacturing processes, impacting air quality and GHG emissions. As discussed previously, however, these processes are likely to be offshored from England, and as such, there will be no direct impact from the extraction and processing of the aforementioned raw materials.

Lead-acid batteries, commonly used in BESS, have comparatively lower energy density but entail the mining and smelting of lead, posing risks of lead pollution. Nickel-cadmium batteries involve the extraction of nickel and cadmium, potentially contributing to the pollution of soil and water with hydroxides. Vanadium flow batteries, although more durable, require vanadium electrolyte production, impacting ecosystems during mining and processing.

The transportation of batteries to BESS sites involves the importation of raw materials or finished batteries from overseas, resulting in notable environmental impacts. The shipping or air transport of batteries over large distances contributes significantly to GHG emissions, and air pollution. Importing raw materials for battery production can entail resource depletion, extracting finite resources and leading to habitat disruption and biodiversity loss. Additionally, the transportation process itself requires energy, primarily derived from fossil fuels, further adding to the carbon footprint associated with battery production and transportation. Importing batteries or their components introduces complexity to the supply chain, involving multiple transportation stages, which may lead to inefficiencies, delays, and increased environmental impact. Moreover, transportation poses inherent risks of accidents, spills, or leaks during transit, potentially resulting in the release of hazardous materials, thereby posing risks to both the environment and human health. These factors must also be considered during the transportation of redundant batteries away from the site before they undergo recovery or disposal.

8.3.3 Environmental impacts at end-of-life

8.3.3.1 Disposal of battery packs

8.3.3.1.1 Lithium-ion

Improper disposal of lithium-ion batteries, especially at the end of their utility-scale BESS life, poses significant environmental threats due to hazardous materials like lithium, cobalt, and nickel. These materials, if not properly managed, can lead to severe ecological and human health risks. Moreover, the improper disposal of lithium-ion batteries may also lead to fires due to lithium’s high reactivity with water.

Lithium, a key component in lithium-ion batteries, can contaminate soil and water, affecting plant life and aquatic ecosystems (Daim et al., 2012). In higher concentrations, it may disrupt nutrient uptake in plants and harm aquatic organisms, subsequently impacting the entire food chain. Cobalt, another common component, poses risks due to its potential to cause respiratory and cardiovascular issues in humans. Additionally, cobalt exposure can harm aquatic life, with detrimental effects on fish and other organisms. Nickel, found in various battery components, can contaminate soil and water, leading to toxic effects on plants, aquatic life, and human health.

Historical disposal methods, including landfilling and incineration, are unsuitable for lithium-ion batteries due to the risk of hazardous material[31] release. Landfilling poses the risk of leaching toxic metals into the soil, affecting groundwater and potentially leading to long-term environmental contamination (Institute for Energy Research, 2021). Incineration can release harmful emissions and fails to recover valuable materials, contributing to resource depletion.

Recycling is the better environmental option, aligning with the United Kingdom's regulations like the Waste Electrical and Electronic Equipment (WEEE) Regulations (Legislation.gov.uk, 2013). Lithium-ion battery recycling prevents hazardous materials from entering landfills or being incinerated. Advanced recycling practices efficiently extract valuable metals like lithium, cobalt, and nickel, reducing the need for new resource extraction and contributing to the circular economy (Lander et al., 2023). Batteries manufactured using recycled materials have been shown to have identical performance metrics to batteries using pristine materials; although, a review of current literature suggests that no currently operational BESS site primarily uses recycled critical materials in its battery cells (Wang et al., 2023). These practices play a crucial role in achieving net zero goals by promoting resource efficiency, reducing GHG emissions, and minimising the environmental impact of BESS deployment.

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[31] Lithium-ion batteries contain lithium, cobalt, nickel, and manganese.

8.3.3.1.2 Lead

Lead, a primary component in lead-acid batteries, is highly toxic. Inappropriately discarded batteries can result in lead leaching into the soil and water, endangering plant life and aquatic ecosystems. This contamination poses severe health risks for humans, including neurological damage, developmental issues in children, and cardiovascular problems in adults (World Health Organization, 2021). Sulphuric acid, another essential component, contributes to soil and water acidification, negatively impacting ecosystems and aquatic life.

Traditional disposal methods, such as landfilling and incineration, are ill-suited for lead-acid batteries. Landfilling risks lead leaching, causing persistent environmental contamination, while incineration can release harmful emissions.

Efficient recycling processes recover lead and other materials, preventing environmental contamination and reducing the need for new resource extraction. Adopting responsible waste management practices, particularly recycling, is essential to mitigate environmental risks associated with lead-acid batteries and support a sustainable approach to BESS deployment.

8.3.3.1.3 Nickel-cadmium

Similarly, to lead-acid batteries, the improper disposal of nickel-cadmium batteries upon the end of life of the BESS site would cause significant harm to the environment due to the leaching of critical heavy metals such as nickel and cobalt (Lin et al., 2016; Yu et al., 2014). Moreover, most nickel in the consumer market is from recycled sources (Nickel Institute, n.d.) and, therefore, the landfilling of nickel-containing batteries prevents this reuse leading to additional mining of nickel.

8.3.3.1.4 Sodium-ion

Recycling spent sodium-ion batteries and lithium-ion batteries entails similar environmental and economic challenges, yet the recycling of sodium-ion batteries faces a notably higher economic barrier. While lithium-ion battery recycling can prove financially viable due to the recovery of valuable metals like lithium and cobalt, the lower material valuation associated with spent sodium-ion batteries diminishes the economic feasibility of recycling and may impede industrial recycling efforts. This economic disparity underscores the importance of addressing the financial hurdles specific to sodium-ion battery recycling to ensure the sustainable and efficient management of these batteries at the end of their lifecycle (Zhao et al., 2023).

As with lithium-ion batteries, sodium-ion batteries are not suitable for traditional disposal methods, such as landfilling and incineration, due to the release of hazardous critical heavy metals into the environment.

8.3.3.1.5 Redox flow

Improper disposal of vanadium redox flow batteries poses environmental risks due to the potential release of vanadium, electrolytes, and other chemicals into the soil and water. These hazardous materials can lead to soil contamination and groundwater pollution, impacting ecosystems and potentially harming human health. In contrast, proper disposal methods, including recycling, aim to mitigate these environmental risks.

A study published in 2021 concluded that the manufacture of vanadium redox flow batteries with 50% of recycled electrolyte, the source of the highest environmental impact, results in 45.2% lower terrestrial acidification and 11.1% lower global warming potential (Da et al., 2021). Moreover, it has been found that up to 97% of the electrolyte for vanadium redox flow batteries can be sourced sustainably, meaning much of the harmful material can be recycled upon the BESS's end of life.

Due to the novel nature of redox flow battery technology for grid-scale applications, there is little information regarding the recyclability of the entire system upon end of life. Furthermore, no redox flow BESS of such scale has been commercially operational and reached the end of its service life, so there is no existing data to evaluate.

8.3.3.1.6 Organic redox flow

Much like their nonorganic counterpart, the electrolyte from organic redox flow batteries can be mostly sourced sustainably. Moreover, further study has been carried out to evaluate the suitability of sourcing historically petroleum-based components with bio-alternatives, such as biomass waste, algae, and cellulose (Bamgbopa et al., 2022). This practice would make a high proportion of the materials required for operation sustainably sourced, these materials could then be re-used in future organic redox flow battery projects. There is no literature yet describing the suitability of recycling a high proportion of the BESS components.

8.3.3.2 Disposal of HVAC system

PFAS present in HVAC systems pose significant environmental risks, especially upon reaching the end of their service life. Improper disposal of HVAC systems containing PFAS can result in the release of these substances into the environment, leading to contamination of soil, water, and air. PFAS have been linked to various adverse health effects in humans and wildlife, including developmental issues, immune system dysfunction, and cancer (ECHA, n.d.).

8.3.3.3 Deconstruction of BESS site

As for the decommissioning of the BESS site, the process would involve similar environmental emissions to the construction of the site, where noise and a reduction in air quality from decommissioning machinery and traffic would be the main drivers for environmental damage.

8.4 Social aspects of BESS technologies

Social scientific research on battery storage is diverse, reflecting the different applications and scales at which batteries are – and could be – deployed. There is a small body of literature on public perceptions and acceptance of grid-scale battery storage, which will be discussed here. However, as this literature shows, it is important to consider the fact that most people are familiar with batteries through small-scale domestic and individualised usage and this familiarity is likely to inform their understandings and perceptions of grid-scale battery technologies.

8.4.1 Public perceptions

8.4.1.1 Safety

Battery storage has received some recent media attention, including from the BBC, mostly in relation to domestic fires related to charging electric bicycles and vehicles and poor working conditions in the lithium mining industry (BBC, 2023a). Social scientific research shows that members of the public are also somewhat concerned about safety in relation to BESS, including especially from fire and toxic risks (Brennan and van Rensburg, 2023); a German study found electrosmog was an additional concern (Baur et al., 2022).

8.4.1.2 Neutral, positive and negative perceptions

Thomas et al. (2019) conducted deliberative workshops discussing different ESTs in the UK. The participants' perceptions of grid-scale battery storage in the workshops ranged between benefits, risks, and ambivalent or conditional views. Benefits centred on perceptions that BESS would reduce carbon emissions and enable more renewable energy. Ambivalent or conditional views tended to relate to appropriate and desirable siting and the need for health and safety checks. Risks related to siting, health and safety concerns, pollution from mining and disposal, a lack of durability, concerns about vandalism, and a sense of the technology being unrealistic.

Research participants in Ireland seem to accept that batteries could provide a solution to intermittency in renewable energy distribution (Brennan and van Rensburg, 2023) and British participants in deliberative workshops associate battery storage technologies with technological progress (Thomas et al., 2019). The handful of studies reviewed here found evidence of positive attitudes towards battery storage in Germany (Baur et al., 2022) and in the UK (Ambrosio-Albalá et al., 2020), where the public 'has strong expectations about the technology, its benefits and its management' (Ambrosio-Albalá et al., 2020: 1).

In addition to safety risks, some research participants have expressed concerns about the cost of battery storage in the UK (Ambrosio-Albalá et al., 2019) and an unwillingness to pay more for decarbonised electricity in Ireland (Brennan and van Rensburg, 2023). In Germany, additional concerns related to 'the environmental impact of the technology (production and disposal, unsustainable raw materials, impairment of flora and fauna)' and ‘concerns about costs related to the use of the technology (disposal costs, decline in land and property values, high taxes)' (Baur et al., 2022: 7).

8.4.2 Acceptance and opposition

Existing research shows generally favourable attitudes towards BESS in the UK, Germany and Canada (Baur et al., 2022). In their UK study, Thomas et al. (2019) found that, although participants expressed some concerns about safety and environmental risks in relation to BESS, they also discussed measures to mitigate these risks including safety certification and recycling, which the authors suggest ‘points the way to regulatory pre-conditions on which future acceptability may rest' (Thomas et al., 2019: 9). In a nationally representative survey of British people about distributed energy storage using batteries, Ambrosio-Albalá et al. (2020) found that only age was a significant demographic factor in acceptance of this technology, with younger people having more positive attitudes towards battery storage and being more willing to install a battery system in their dwellings.

In Ireland, where the government is committed to BESS to support increased wind power generation, Brennan and van Rensburg (2023) found that while most respondents were willing to accept battery storage, nearly a quarter felt that the risks of this technology did not outweigh the benefits. The reason for this negative perception is unclear, but they suggest that fears about negative impacts on the environment, health and property prices, along with uncertainty or a lack of information about the technology, may drive this opposition. In the UK, it was found that effect plays a part in acceptance of BESS (Thomas et al, 2019), which has also been found in other studies of ESTs:

> “The likelihood of installing a domestic battery system is shaped by a favourable global attitude towards energy storage as a whole, interest and hope, and the level of worry and aversion to the technology. ... [E]xpectations of being affordable and of being environmentally friendly were positively associated with the likelihood of installing a battery at home and with the willingness to invest in a battery system for domestic use.” (Ambrosio-Albalá et al., 2020: 11).

While this finding obviously relates to the domestic level, it may be reasonable to assume that attitudes similarly play a part in acceptance of larger-scale battery technologies, though this would be an area to investigate in future research.

8.4.2.1 Siting and local acceptance

As with other ESTs, research on BESS shows that there can be a difference between people’s general acceptance of this technology and their local acceptance – i.e. they show positive attitudes towards it in general terms but are more hesitant to accept it in their local area. This may reflect concerns about a loss of living space or fire and explosion risks (Baur et al., 2022). In Ireland, a majority of respondents expressed unwillingness or uncertainty about having a BESS plant located within 1 km of their dwelling because of negative perceptions of its impact on health, environment, property prices, and the appearance of the landscape (Brennan and van Rensburg, 2023).

One issue that emerges in the literature on BESS is the specific question of community battery storage (Thomas et al., 2019). Ambrosio-Albalá et al. (2019) found that, in the UK, people could not imagine the case where a community would share a battery bank or pay to use a portion of the battery. For this possibility to be successful, it should be “a win-win situation”. That is, that the households would receive something in return, e.g. monetary compensation. Another issue that raised concern was how they could control and have knowledge about others’ – mostly neighbours’ – energy use (Ambrosio-Albalá et al., 2019).

An Australian study (Ransan-Cooper et al., 2022), by contrast, found that citizens felt that having a local, decentralised energy storage system would result in greater engagement in energy consumption and sense of agency amongst local communities. Others, including particularly Aboriginal participants, expressed a desire for financial benefits from such schemes to remain local. As the authors remark, ‘The desire for benefits to stay locally could be mediated through the design of the battery algorithm, but concerns around ownership and its linkages with benefits, belie the need to take a broader view beyond algorithm design to the broader funding, ownership and governance of the technology’ (Ransan-Cooper et al., 2022: 5).

8.4.3 Knowledge and familiarity

As with other emerging ESTs, the public’s knowledge of BESS is low (Ambrosio-Albalá et al., 2020), though as noted the concept of batteries is probably more understandable than other ESTs for most people, through their familiarity with batteries for personal appliances, electric vehicles and so on. As with other novel technologies, exposure to further information is desired by research participants (Brennan and van Rensburg, 2023) and can be associated with positive attitudes, though this will of course depend on their political, economic and ethical values, sociodemographic factors, as well as issues like affect and trust – and the ways in which information is framed and disseminated.

8.4.4 Trust

In their deliberative workshops, Thomas et al. found that issues of trust were related to people’s perceptions of batteries’ potential to facilitate self-sufficiency and the risks and benefits of (de)centralised energy systems:

> ”A salient discourse emerging around domestic batteries focused on how these might facilitate energy self-sufficiency. The capacity for batteries, and to a lesser extent other domestic and community storage technologies to enhance utilisation of locally produced energy and to deliver financial returns, both fed into a perception of storage as reducing reliance on national energy networks, and as empowering households and communities to take greater control of the energy they use. Combined with perceptions of energy companies as untrustworthy and exploitative, and some municipal authorities this discourse led to a feeling among some participants that maintaining a centralised energy system equated to maintaining an

undesirable status quo that denied users a say in how it is governed, with potentially deleterious impacts on consumers and the environment" (Thomas et al., 2019: 8).

8.4.5 Gaps in the literature and future research

As well as more evidence about attitudes towards BESS, one specific issue that would bear greater research is public perceptions of, and attitudes towards, the extraction of metals for batteries, which tends to happen in other countries, though lithium mining is due to commence in Cornwall in 2024 and has also been extracted in County Durham (BBC, 2023b). In Portugal, for example, where the government has set ambitious targets on net zero, there has been public debate and opposition to local lithium mining (Silva and Sareen, 2023). Research into British people's understandings and perceptions of this could help indicate whether concerns about lithium mining might inform opposition to lithium mining in the UK and/or societal and community acceptance of BESS.

8.5 Remaining data gaps

The compilation of evidence relating to the deployment and environmental impacts of BESS for energy applications highlighted the relative lack of available academic or commercial literature for battery technologies, apart from lithium-ion, that are suitable for BESS facilities. Lithium-ion batteries have, on the whole, received the highest R&D focus from industry in recent years, resulting in accelerated technological development. While it is expected that novel technologies, such as redox flow batteries, are subject to slower development (due to their minimal exposure to R&D), long-standing existing technologies, like lead-acid or nickel-cadmium, remain underdeveloped compared to their lithium-based counterparts.

This work found multiple sources of information regarding active BESS sites in England. A complication of the matter was the disparity of essential information available between sources. Each source of information provided varying degrees of detail of the BESS sites or omitted certain aspects of essential information altogether (the most common of which being what battery technology is utilised).

Organic redox flow batteries represent an emerging technology with promising potential for grid-scale energy storage applications. However, despite their advancements, there are notable data gaps that warrant further investigation and evaluation. One critical aspect is the lack of comprehensive studies assessing their suitability and performance at the grid-scale level. While initial research suggests promising characteristics such as high flexibility and scalability, a thorough understanding of their operational efficiency, reliability, and long-term performance in real-world grid environments is essential. Additionally, there is a need to address uncertainties regarding the environmental impacts associated with organic redox flow batteries, particularly concerning their sustainability and lifecycle analysis.

8.6 Conclusions and summary

The literature surrounding the deployment and environmental impacts of BESS is well developed. A number of sources including the electricity system operator (ESO) for England have given estimations on the number of batteries and BESS which will be both made and imported into England in the coming years. It has also been highlighted that the majority of BESS used in England will use lithium-ion technology, though emerging technologies such as vanadium redox flow batteries are beginning to enter the supply chain. A sizable number of BESS sites are currently undergoing planning or are awaiting construction and will be operational within the next few years.

The environmental impacts of BESS technologies and sites are also relatively well documented. The principal environmental risks associated with the operation of BESS arise from their constituent chemical substances. A major concern with lithium-ion batteries is their fire risk, which would result in the release of these substances (including cobalt, manganese, and PFAS) into the air, land, and water.

Construction of batteries involves the mining and refining of lithium metal, a significant proportion of which is proposed to take place in England at newly opened lithium mines. This mining and refining will be associated with a number of environmental implications, the clearest of which being the vast volume of water required to refine lithium ore into lithium metal.

The end-of-life environmental impacts of BESS are much less clear, as there are significant data gaps with regards to how and where batteries will be disposed of and what measures will be taken to limit the risks of fire and release of polluting effluents. It is clear that further research and transparency, in how England plans to deal with large volumes of battery waste in the coming years, would be highly beneficial in monitoring and controlling their environmental impacts.

The key potential environmental issues of BESS technologies, namely lithium-ion are summarised in Table 21 below.

Table 21: Summary of potential environmental issues associated with the construction, operation, and use of BESS

Receptor	Description	Environmental Issues
Air, land, and water quality	Mining and processing of raw materials such as lithium, sodium, cobalt, or nickel. Transportation of new battery cells to replace those at the end of their service life.	Likely offshoring of environmental impacts caused by mineral extraction. The first UK lithium mine is planned to be located in Cornwall. Geothermal energy from the deposits may offset GHG emissions from mining activities to a degree (Cornish Lithium Plc., n.d.) Water usage for processing lithium is vast (approximately 2 million tonnes per tonne of lithium). Potential effects on water availability and quality (Vera et al., 2023). Emission of GHGs from mining activities and equipment and battery transportation.
Terrestrial and aquatic ecosystems	Leaching of harmful materials in the end-of-life stage if mismanaged (i.e., not recycled, landfilled or incinerated in a sanitary way). Leaking of HVAC refrigerants into immediate environment during service and disposal.	Potential for heavy metals and other persistent, toxic or bioaccumulative battery materials (including electrolytes and perfluoroalkyl substances (PFAS) in structural components). HVAC refrigerants can be PFAS, which are persistent and potentially toxic to human health and environment. PFAS refrigerants typically decompose to trifluoroacetic acid which is known to be harmful to the environment (David et al., 2021).
Acute human or environmental health	In the event of thermal runaway of one or multiple battery cells, harmful constituent materials will be ejected into the immediate environment, as well as being carried by heat generated by combustion.	Exposure to lead may cause effects on the nervous system, kidney, and may lead to infertility (HSE, n.d.). Lithium exposure during pregnancy may cause developmental effects to the foetus, such as stunted growth (Harari et al., 2015).

Receptor	Description	Environmental Issues
	Firewater can leach into land, air, and water, carrying toxic elements and PFAS into nearby receptors.	Exposure to cobalt may cause cancer as well as neurological, cardiovascular, and endocrine deficits (Leyssens et al., 2017). Up to 6 micrograms/litre of PFAS measured in firewater from battery firefighting. Approximately 3,600 litres of water are used over 30 minutes to extinguish a battery fire (Quant et al., 2023b). The National Fire Chiefs Council recommends focus on the prevention of fires spreading from one battery to another by means of water-based firefighting intervention (National Fire Chiefs Council, 2022). PFAS-incumbent firefighting foams may be used to combat the fire, which could lead to its emission into the surrounding environment via soil and groundwater. PFAS are persistent and potentially toxic to human health and the environment. PFAS firefighting foams are set to be restricted in use in the UK as of July 2025.

9 Overall conclusions

9.1 Overview

This report has considered two research questions. It investigated the expected deployment trajectories of six energy storage technologies in England and it researched the environmental impacts associated with the construction and implementation, operation, and end-of-life of these technologies. This section provides overall conclusions on these two questions, and highlights key data gaps for further investigation.

9.2 Deployment of energy storage technologies

Table 22 provides an overview of the current and planned deployment for each energy storage technology, as identified through desk-based research. There could be additional sites that do not have much of a public profile and so have not appeared in the search results. However, the information presented does show that the extent of deployment of the technologies varies by type. Deployment ranges from the technology being in current use with more sites being developed (BESS), to no current sites in England but active research projects (CAES), to there not being any evidence of the technology being used commercially in England (UPHS). The lack of UPHS sites could reflect topographical limitations as much as technological ones, whilst the seemingly advanced position of BESS could reflect the prominence it is given in government policy documents. The publication of the UK Battery Strategy (UK Department for Business & Trade, 2023) during the lifetime of this project shows the attention being paid to BESS.

Table 22: Summary of current and planned sites/projects for the six technologies

Technology	Current sites	Planned sites/projects
Hydrogen storage	Above ground - no active sites in England Underground – existing large-scale site at Teesside	Above ground – (HyDUS (Hydrogen in Depleted Uranium Storage), Corre Energy Consortium and SHyLO (Storage of Hydrogen at Low pressure) Underground – Keuper Gas Storage Project (Cheshire), Rough (offshore) and Aldbrough Hydrogen Storage
Ammonia storage	Difficult to estimate given dynamic nature of the industry	Plans for sites at Liverpool (by Stanlow Terminals Ltd) and Immingham (by Air Products and Associated British Ports)

Technology	Current sites	Planned sites/projects
Compressed Air Energy Storage (CAES)	No commercial sites in England or wider UK	StrataStore Project, Cheshire (by EDF, iO Consulting, and Hydrostor) aims to store more than 100 MW of power
Underground pumped hydroelectric storage (UPHS)	No evidence of sites in England	No evidence of sites in England
Thermal energy storage (TES)	Many examples e.g. aquifers (London Chalk basin), manmade (e.g. Gateshead district heating scheme)	2 research projects including EXTEND, led by Sunamp Ltd, aiming to extend thermal battery duration and capacity, and ADSorB (Advanced Distributed Storage for Grid Benefit), led by the University of Sheffield
Battery energy storage systems (BESS)	UK operational BESS capacity of 2.8 GW	1.6 GW of capacity under construction (UK level)

9.3 Environmental impacts associated with the energy storage technologies

Given the variation in the extent to which the technologies have been deployed, it is not unexpected that there is also variation in the availability of evidence on their environmental impacts. For example, for BESS, the literature on environmental impacts appears well developed, yet for CAES there is far less information available. Considering the three life stages of construction, operation and end-of-life, all the technologies are likely to share various site-based impacts (e.g. noise, dust) that are associated with construction of a facility and its ultimate decommissioning/end-of-life. The following paragraphs therefore pick out the technology specific impacts that have been identified.

For hydrogen, impacts could result from leakage of fugitive hydrogen (note that levels of emissions from this are not clear). Other impacts are specific to the type of hydrogen storage. Metal hydride storage requires mining to source the metals, alongside associated water use for processing of ores. LOHC storage requires substances that may be persistent, bioaccumulative, and toxic. For underground storage in salt caverns, creation of new caverns results in the generation of brine which requires disposal. Underground storage also has implications for microbial activity, geochemical impacts in the caverns and geomechanical impacts due to the high pressures used.

Considering ammonia storage, there may be impacts from the emission of ammonia to the atmosphere (e.g. when filling storage tanks), as well as the potential for leakage and fugitive emissions during operation. These releases will have impacts for the global nitrogen cycle. There is also evidence that suggests that ammonia has been assimilated into soil, as ammonium is then converted to nitrous oxide by bacteria (Huang et al., 2019). Given the global warming potential of nitrous oxide, this has implications for climate change.

For CAES, there may be impacts from the creation of new salt caverns, similar to those for underground hydrogen storage (i.e. production of brine followed by the need for its disposal). The use of salt caverns could also result in impacts for geomechanical stability, as well as the type and extent of chemical reactions and microbial activity within the caverns. These may all be influenced by the storage of compressed air. CAES typically also uses water as a coolant, although an organic liquid coolant may be utilised. For D-CAES, it is important to remember that fossil fuels are used to raise the temperature of the expanded gas during operation. A D-CAES system will therefore result in emissions of GHGs, with the extent and composition of the emissions dependent on the fuel.

Environmental impacts resulting from UPHS relate to the use of water resources. There is also the potential for contamination of water dependent on the type of UPHS system deployed (e.g. if the lower reservoir were to be a disused mine, this could result in contamination by mine water which may include heavy metals). The use of underground caverns would likely result in similar impacts to other underground energy storage technologies, namely geological instability and potential release of gases due to excavation of the cavern and changes in pressure during operation.

For TES, the construction phase could impact local ecosystems (e.g. when boreholes are drilled or pipes installed). However, such impacts are likely to be shared by several of the technologies. Considering TES specifically, there may be impacts from the use and disposal of PCMs, which are used in LTES systems. Compounds used in some PCMs are toxic and therefore could pose hazards during operation and at end-of-life. Other impacts from TES systems could include the transfer of thermal energy to underground systems, alongside impacts for hydrology at the site, and salinisation as mixing occurs and reaction kinetics are altered.

For BESS, similar to metal hydride storage for hydrogen, there are likely to be impacts from the mining of raw materials. There may also be human health impacts associated with exposure of workers to hazardous substances during production of batteries. Dependent on where batteries are produced, there may be transport emissions associated with moving them to the storage site. Impacts associated with operation could include the leakage of HVAC refrigerants with implications for human health, as well as for terrestrial and aquatic ecosystems. If thermal runaway occurs, various hazardous materials may be emitted dependent on the battery type. For example, lead acid batteries may release sulphuric acid. Incidents at BESS sites may result in the leaching of contaminated fire water to the surrounding land and watercourses. Finally, at the end-of-life stage, there could be leaching of harmful materials (including heavy metals, HVAC refrigerants) if appropriate disposal of BESS components does not occur.

9.4 Gaps for future investigation

During the research, various evidence gaps were identified. This section highlights a few of the gaps for the individual technologies.

Gaps linked to hydrogen storage include:

- The volume of compressed and cryogenic hydrogen expected to be used in England in the next few years is not known. This links to another uncertainty around the extent to which above ground hydrogen storage technologies will be adopted;
- There is uncertainty regarding the number of cycles a hydrogen carrier can undergo and still retain its performance;
- There is minimal evidence on hydrogen leakage rates for underground storage; and
- There is limited understanding of the environmental impacts from sourcing and manufacturing the components needed for above ground storage systems.

Evidence gaps for ammonia, which show some overlap with the gaps for hydrogen, are listed below:

- There is a lack of robust storage capacity data;
- There is a lack of data on fugitive emissions;
- Sector specific breakdown of ammonia emissions data is limited; and
- The evidence linking ammonia to atmospheric nitrous oxide is unclear in that, whilst it has been determined that the conversion of ammonia to nitrous oxide happens, there is no evidence that quantifies the proportion of atmospheric nitrous oxide that originates from anthropogenic ammonia emissions.

For CAES, evidence gaps primarily related to example sites, with a lack of grid scale sites for A-CAES and a global absence of I-CAES sites from which to draw lessons and determine environmental impacts.

UPHS shows similarities to CAES in that the technology is evolving and there is still much to be learnt on which sites are suitable, what the optimal operating conditions are, and what the extent of environmental impacts might be.

For TES, there is also a lack of information on environmental impacts, with specific technology gaps including:

- The pathways by which PCMs could enter the environment; and
- The leakage rate of PCMs.

Key evidence gaps identified for BESS included:

- A lack of research literature on specific battery technologies (excluding lithium-ion batteries);
- Considerable variation in the level of detail available on existing BESS sites; and

- Lack of information on organic redox flow batteries, in particular, evidence on their suitability and performance at the grid-scale level.

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11 Glossary

Term/acronym	Definition
BAT	Best available techniques
BESS	Battery energy storage system
BEIS	Department for Business, Energy & Industrial Strategy (in existence until 2023 when it was replaced by the Department for Energy Security and Net Zero, the Department for Science, Innovation and Technology and the Department for Business and Trade)
BREF	BAT reference document
CAES	Compressed air energy storage
COMAH	Control of Major Accident Hazards
DESNZ	Department for Energy Security and Net Zero
DGF	Depleted Gas Field
EIA	Environmental Impact Assessment
GHG	Greenhouse gas
HVAC	Heating, ventilation and air conditioning
Industrial cluster	Industrial clusters are areas with several industrial sites that produce materials such as chemicals, cement and ceramics
LCOS	Levelised cost of storage
MoF	Metal-organic frameworks
TES	Thermal energy storage

Term/acronym	Definition
TRL	Technology readiness level
UPHS	Underground pumped hydroelectric storage

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