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Revising the theoretical storage potential of hydrogen in UK salt caverns: a multi-criteria assessment of the east coast of England

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Abstract: Hydrogen is expected to play a crucial role in decarbonizing hard-to-electrify industries and in serving as an energy storage vector in the UK's net zero transition. While many studies estimate the hydrogen storage capacity in onshore and offshore UK, they often do not account for feasibility constraints. This study reassesses the hydrogen storage capacity potential of salt caverns in England's east coast, defining a new 'storage reserve potential'. This integrates the geographical distribution of Zechstein halite-bearing strata with land-use restrictions, including existing and planned industrial, social and environmental constraints. By considering high-level technical constraints, this study refines previous storage estimates, reducing them by *c.* 95%. Despite this significant reduction, the region still offers a hydrogen storage capacity of more than 22 TWh of. However, major challenges remain, particularly the long timescales required to develop and commission new salt cavern storage at scale, limiting its feasibility by 2050. These findings highlight the need for strategic planning and investment to overcome deployment challenges. The methodology presented can be applied to other key regions in the UK and internationally, providing a more realistic assessment of hydrogen storage potential in salt caverns.

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Hydrogen has emerged as an increasingly important component in the transition from fossil fuels to low-carbon energy sources (IPCC 2023). Low-carbon hydrogen not only has the potential to deliver the grid-scale energy storage required to manage a future electricity grid based on variable renewable energy but can also support the decarbonization of hard-to-electrify sectors such as heavy industry, transportation and shipping. The UK, alongside other governments, has set out clear targets for hydrogen use as part of its strategy to reach net zero emissions by 2050. The National Energy System Operator (NESO 2025*a*, *b*) forecasts hydrogen demand in the UK to be 182–393 TWh a^{-1} by 2050. Additional interim Clean Power 2030 targets also heavily rely on hydrogen to be used for low-carbon dispatchable power, alongside biomass and natural gas with carbon capture and storage. These ambitious targets underscore the critical need for an extensive hydrogen storage infrastructure to balance production and demand fluctuations and to deliver the decarbonization of industry, heat and transport.

Published estimates of UK hydrogen storage requirements range between 11 and 100 TWh by 2050 (BEIS 2021; National Grid ESO 2023; The Royal Society 2024; NESO 2025*a*, *b*). The range of demand for storage is associated with uncertainty around the likely end users for hydrogen, specifically hydrogen for domestic heating and power generation. Irrespective of the uncertainty in the hydrogen storage requirements, in the UK a significant effort is required to mobilize storage on the scale anticipated by 2050, particularly given that only 0.025 TWh is theoretically currently available (UK Parliament 2023).

Storage technologies

Subsurface options that are currently considered for large-scale underground hydrogen storage include depleted oil and gas fields, salt caverns, lined rock caverns, and shafts (Fig. 1). The current technical development is either at a conceptual level or in the stage of preparing large prototypes and pre-commercial pilot plans.

The UK currently has *c.* 0.025 TWh of hydrogen storage in three salt caverns at Teesside (UK Parliament 2023). These caverns currently operate commercially as wet static storage and are at an operational deployment technology readiness level (TRL) of 9. As the demand and use case for hydrogen expands, it is likely to bring a need for caverns that are operated dry, with a cushion gas and cycled rapidly, and many times throughout the year (The Royal Society 2024). Although fast-cycle storage caverns for hydrogen have yet to be piloted in the UK, the UK's Hydrogen Storage Business Model (HSBM) is looking to support this mode of operation.

Several proposed projects will look to add up to 8 TWh of onshore salt cavern storage for hydrogen as either seasonal (long-duration) or load shifting (medium-duration) energy systems (Fig. 2), these include the Aldbrough Hydrogen Pathfinder project, the Aldbrough Hydrogen Storage project, the HyNet Keuper Gas Storage project and the UKEn Portland project.

Salt cavern storage potential in the UK

Estimates of the salt cavern hydrogen storage capacity potential range from hundreds to thousands of terawatt-hours (TWh) and have been reviewed in several recent publications (East Coast Delivery Plan 2023; House of Lords Science and Technology Committee 2024; The Royal Society 2024). The storage potential of hydrogen in salt caverns is naturally dependent on the geology and is largely focused in three onshore areas across the UK: Cheshire, Wessex and England's East Coast region (Evans and Holloway 2009), with other areas (e.g. West Lancashire, and offshore East Irish Sea and Southern North Sea) also offering potential areas for storage.

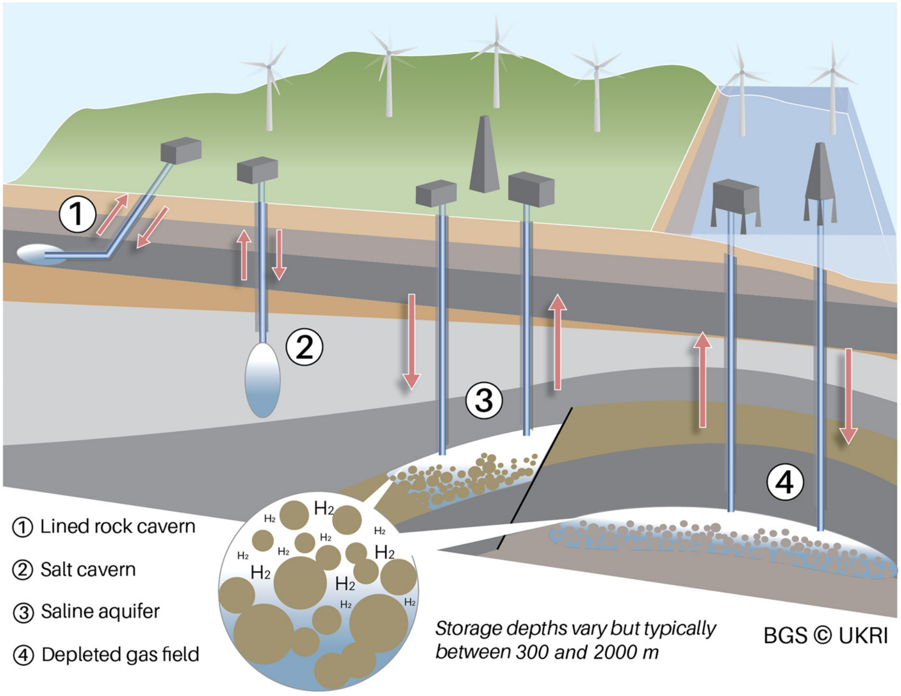


Fig. 1. A schematic overview of different technologies considered for hydrogen storage. Source: from Armitage (2025).

The East Coast region contains two industrial clusters that have been identified by the UK Government for prioritized industrial decarbonization; they are the Teesside and Humber industrial zones. The clusters are geographically well located to benefit from the underlying Permian halite geology. The regional onshore salt field is typically between 350 and 1800 m below ground level and has historically been exploited for underground gas storage in Teesside and Aldbrough (East Yorkshire) (Evans and Holloway 2009).

The East Coast holds significant potential to be utilized further for salt cavern storage of hydrogen, with various authors having presented studies estimating storage capacity for onshore salt caverns (Evans and Holloway 2009) (Fig. 3). Caglayan *et al.* (2020) initially presented a storage capacity estimate of *c.* 1000 TWh by assuming highly idealized salt deposits with uniform depth and thickness across the entire extent of the salt deposit for the UK South Permian Basin. Following this, current best estimates of storage capacity ranged from 747 to 1465 TWh, meaning that developments would require thousands of caverns to achieve this, assuming an individual cavern has a capacity of up to 170 GWh. Here, Williams *et al.* (2022) used regional geological data to characterize target salt formations, applying a stand-off distance from unsuitable halite accumulations (shallow, thin or poor quality) and appraised eligible development land by considering the spatial distribution of surface infrastructure such as roads and railways.

Notwithstanding the huge variability in the range of storage capacities, it is important to consider the development programme of large underground storage facilities (typically 10–20 caverns: Table 1), which can take in excess of 10 years to plan, permit and develop (e.g. HyPSTER 2024). Therefore, the ability to exploit the storage potential within the time frames required to support the UK's net zero targets poses a significant challenge.

The successful and safe deployment of large-scale hydrogen storage in salt caverns hinges on the ability to utilize the subsurface in the most optimal way within the hydrogen economy, linking hydrogen production facilities, transportation, storage and end users. Therefore, the spatial planning and the re-risking of the initial site selection (e.g. National Energy System Operators Strategic Spatial Energy Planning: Harati *et al.* 2024; NESO 2025*a*, *b*) are a critical first step in project pre-feasibility studies.

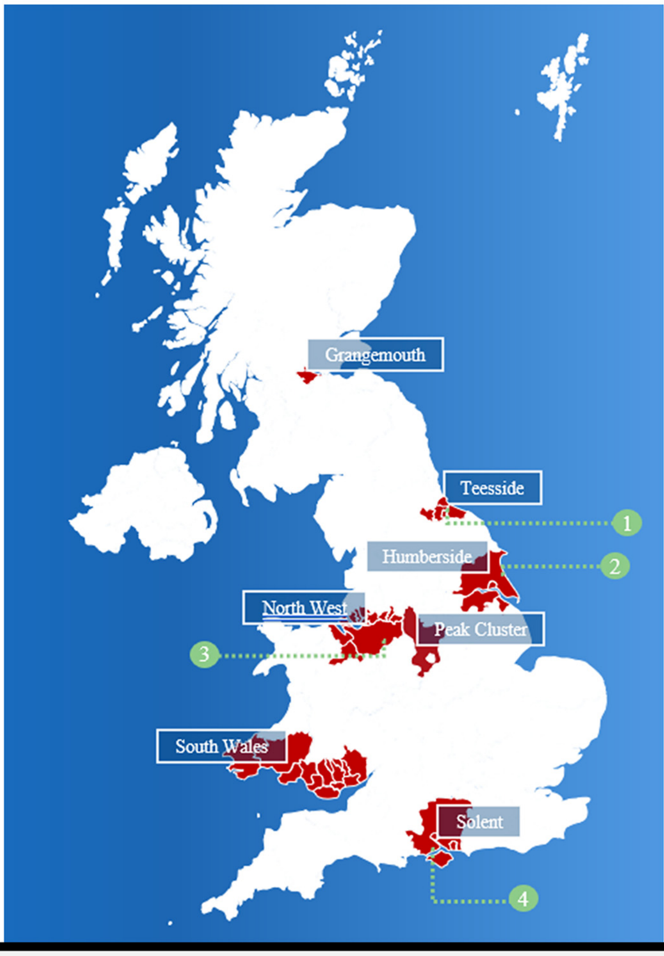
To assist in de-risking the initial site selection activities and increase the likelihood that storage projects will progress at the pace required to meet our net zero targets, the presented study refines previous storage capacity estimates. Although previous studies (Caglayan *et al.* 2020; Allsop *et al.* 2023; Barnett *et al.* 2024) have delivered in detail a geological estimate of the total resource available (e.g. Williams *et al.* 2022), few have comprehensively accounted for the surface and subsurface constraints to development of such a large infrastructure deployment. This study offers a revised energy storage estimate of hydrogen in salt caverns by considering viable geology and a comprehensive set of surface constraints to development, and terms it a reserve potential.

Purpose of this study

It is important to differentiate between 'resource' and 'reserve' potential in the context of this study. The resource potential is the total volume of salt geologically present and potentially suitable for hosting salt caverns, and the reserve potential is the portion of the resource that is likely to be technically feasible and economically and socially viable to develop caverns now. Further study is, however, required to establish if sites are truly technically feasible, and economically, environmentally and socially viable. The portion of the resource that is truly technically feasible and economically and socially viable is termed the 'reserve potential'.

This study addresses some of these uncertainties by: (1) developing a geological model of the East Coast region, specifically delineating the halite members within the Boulby Halite (BbH) and Fordon Evaporite (FoE) formations; and (2) completing a 3D geospatial analysis that integrates surface and subsurface constraints to indicatively present suitable land parcels that could be utilized for cavern development.

Halite stratigraphy of the East Coast region is modelled on a regional scale, accounting for regional structures such as faulting and folding, and a spatial assessment of land-based constraints such as urban environments, major infrastructure or environmentally sensitive sites. In a refinement of previous studies of the reserve potential (e.g. Parkes *et al.* 2018; Williams *et al.* 2022; Allsop *et al.* 2023; Lankof and Tarkowski 2023; Huang *et al.* 2024), the East



	Developer(s)	Project	Capacity	COD	Status	Summary
1	سابك sabic	Teesside Hydrogen Storage	0.03 TWh	2025-30	Brine-filled to surface	Commissioned in 1972 to become the first globally deployed hydrogen salt caverns. One of four sites deployed pre-2016; rest in the USA.
2	sse Thermal equinor	Aldborough Hydrogen Storage [& Pathfinder]	0.32 TWh [0.02 TWh]	2028	FEED	To support the hydrogen economy in the Humber by upgrading the former Aldborough natural gas store (commissioned in 2011).
3	INEOS Inovyn	Keuper Gas Storage Project	1.38 TWh	2030 (phase 1)	Feasibility	To be the third gas storage project at the Holford Brinefield site through creation of an additional 19 gas storage cavities for hydrogen.
4	UKOG ENERGY FOR BRITAIN	Portland Port Energy Storage	6 TWh[2]	2028	Concept	Development of Bcm of hydrogen-ready salt cavern methane storage, as part of an energy hub at the former Royal Navy Port in Dorset.

Fig. 2. (Top) Subsurface hydrogen storage sites (1–4) are projected onto a map indicating the UK's industrial clusters, which are shown in red. (Bottom) A summary of hydrogen storage projects on onshore UK. Bcm, billion cubic metres; COD, Commercial Operation Date; FEED, Front-End Engineering and Design.

Coast region is split into a hexagonal mesh prior to geospatial analysis, where each hexagon is of a size similar to existing developments of clusters of caverns in the UK. By integrating the geological model with the land-based constraints, available land parcels in the form of hexagons are determined. In each parcel, caverns are modelled with idealized geometries based on published concepts (Noroozi *et al*. 2025).

It is acknowledged that although this study continues and refines the research made by others, it is still limited by the inherent granularity of a regional-scale assessment of the reserve potential. There is a need to pursue further site-specific investigation, analysis and stakeholder engagement to begin to approach an estimate of the reserve potential energy storage. Having said that, it is also hoped that the findings of the study will provide supporting data to the growing evidence that the UK's long-duration energy storage requirements cannot be met through just one technology but will require a mix of technologies, and associated research and development de-risk alternative technologies.

Geology

Host geology

The subsurface geology of onshore NE England and the adjacent offshore region has the potential capacity to contribute significantly to fulfilling the UK's future long-duration energy storage needs and

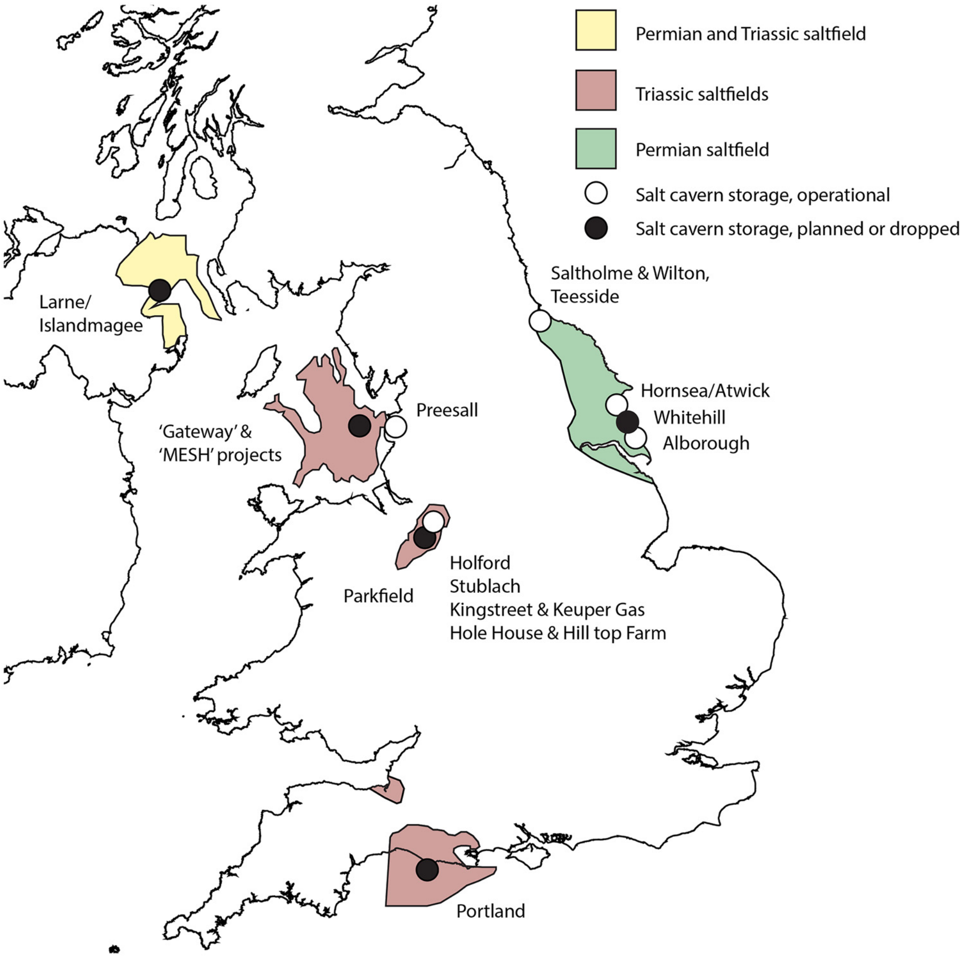


Fig. 3. UK salt fields, with operational and planned salt cavern facilities. Source: adapted from Evans and Holloway (2009).

carbon dioxide sequestration targets (Underhill *et al.* 2023; Barnett *et al.* 2024) (Fig. 3). Underlying this region is the Southern Permian Basin and the Zechstein Group. Historically, the region has been a significant energy producer for hydrocarbons since the 1960s, with exploration of the Southern North Sea for natural gas. However, recently the region has become the target of carbon capture and storage (CCS) and hydrogen storage investigations (Fyfe and Underhill 2023*a*, *b*).

The Upper Permian Zechstein Group is a cyclical carbonate–evaporite succession that was deposited extensively in partially restricted marine conditions across NW Europe in the Southern and Northern Permian basins (Cameron *et al.* 1992; Johnson *et al.* 1994; Cameron and Ziegler 1997; Peryt *et al.* 2010; Fyfe and Underhill 2023*a*).

Cyclical carbonate–evaporites sequences mark the onset of the Zechstein Group, resulting from episodic flooding and isolation of the basin that led to the development of five major transgressive and regressive cycles, which in the UK are partially preserved and referred to as the (Zechstein) Z1–Z5 cycles (Cameron *et al.* 1992; Johnson *et al.* 1994; Peryt *et al.* 2010). A typical Zechstein cycle is represented by a thin transgressive mudstone overlain by a carbonate interval, deposited during periods of normal marine salinity; the carbonates are overlain by anhydrites, which were deposited as the basin became restricted and more saline, and then by halite and K- and Na-salts (Armitage *et al.* 2024). However, significant vertical and lateral variations in the homogeneity, thickness and depth occur, which are likely to be a result of basin subsidence, basin geometry and surface water run-off during formation (Peryt *et al.* 2010).

Table 1. Storage cavern facilities ('cavern clusters') in the UK and the approximate land area for each

Gas storage facility	No. of caverns forming the storage facility	Approximate footprint of the facility (km^2)
Hornsea (Atwick)	9 (Ofgem 2022)	2
Aldbrough	9 (Ofgem 2022)	2
Holford	8 (Uniper 2025)	1
Hill Top Farm*	10 (Ofgem 2010)	1
Stublach	20 (Storengy 2025)	2.5
HyKeuper (proposed)	19 (INEOS Inovyn and Storengy UK 2024)	Not known

*Repurposed brine caverns.

The region's principal structural controls are defined by the east–west-trending Flamborough Head Fault Zone and associated Cleveland Basin, both of which are likely to be related to the underlying Caledonian basement structure (Kirby and Swallow 1987; Pharaoh *et al.* 2011; Wijanarko *et al.* 2026). Faulting within and adjacent to the Zechstein evaporites, particularly the deep-seated basement-controlled faults, must be meticulously assessed, as any fault continuity through the overlying seals and into the storage cavern roof presents a potential pathway for hydrogen leakage, severely compromising the security and integrity of the storage facility (Tackie-Otoo and Haq 2024).

Gas storage in the East Coast region is focused on two halite-bearing formations: the Boulby Halite (Zechstein Z3 cycle) (BbH) Formation and the Fordon Evaporite (Zechstein Z2 cycle) (FoE) Formation. Both formations are currently utilized for small-scale natural gas and hydrogen storage, with the wider basin showing potential for further storage cavern (Evans and Holloway 2009; Armitage 2025). In the BbH Formation (Fig. 3), which is currently being used for natural gas storage (including hydrogen) in Teesside, the halite beds are typically thin (30–50 m thick), shallow (350–

650 m deep) and heterogeneous – these features can lead to geomechanical instability for any caverns formed within the unit. Storage caverns within the BbH Formation are typically restricted in operational range and boundaries: for example, the Teesside hydrogen storage caverns are operated as wet caverns, where brine is used to maintain the halmostatic pressure, to limit geomechanical instability. Therefore, for the purposes of this onshore study, the BbH Formation is not considered preferable for fast-cycling hydrogen storage.

Instead, the focus of this study is on the FoE Formation. The FoE halite has a thickness of more than 200 m onshore near the coastline of Hull and Middlesbrough at a depth of 1200–1900 m. It pinches out and transitions into the clastic-dominated, marginal-marine to continental Edlington Formation at a maximum distance of about 50 km inland from the coast, and the depositional limit of the halite is located between the cities of Hull and York, indicating a significant variation in thickness and stratigraphy across NE England for the Z2 cycle. Onshore, the bedded salt is more coherent and predictable in sequence and depositional environment when compared to the BbH Formation. East of the English coastline the halite thickens offshore in the Southern North Sea and the effects of halokinesis can be observed on seismic profiles, resulting in significant salt structures such as domes that cut through the overlying stratigraphy and areas of salt withdrawal (Allsop *et al.* 2023; Fyfe and Underhill 2023*a*). Bounding the FoE Formation below and above are the carbonate Kirkham Abbey and Brotherton formations, respectively.

The most extensive gas storage target in eastern England is the FoE Formation, which has been developed for the cavern storage of natural gas (SSE Thermal and Equinor 2022). The formation hosts several gas storage caverns at Hornsea and Aldbrough, each with a maximum volume of around 30×10^6 m^3, where it is found at depths of more than 1600 m and is almost 300 m thick. It is typically *c.* 100 m below the base of the BbH Formation. Elsewhere, the formation is generally buried at depths exceeding 500 m and deepens towards the coast. It is notable that the existing gas storage caverns do not exploit the full thickness of the evaporite sequences due to a variation in the geotechnical limitations (increasing heterogeneity and non-soluble material partway through the succession) and economic business case. Caverns are up to *c.* 100 m in height and are typically formed at depths between 1700 and 1800 m.

Specific risks associated with storing hydrogen in evaporite formations

Halite rock is widely regarded as an appropriate storage vessel of hydrogen gas; in its pure form, it has prohibitively low permeability for gas migration and has the ability to anneal and self-heal through dynamic recrystallization, which close any induced fractures; in addition, it is generally considered to be geochemically inert towards hydrogen gas (Ozarslan 2012; IEA Hydrogen 2024). However, bedded salt layers are usually associated with a certain proportion of impurities such as carbonates, anhydrite and clays that contain varying amounts of sulfur-bearing mineralogy that is reactive with hydrogen (Bo *et al.* 2021; Veshareh *et al.* 2022; Al-Yaseri *et al.* 2023; Minougou *et al.* 2023; Braid *et al.* 2024). Reactions with these lithologies include hydrogen-driven redox reactions with sulfur- and iron-bearing minerals (Reitenbach *et al.* 2015). These reactions may lead to the formation of hydrogen sulfide (H_2S), which decrease the purity of the stored hydrogen (Minougou *et al.* 2024).

The mechanical integrity of the host rock is influenced by variable host-rock conditions (Passaris and Yfantis 2018). Host rock that is heterogeneous (i.e. comprised of multiple lithologies), such as anhydrite, gypsum and carbonate interbeds within the FoE Formation, can behave differently under the same stress conditions and can present uncertainty around cavern integrity over its operational life (Martin-Clave *et al.* 2021). Significant thicknesses and lateral extents of non-halite lithologies could be prohibitive to cavern development due to inherent risks to cavern instability, sealing potential and end cavern volume. The presence of non-halite horizons introduces the potential for wall instabilities, including interbed-slip and tensile fracturing, both of which could induce wall instabilities and fracturing, so introducing the potential for fluid leakage points. These non-halite horizons contribute to the cavern sump, decreasing the cavern volume and subsequent storage capacity. To mitigate against geomechanical integrity risk and cavern volume reduction, the careful placement of caverns within a halite formation is a priority, avoiding lithological heterogeneities such as anhydrite or clays (Harati and Rezaei Gomari 2025).

Fordon Evaporite Formation

Given the preference for large-scale, long-duration energy storage in the FoE Formation over other salt-bearing units such as the BbH Formation, this study assessed the storage capacity from the halite-bearing strata in the FoE Formation only. The halite member of the FoE Formation has been modelled from deep onshore boreholes with downhole geophysical gamma-ray logs. It has been mapped to be up to 300 m thick in places but is typically around 100–150 m thick (Fig. 4), which makes up *c.* 50% of the complete FoE Formation thickness. The rest of the FoE Formation comprises thin layers of halite (<5 m), polyhalite, sylvite, carnallite anhydrite and other evaporitic lithologies.

It is noted that previous studies (e.g. Williams *et al.* 2022) have considered the complete thickness of the FoE Formation for salt cavern development and therefore they have indirectly considered non-halite lithologies, such as anhydrite and polyhalite, as appropriate hosts for hydrogen storage. As outlined above, significant thicknesses of non-halite lithologies present development and operational risks, and are not desirable in the cavern walls and in the region around the cavern that could affect its geomechanical behaviour (Martin-Clave *et al.* 2021). However, in practice, these non-halite lithologies cannot be avoided, and if these horizons do not comprise a significant section of the target horizon in which the cavern is dissolved they should be able to be constructed. Examples of this practice include the presence of the '30 ft Marl' within the Cheshire Basin in which a number of caverns have been constructed (Storengie 2015).

Methodology

General approach

A GIS-based methodology (Fig. 5) was used to identify potential locations for new underground storage caverns together with an estimation of the physical volumes of salt suitable to host a cavern for storage and the corresponding hydrogen energy potential. These methods utilized a diverse and well-established range of publicly available datasets from sources including the British Geological Survey (BGS), the UK Onshore Geophysical Library (UKOGL) and peer-reviewed scientific research papers (Table 2). The incorporation of selected published datasets from peer-reviewed literature validated the approach and its applicability to any halite-bearing strata, ensuring a level of confidence in the data and the methodology. The approach initially follows previous authors methodologies (e.g. Parkes *et al.* 2018; Williams *et al.* 2022; Allsop *et al.* 2023; Lankof and Tarkowski 2023; Huang *et al.* 2024) by describing the 3D spatial distribution of salt formations, modelling theoretical cavern placements within a 3D geological model, applying spatial buffers based on geological and surface constraints, and finally applying volumetric calculations to infer the energy storage capacity for

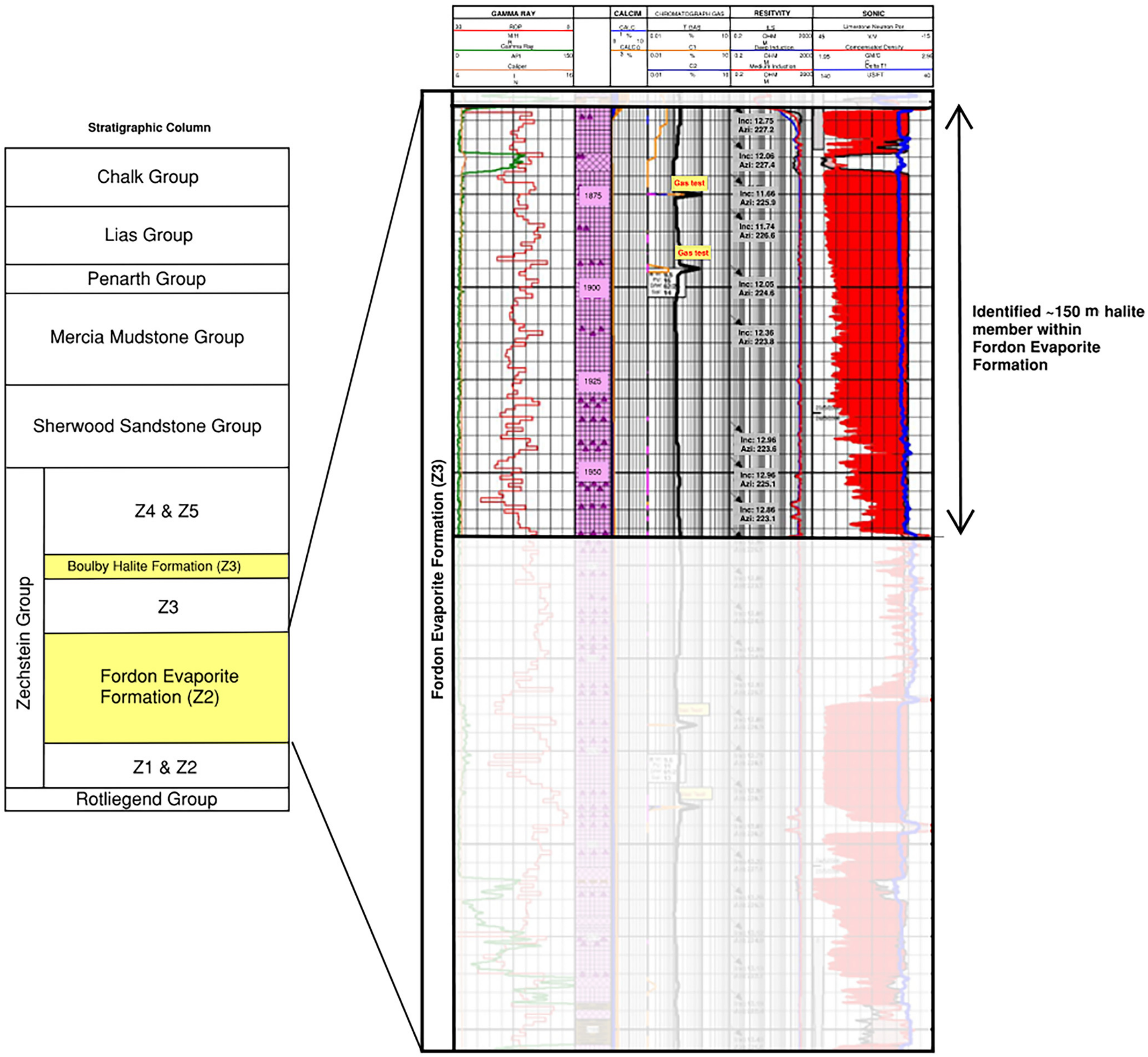


Fig. 4. General stratigraphy of the Zechstein Group and Z2 Fordon Evaporite (FoE) Formation juxtaposed with an example geophysical well log, showing the uppermost halite member as being the most suitable for salt cavern construction and operation. Note the presence of a non-halite lithological band of *c*. 5 m thickness at the top of the sequence. Source: modified from Williams *et al*. (2022).

each cavern location. The 3D geological model of the regional stratigraphy is fundamental to the assessment, and while, as discussed later in the following 'Storage cavern design' subsection, the principal halite member could typically be described as 100–150 m thick, it is modelled to be spatially variable, generally thickening to the south and east across the East Coast region.

Diverging from previous studies, we develop this methodology further to not only specifically delineate the principal halite member within the FoE Formation, but also to integrate surface and subsurface constraints to cavern development. The result is that land parcels are identified that have favourable subsurface conditions for cavern development and are not conflicted by sensitive surface assets, thus moving from estimates of resource potential to estimates of reserve potential.

Storage cavern design

Cavern geometry is influenced by the thickness and heterogeneity of the host halite layer. Figure 6 provides a schematic illustration of the section geometry for a dry operated cavern in a homogenous halite body, as assumed for this study.

To ensure cavern geomechanical stability, each cavern must have a sufficient thickness of salt between the cavern boundary and the non-halite geology above and below the cavern. This is termed the roof and floor salt thickness, respectively (see Fig. 7). A minimum roof salt thickness was set at 0.75 × cavern diameter, and a minimum floor salt thickness of 0.20 × cavern diameter was allowed for below the base of the cavern (Wang *et al*. 2015; Caglayan *et al*. 2020). The cavern geometry was approximated to a cylinder with a height/diameter ratio of 2 (Cyran 2020).

The size of each cavern was also informed by its use case: for example, to provide an economical demand and deliverability balance. Therefore, it is most useful to model the storage capacity for caverns of a given size. This study assumes a minimum cavern radius of 20 m. This is similar to what had been chosen in previous studies for the FoE Formation (e.g. Williams *et al*. 2022; Allsop *et al*. 2023; Barnett *et al*. 2024) and is restricted by the thickness of the halite-bearing strata that is the most suitable geology for solution

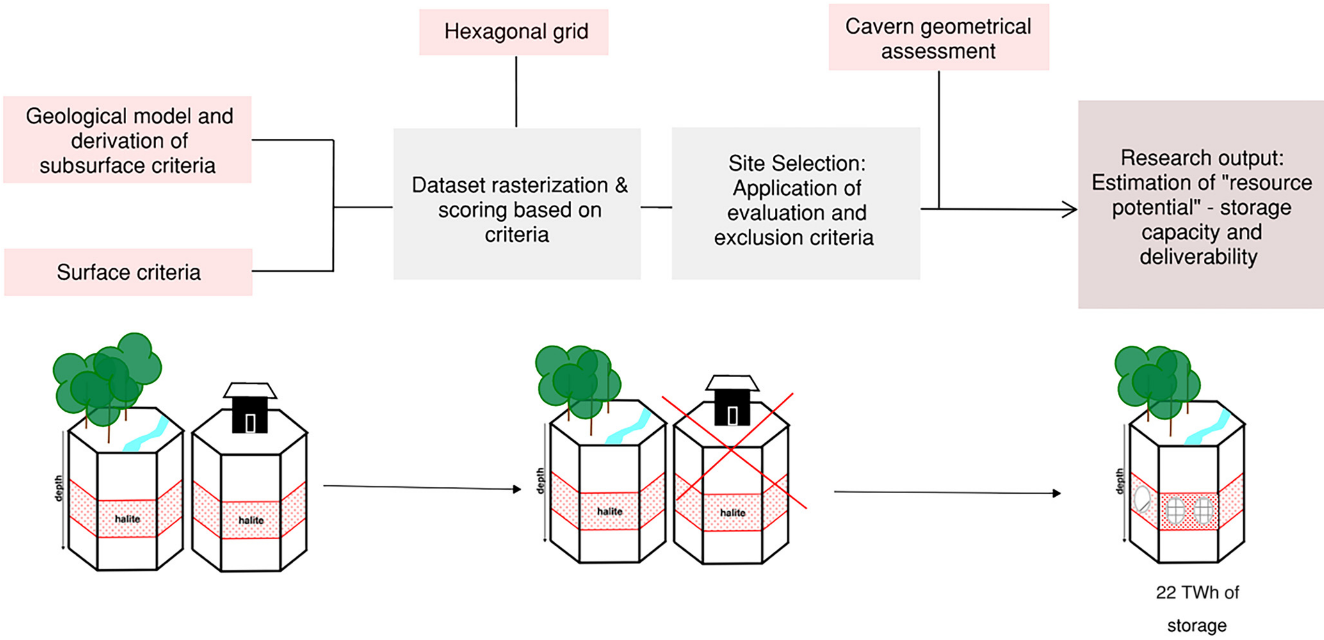


Fig. 5. Summary workflow of the applied methodology, including geological, geospatial and digital aspects of the site selection and application of the multi-criteria analysis (MCA).

mining and the storage of hydrogen. The minimum radius was selected based on known minimum dimensions of salt caverns in bedded halite formations, thereby indicating the minimum dimensions that are economically viable. In practice, based on the assumptions outlined above, a 20 m-radius cavern has a height of 80 m, and requires a roof salt thickness of 30 m and a floor salt thickness of 8 m, and hence requires an overall halite thickness of at least 118 m. This study, therefore, reveals the potential storage capacity of cylindrical-shaped caverns in halite of at least *c.* 118 m thick; cavern sites with less than a 118 m-thick layer of halite were excluded from the analysis.

Storage cavern siting

Caverns are mapped spatially based on a cavern separation rule; the pillar width of intact halite between each cavern is typically between 3 × cavern radius and 5 × cavern radius as the depth increases (e.g. as per Williams *et al.* 2022; Allsop *et al.* 2023). An algorithm has been developed that optimizes the fit of caverns of a set diameter within a hexagonal column (Fig. 7).

Each hexagon is treated as a potential site for the development of caverns. The footprint of each hexagon is *c.* 2.5 km^2, which is similar to existing cavern storage facilities in the UK (Table 1). This approach aims to replicate the development of ‘cavern clusters’ (Table 1), where caverns are typically developed in groups, or clusters, of 10–20. The method represents a deviation from the existing methodologies (Caglayan *et al.* 2020; Williams *et al.* 2022), which select individual caverns first and can lead to stranded or isolated caverns in small sites that are unlikely to be attractive to developers (Fig. 8).

Revising the theoretical storage potential through a surface and subsurface criteria assessment

Assessment criteria

Nineteen spatial datasets were considered in determining the storage capacity in the East Coast region, and were used to establish the spatial constraints for five subsurface criteria and eight surface criteria (Table 2). Each criterion was analysed for its impact on the development potential of a site. Sites were excluded where they did not meet the criteria: for example, if they intersected the criterion or lay outside the allowable range. Sites that were not excluded were evaluated on their development opportunity and ranked accordingly: for example, the further a site is from a built-up area the better, therefore a site far away from a built-up area will have a relatively high rank.

Evaluation of assessment criteria

Each dataset was integrated with a base grid of hexagons and the proximity of each hexagon to the dataset was calculated (Figs 7 and 8) (Jing *et al.* 2012). Each hexagon that was not excluded was evaluated through a ranking system, which is based on how well the hexagon can meet the allowable range of each spatial criterion (Table 2). A weighting was then applied to each criterion based on the perceived impact that it has on development, such that weighting × rank determines the score for each hexagon.

For example, there are 1000 hexagons to be evaluated based on the proximity to built-up areas and Hexagon A is far away from any urban development and does not intersect any mapped built-up area. Hexagon A is ranked 900 out of 1000, a higher number indicates that the hexagon is a relatively good site for cavern development. This rank is then normalized to 0.9 out of 1.0. If built-up areas are considered to be a critical criterion to the development of salt caverns, a weighting of 1.0 (from a range of 0.0–1.0, a higher number being most critical) may be applied. Subsequently, Hexagon A would have a resultant weighted score of 1.0 × 0.9 = 0.9.

When many criteria are considered concurrently, an overall score is derived based on the ‘weighted sum method’. The weighted sum method is a multi-criterion decision-making method to evaluate an outcome based on multiple criteria. A generalized equation for the weighted sum method is provided in equation (1), where the weighted score of each criterion is summed to derive an overall score for a hexagon. The overall score indicates the relative suitability to store hydrogen in salt caverns at each hexagon site (Fig. 9):

$$\text{Weighted rank} = \sum [(\text{normalized}_{\text{rank}_{\text{criteria}_1}} \times \text{weighting}_{\text{criteria}_1}) + (\text{normalized}_{\text{rank}_{\text{criteria}_2}} \times \text{weighting}_{\text{criteria}_2}) + \cdots] \quad (1)$$

Table 2. Subsurface and surface evaluation and exclusion criteria

Relevance	Criterion	Allowable range/terms	Reference	Comment	Data sources
Subsurface	Subsurface temperature	Below 80°C. Excludes temperature above 80°C. Based on a geothermal gradient of 30°C km^{-1}	Farr *et al.* (2021)	Exclusion criteria only	Not applicable (n/a)
Subsurface	Depth to top of salt	Above 300 m	Jing *et al.* (2012); Cyran (2020); Lankof and Tarkowski (2023); Huang *et al.* (2024)	Exclusion and evaluation criteria	UK Onshore Geophysical Library (UKOGL); British Geological Survey (BGS)
Subsurface	Salt thickness	Above 30 m	Previous work considers a site if the salt thickness is greater than 50 m (cavern height of 20 m + roof and floor thickness of 30 m) (e.g. Williams *et al.* 2022)	Exclusion and evaluation criteria	UKOGL; Evans and Holloway (2009)
Subsurface	Proximity to major fault	Above 200 m or 3 × cavern radius (whichever is greater). No grading	Wang *et al.* (2015); ETI (2018)	Exclusion and evaluation criteria	Powell (2010); Wright (2022)
Subsurface	Geological uncertainty – proximity from edge of mapped salt	The further the site is from the edge of the salt boundary, the better	Assumption based on Caglayan *et al.* (2020)	Exclusion and evaluation criteria	UKOGL; BGS UKOGL; Evans and Holloway (2009)
Surface	Proximity to restricted development area (Sites of Special Scientific Interest (SSSIs), Special Areas of Conservation (SACs), Ramsar sites, major watercourses (named rivers), National Parks)	Above 0 m from boundary. The greater the better	Assumption based on Caglayan *et al.* (2020)	Exclusion and evaluation criteria. Does not account for minor watercourses	JNCC (2019*a*, *b*); UK Government (2022, 2023); Defra (2023)
Surface	Proximity to built-up areas	Above 2500 m or 3 × cavern radius (whichever is greater). The further the better	Assumption based on Caglayan *et al.* (2020)		ArcGIS (2022)
Surface	Proximity to water reservoirs	Above 200 m or 3 × cavern radius (whichever is greater). He closer the better	Assumption based on Lankof and Tarkowski (2023)	Exclusion and evaluation criteria	Durant and Counsell (2018)
Surface	Proximity to railways and major roads	Above 200 m or 3 × cavern radius (whichever is greater). The closer the better	Assumption based on Caglayan *et al.* (2020) and Lankof and Tarkowski (2023)	Exclusion and evaluation criteria	Pope (2017); DfT (2021)
Surface	Proximity to major pipeline networks/corridors including the Project Union pipeline	Above 200 m or 3 × cavern radius (whichever is greater). The closer the better	Assumption based on Caglayan *et al.* (2020) and Lankof and Tarkowski (2023)	Exclusion and evaluation criteria	National Gas (2022, 2023)
Surface	Proximity to Control of Major Accident Hazards (COMAH) sites	Above 1000 m or 3 × cavern radius (whichever is greater). The further the better	Assumption	Exclusion and evaluation criteria. Does not represent site-specific COMAH requirements	HSE (2021)
Surface	Proximity to planned hydrogen projects (i.e. offtakers)	Closer the better	Assumption	Evaluation criteria only	Hydrogen UK (2023)
Surface	Surface expression of salt extents to define the boundary of surface constraints	The further the site from the edge of the salt boundary, the better	Assumption based on Caglayan *et al.* (2020)	Exclusion and evaluation criteria	UKOGL; BGS UKOGL; Evans and Holloway (2009)

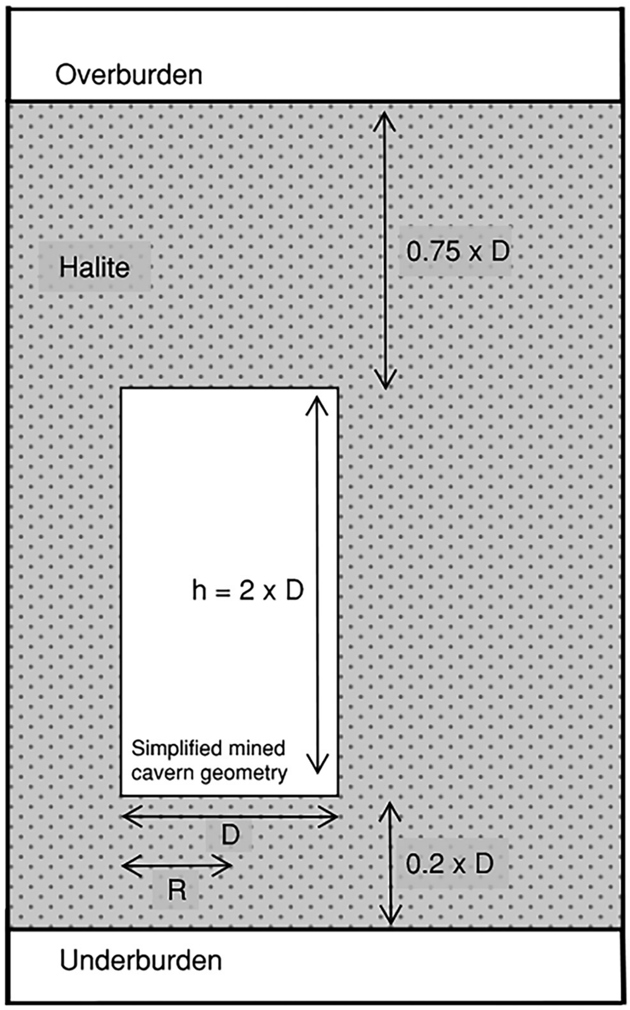


Fig. 6. Schematic drawing of a general salt cavern placement within a halite layer bounded by non-halite underburden and overburden. D, diameter; h, height; R, radius. Source: adapted from Williams *et al.* (2022).

For this study, each criterion was given equal weighting. This ensured transparency and neutrality in early-stage screening; however, it is considered that some criteria will have a greater influence on feasibility, and future iterations may benefit from stakeholder-informed or sensitivity-tested weighting schemes.

Modelling cavern volumes

Storage capacity calculations are undertaken following previous published approaches, using the real gas law (Caglayan *et al.* 2020; Williams *et al.* 2022; Allsop *et al.* 2023). The mined cavern volume (V_{bulk}) is corrected to account for a reduction in the usable cavern volume (V_{corr}) due to the deviation from the idealized cavern geometry (shape correction factor (SCF) of 0.7), the presence of insoluble materials within the salt that remain in the cavern following solution mining (insoluble fraction (IF) of 25%) and the bulking factor (BF of 1.46) to account for the uneven stacking of insoluble material retained in the sump.

The mass capacity is calculated by assuming the temperature at the midpoint of the cavern ($T_{midpoint}$), and the maximum and minimum operating pressures ($P_{max\_operating}$ and $P_{min\_operating}$) relative to the lithostatic pressure at the casing shoe (P_{casing}). The hydrogen density at the operating pressure limits is multiplied by the usable cavern volume to determine the working mass ($m_{working}$), which is converted to energy using the lower heating value (LHV) of 33.33 kWh kg^{-1}.

It is widely regarded that fast-cycling storage caverns are limited to a withdrawal capacity equivalent of 10–20 barg/day (Energystock 2017; Equinor H21 2018; ETI 2018; TNO 2020). Note that wet storage caverns are not a preferred option for deliverability as they require additional infrastructure such as surface brine ponds and dehydration equipment, and the flow is restricted by the brine-compensation system. However, it is noted that in order to stabilize caverns at depths where plastic deformation of halite occurs over short timescales, it may be necessary to operate wet caverns to maintain the cavern volumes at lower pressures.

For this study, a typical dry cavern of 20 m radius (i.e. 40 m diameter) at 1000 m depth can deliver the following:

- Working energy capacity: 16 GWh
- Deliverability: 1.3 GWh/day at 10 barg/day:

$$V_{corr} = SCF \times ((1 - IF) \times BF)) \times V_{bulk} \tag{2}$$

where V_{corr} is the available cavern volume.

$$T_{midpoint} = T_0 + \Delta T \times (Z_{casing} + 0.5H_{cavern}) \tag{3}$$

where T is temperature; T_0 is ambient surface temperature; ΔT is geothermal gradient; Z_{casing} is the depth to the casing shoe; and H_{cavern} is the height of the cavern.

$$P_{casing} = (\rho_{overburden} t_{overburden}) g \tag{4}$$

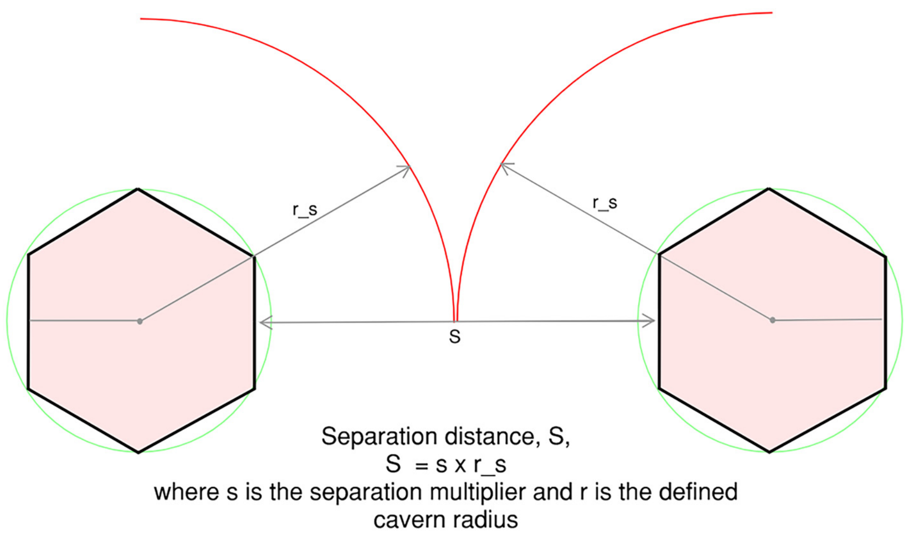


Fig. 7. A schematic representation of a cavern cluster within a hexagonal column.

where P is pressure; ρ is density; t is thickness; and g is gravitational acceleration.

$$P_{\mathrm{max\_operating}} = 0.8P_{\mathrm{casing}} \quad (5)$$

$$P_{\mathrm{min\_operating}} = 0.24P_{\mathrm{casing}} \quad (6)$$

$$m_{\mathrm{max\_operating}} = \rho_{\mathrm{H_2 max}} V_{\mathrm{corr}} \quad (7)$$

$$m_{\mathrm{min\_operating}} = \rho_{\mathrm{H_2 min}} V_{\mathrm{corr}} \quad (8)$$

- where m is mass and ρ is density.

$$m_{\mathrm{working}} = m_{\mathrm{max\_operating}} - m_{\mathrm{min\_operating}} \quad (9)$$

$$E = m_{\mathrm{working}} \mathrm{LHV} \quad (10)$$

where E is energy (kWh) and LHV is the lower heating value of 33.33 kWh H_2 kg^{-1}.

Results

A revised theoretical storage potential

Across the East Coast region, several sites were found to be free from restrictive surface criteria (Table 2) and with geological conditions suitable to theoretically develop salt caverns. The resultant potential storage capacity (reserve potential) for each modelled hexagonal site can be calculated by summing the estimates from all modelled caverns within each hexagon. Each hexagon can be thought of as a ‘development site’, within which a hydrogen storage facility, comprising storage caverns and surface infrastructure, can be developed. It should be stressed that the estimates are only relevant for the storage of hydrogen in the FoE Formation, and that additional storage potential may be available in other halite units (e.g. the BbH Formation). Further, they provide only a static estimate of the storage capacity and therefore do not account for turnovers or optimized use of hydrogen in the storage caverns.

The reserve potential across all available hexagons is between 22 and 48 TWh, the latter equivalent to approximately 1000 caverns of 20 m radius (Table 3). Given the coarse granularity of the data, the findings are also subject to significant uncertainty such as those related to depth, thickness and purity of the host geology, and assumptions made on the ability to build-out caverns at scale and at a certain size. The capacity estimate is represented as a range that reflects uncertainty in the geological suitability of the host rock and the ability to site caverns at optimized distances; 22 TWh is representative of a cavern-to-cavern pillar width of 5 × cavern radius (R) and 48 TWh is representative of caverns sited at 3R.

Table 3. This study’s estimate for salt cavern storage capacity and deliverability

Cavern spacing scenario	Reserve potential of salt cavern storage (TWh)	Available sites	Caverns required to be developed	Mean deliverability rate per cavern (GWh/day)
3 × cavern radius	48	8	2200	1.2
5 × cavern radius	22		1000	

Additional sensitivity analyses of storage potential are presented in the following sections, which capture other key uncertainties; the results are initially compared to previous best estimates, then an assessment is undertaken that optimizes cavern sizes to deliver the highest possible storage potential, and lastly a view on the practical number of caverns that can be developed per site.

To provide an indication of where the capacity lies geographically, available hexagons are shown spatially in Figure 10, and plot in land between Pocklington and Driffield in East Yorkshire. The darker the colour on the map, the less suitable it is to development, as calculated by the mean weighted sum method. In this case, the score across seven of the eight hexagons does not vary significantly (the deviation is within 0.06 points), and the poorest scoring site is largely influenced by its relative proximity to built-up areas.

Sensitivity analysis

Reviewing the estimate of resource potential

A sensitivity analysis was undertaken that reviews the estimate of resource potential from this study. It is anticipated that the resource potential – that is, energy storage provided by viable geology only – should be much greater than the reserve potential – that is, energy storage that is likely to be technically feasible and economically and socially viable. It is therefore curious to see in Table 4 that the resource potential from this study is similar/slightly less than the reserve potential estimated by Williams *et al.* (2022), 1200 TWh compared to 1465 TWh, respectively. A resource estimate is not provided in Williams *et al.* (2022); however, the findings suggest that this study has defined a much-reduced volume of viable

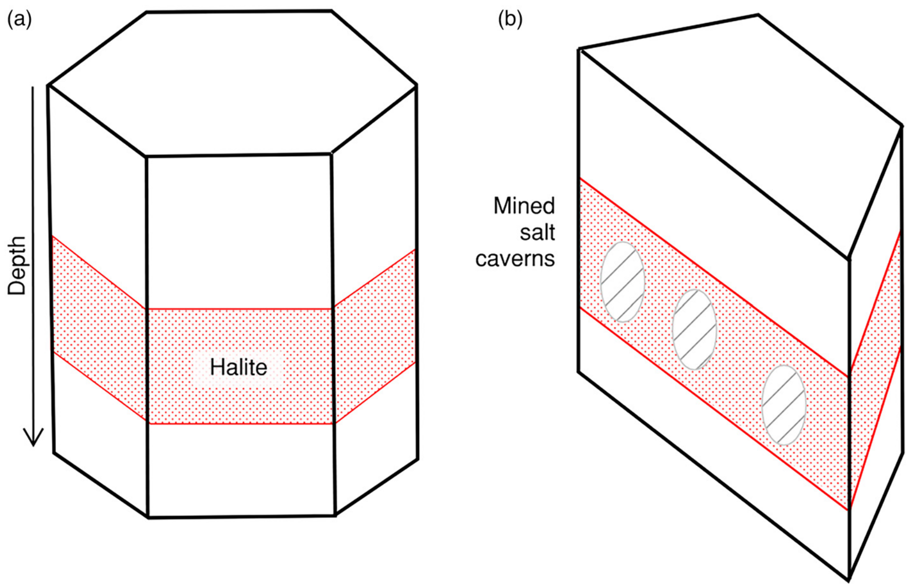


Fig. 8. Schematic 3D representation of caverns located within each hexagonal column: (**a**) a hexagonal column and (**b**) a section through the column showing caverns (grey) located in the halite layer.

geology suitable for salt cavern development. This study considers only the halite member of the FoE Formation for solution mining of salt caverns, and the impact of this is evidently significant on the findings: by constraining mining to a thinner host geology (i.e. the halite-only member of the FoE Formation rather than the entire thickness of the FoE Formation), viable caverns are shorter in height (and therefore diameter and volume) and the resultant energy storage capacity is reduced.

Comparing the effect of cavern radius on storage volume

The findings shared from this study are based on a uniform cavern radius of 20 m. This cavern radius was selected as: (i) the relative thickness of the halite member of the FoE Formation only supports caverns of a larger diameter at eight sites (and these sites in turn only support caverns of cavern radius up to 29 m); and (ii) it is the minimum geometry required for economic viability of mining and development based on industry knowledge (i.e. disregarding thin layers of halite that cannot host a cavern of at least 20 m radius). By removing these boundaries and allowing the cavern radius to vary between hexagon sites, the cavern geometry can be optimized based on the halite thickness.

The analysis found that the reserve potential increases by between three and four times, and lies between 88 and 174 TWh (Table 5). However, due to the large proportion of smaller radius caverns – 75% of caverns are smaller than 20 m in radius – the total number of caverns required to meet this increase in storage capacity is more than 10 times greater than developing caverns of a uniform 20 m radius.

To provide a benchmark against current proposals, salt caverns at Aldbrough, which are located in the FoE Formation, have a physical volume of *c*. 300 000 m^3 (Equnior H21 2018). This is similar to the physical volume of *c*. 317 000 m^3 of the largest cavern modelled in this study with a horizontal radius of 29 m. Caverns modelled at 20 m radius have a physical volume of *c*. 100 000 m^3.

Investigating the effect of restricting the quantity of caverns in each hexagon (i.e. the number of caverns to be developed within each cavern cluster)

A reserve potential of 22 TWh is derived from a theoretical maximum of 2200 caverns, distributed with up to 127 caverns within each hexagon of 2.5 km^2 (Table 6). This scenario assumes an optimized, high-density packing of caverns, limited only by the

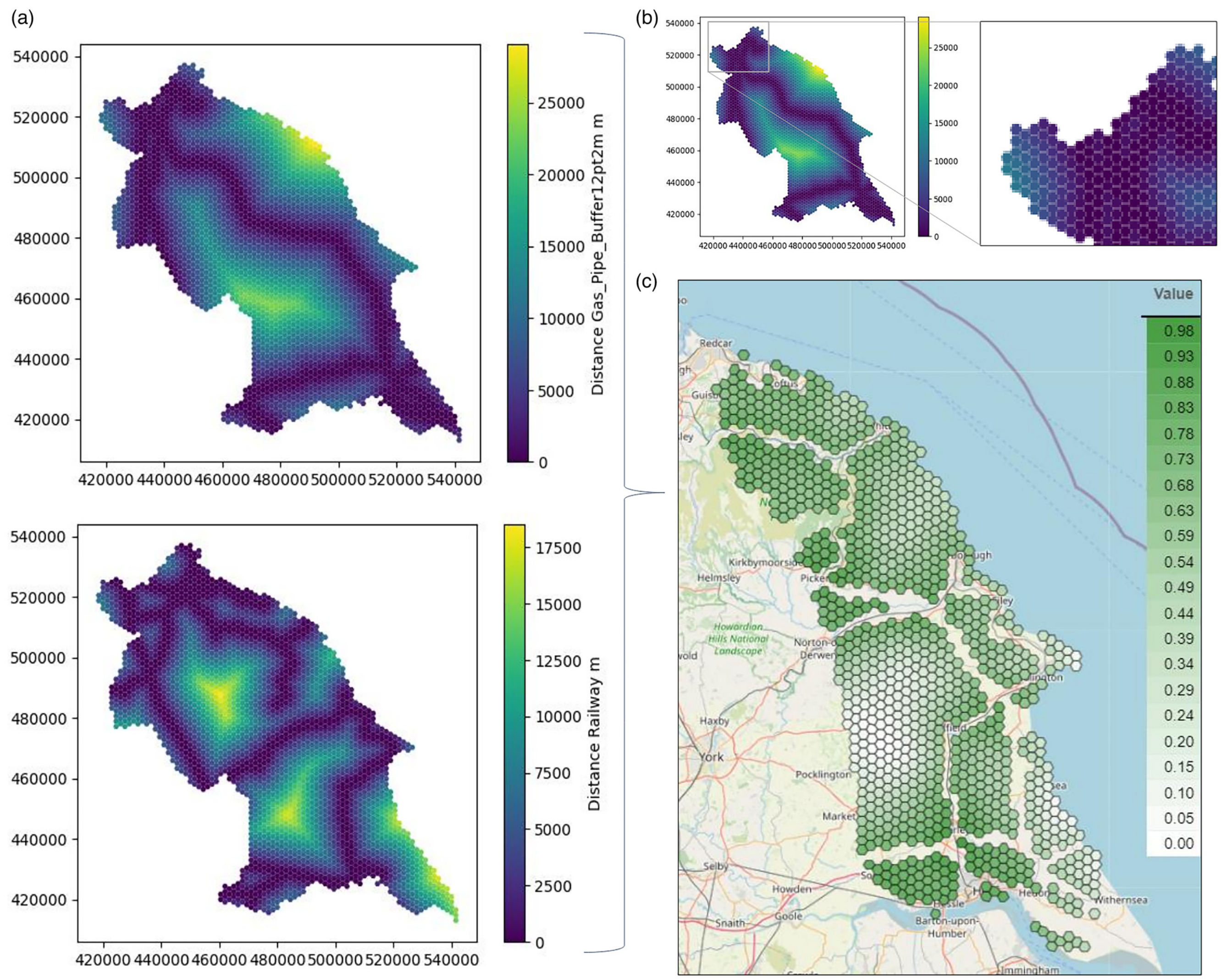


Fig. 9. (**a**) Rasterization of datasets and calculation of the proximity to constraints. Examples provided hexagons shaded according to their proximity to (top) gas pipelines and (bottom) railways. Brighter colours indicate sites that are further away. (**b**) Integration of spatial datasets with a hexagonal grid. Hexagons of 1 km side length. Darker colours indicate where the datasets exist: in this example, gas pipelines. (**c**) Implementation of evaluation and exclusion criteria for the spatial constraints. The example provided considers only gas pipelines and railways. Note the higher scoring hexagons (i.e. above development sites) closer to gas and railway infrastructure; perceived as beneficial to site development.

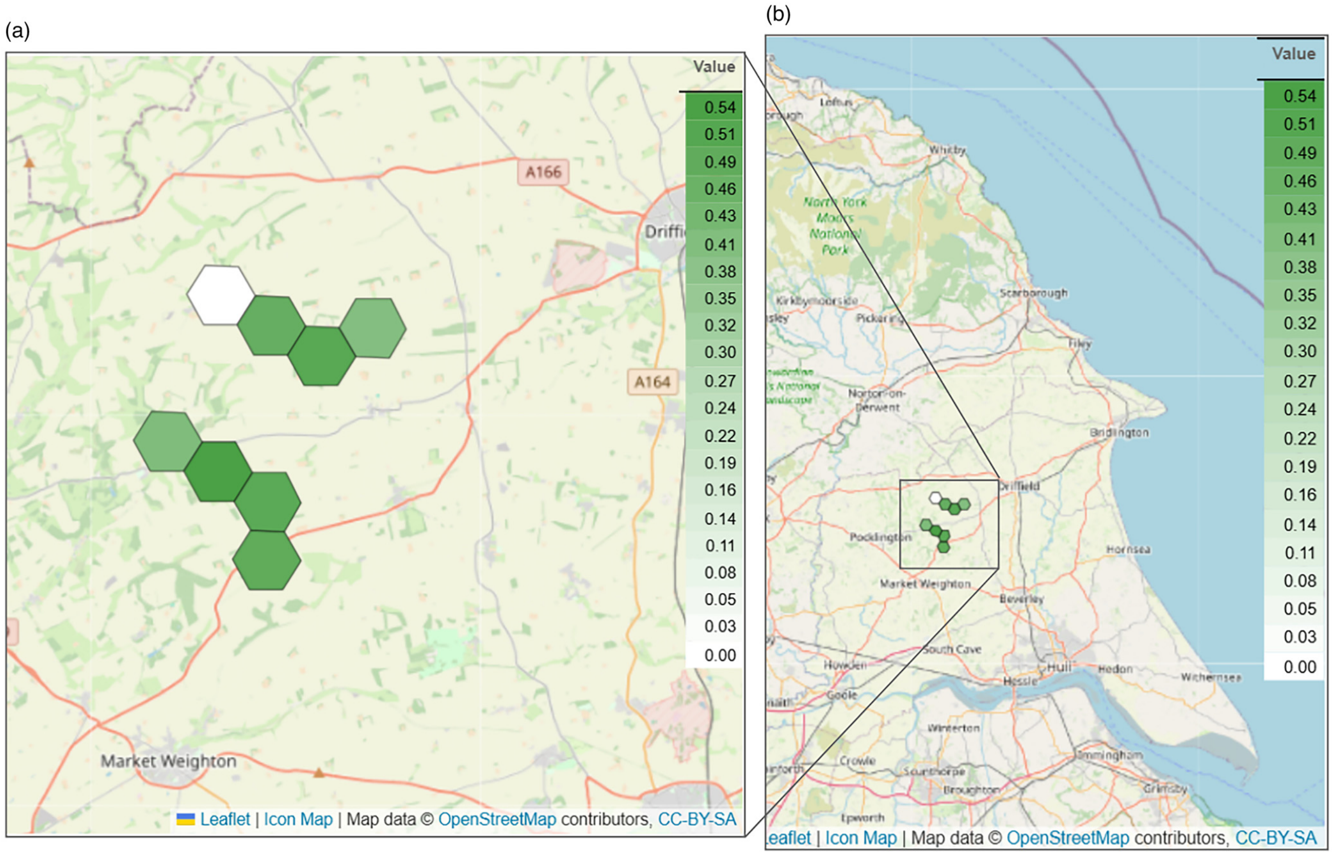


Fig. 10. (**a**) Available development sites for salt cavern storage of hydrogen. (**b**) Regional context for development site locations. The combined reserve potential of the hydrogen storage is 22 TWh based on a cavern to cavern pillar thickness of 5 × cavern radius (*R*).

minimum spacing required for geomechanical stability (3× and 5 × cavern radius). However, practical considerations often necessitate restrictions on the number of caverns within a given area. If the number of caverns developed per hexagon is limited to 20, a figure consistent with existing underground gas storage facilities in the UK (Table 1), the reserve potential is reduced to only *c.* 3.6 TWh (Tables 6 and 7). This represents a substantial reduction in storage capacity of *c.* 84%, highlighting the critical impact of development constraints on the overall hydrogen storage potential.

This significant decrease raises a crucial question: why are so few development sites available? The challenge, and thus a key area for further research, lies in understanding and potentially refining the criteria that currently limit site availability, and should aim to challenge or refine onerous 'rules-of-thumb' (typically referenced as industry 'good practice') where they exist (Table 2), with the ambition to unlock more development sites. This includes addressing potential constraints such as the sensitivity of the following to salt cavern development:

- linear infrastructure (e.g. major roads and railways);
- environmentally protected sites (e.g. major waterways and National Parks); and
- urban areas.

Discussion

Theoretical storage potential

Hydrogen is noted as a key component of international decarbonization plans, particularly for the UK where low-carbon hydrogen may deliver the grid-scale energy storage required to manage a future electricity grid based on variable renewable energy. Hydrogen production is set to rapidly increase in the next decade, yet expanding hydrogen supply and demand depends on the development of cost-effective infrastructure to ensure a reliable supply. Large-scale hydrogen storage, particularly in salt caverns, can help to reduce supply costs and improve system flexibility. Many authors have investigated the potential for UK halite-bearing

Table 4. Comparison of the theoretical storage potential from the Industrial Decarbonisation Research and Innovation Centre (IDRIC) Study and findings from Williams et al. (2022)

Parameter	Williams *et al.* (2022)	This study, 2024	This study, 2024
Conditions	Geological and surface constraints applied* Surface constraints considered: roads, railways, urban settings	Geological constraints applied only (availability of suitable halite). Surface constraints not applied	Geological and surface constraints applied Surface constraints considered: roads, railways, urban settings, restricted development areas (National Parks, Sites of Special Scientific Interest (SSSIs), etc.), reservoirs, existing and proposed gas pipelines
Level of estimate	Reserve potential	Resource potential	Reserve potential
3 × cavern radius	1465 TWh	1200 TWh	48 TWh
5 × cavern radius	747 TWh	600 TWh	22 TWh

*Where relevant, it has not been possible to ensure the same datasets have been used across both studies.

Table 5. Potential salt cavern storage for variable cavern radii

Cavern radius (m)	Cavern spacing scenario	Reserve potential of salt cavern storage (TWh)	Available sites	Number of caverns required to be developed
20	3 × cavern radius	48	8	2200
	5 × cavern radius	22		1000
≥20*	3 × cavern radius	60	8	1750
	5 × cavern radius	29		840
5–29*	3 × cavern radius	174	36	29 700
	5 × cavern radius	88		15 500

*Note that the maximum viable cavern radius is 29 m. Therefore, this option practically represents a range between 20 and 29 m.

strata to store hydrogen in the subsurface via salt caverns, providing estimates on capacity and deliverability (Caglayan *et al.* 2020; Williams *et al.* 2022; Allsop *et al.* 2023; Barnett *et al.* 2024). Although each study has delivered in detail a geological estimate of the total resource available, few have comprehensively accounted for the surface and subsurface constraints to development of such a large infrastructure deployment. The presented study accounts for high-level technical, social and economic constraints to development for onshore salt cavern hydrogen storage across the East Coast region of England.

A key benchmark for estimating the UK's potential deployment of onshore underground hydrogen storage is given in Williams *et al.* (2022). However, influential considerations such as delineating the principal halite member of the FoE Formation sequence in the Zechstein Group and accounting for additional surface constraints, such as restricted development areas, water reservoirs and existing and proposed gas pipeline infrastructure (Table 2) and considering salt cavern development in clusters, represent key differentiators between this study and Williams *et al.* (2022).

In this study, only the halite member of the FoE is considered to be suitable for salt cavern development and non-halite geology, which can cause cavern instability and promote adverse geochemical reactions with stored hydrogen, is disregarded. The halite member typically represents up to one half of the formation thickness and other studies have assumed that the entire thickness (up to *c.* 300 m) of the FoE Formation can be exploited (Williams *et al.* 2022).

In addition, this study assumes a uniform cavern radius of 20 m, in comparison to a previous study (Williams *et al.* 2022) that assumed a cavern radius of 50 m (Table 8). The geological modelling and cavern geometry basis (see the earlier 'Fordon Evaporite Formation' and 'General approach' subsections) identifies that only a handful of potential development sites are able to support a cavern with a radius greater than 20 m, and those sites which can only support caverns with a radius of up to 29 m. In addition, given the size of existing caverns in the UK, caverns with a radius smaller than 20 m are not likely to be economically viable given the high cost of solution mining and facility development.

A sensitivity analysis that considered caverns of variable radius across each hexagon showed that the potential storage capacity is increases three-fold v. adopting a uniform cavern size. However, this presents development challenges as 75% of caverns have a radius less than 20 m and therefore: (i) to achieve the three-fold increase in the potential storage capacity the total number of caverns required rises by 10-fold; and (ii) the small storage volume may mean that they are not viable to develop, although in some scenarios (e.g. where demand is limited) these smaller caverns could represent a niche commercial opportunity.

Furthermore, the assessment of storage capacity is undertaken on a grid basis, where each hexagon within the grid is *c.* 2.5 km^2 and caverns are optimally located to form a theoretical cluster of many caverns. This removes the possibility of having isolated, single caverns that are likely to be impractical to develop and less economical to operate.

A sensitivity analysis showed that if the number of caverns per hexagon is reduced to around 20, which is typical for a storage site in the UK, the total storage potential capacity is reduced by a factor of 6, to between 3.6 and 7.7 TWh.

Estimates of storage capacity (i.e. reserve potential) from this study are an order of magnitude lower than previously determined; 22–48 TWh compared to 750–1465 TWh. From an assessment of the viable regions in the UK for salt cavern storage of hydrogen, Williams *et al.* (2022) estimated that the UK East Coast region represents *c.* 70% of the UK's storage capacity, and this study therefore presents a significant reduction in storage opportunity across the UK.

The mean deliverability of hydrogen per cavern has also been calculated as part of this study. A mean withdrawal rate of 1.2 GWh/day per cavern is provided in Table 6 and represents the rate as limited by a 10 bar/day pressure drop inside the storage cavern (Beutel and Black 2005; Equinor H21 2018; H21 2018; TNO 2020). Note that the delivery rate is unlikely to scale linearly for many caverns; for a cavern cluster (10–20 caverns) the rate will be limited largely by topside infrastructure such as decompressors and dehydrators.

Build-out timescale

Salt caverns, while offering a technically viable and advantageous solution for large-scale hydrogen storage, present significant engineering and construction challenges. The creation of stable voids within a salt formation requires careful planning and execution to manage the inherent complex geomechanical and operational demands. Maintaining the long-term integrity of the surrounding rock, while simultaneously ensuring safe and efficient injection and withdrawal of hydrogen, demands a thorough

Table 6. Number of caverns required to meet theoretical storage capacity scenarios

Cavern spacing scenario	Number of caverns per site (2.5 km^2)	Available development sites	Reserve potential (TWh)	Total number of caverns
3 × cavern radius	271	8	48	2200
5 × cavern radius	127		22	1000

Table 7. Derived theoretical storage capacity limited to 20 caverns per hexagon or cavern site

Cavern spacing scenario	Number of caverns per site (2.5 km^2)	Available development sites	Total number of caverns	Reserve potential (TWh)
3 × cavern radius	43	8	350	7.7
5 × cavern radius	20		160	3.6

Table 8. Key parameters for the modelled caverns

Parameter	Williams *et al.* (2022)	This study
Cavern casing shoe depth (m)	747–1800	650–1800
Cavern height (m)	20–300	80
Cavern operating pressure (MPa)	14–34	12–32
Working hydrogen mass range (t or te)	486–13 239	700–1500
Equivalent energy storage range (GWh)	16–441	23–49

Williams *et al*. (2022) used a cavern radius of 50 m; while this study used a cavern radius of 20 m.

Table 9. Estimate resource potential of hydrogen storage in salt caverns in comparison to Williams *et al.* (2022)

Cavern spacing scenario	Williams *et al.* (2022)		This study	
	East Coast region	UK capacity	East Coast region	UK capacity
3 × cavern radius	1500 TWh	2150 TWh	48 TWh	68 TWh
5 × cavern radius	750 TWh	1100 TWh	22 TWh	35 TWh

understanding of the properties of salt and the stresses induced by cavern creation and operation (e.g. Kumar *et al.* 2023). Consequently, the development timeline for a single salt cavern storage facility, nominally comprising up to 20 caverns, can extend to *c.* 15 years (ETI and Foster-Wheeler 2013; Energystock 2017; ETI 2018; H21 2018; Hydrogen UK 2022; H2eart for Europe 2024; INEOS Inovyn and Storengy UK 2024). This time frame accounts for the various stages involved, including site characterization, cavern design, drilling and solution mining, de-watering and brine disposal, testing, and commissioning.

This 15 year estimate, however, represents an idealized scenario. It assumes a number of facilitating factors, including:

- Accepting local population: public acceptance and support are crucial for the successful development of any large infrastructure project. Community engagement and addressing potential concerns regarding safety, environmental impact and visual intrusion are essential (Edlmann 2024; see also Evans and Holloway 2009). Delays can arise from social and political factors if these aspects are not adequately addressed.
- Robust, mature and available supply chain: the construction of salt cavern facilities requires specialized equipment, materials and expertise. A well-established and readily available supply chain is essential to avoid delays and cost overruns. This includes access to drilling rigs, solution mining equipment, pipelines and other necessary infrastructure.
- Available financial backing: large-scale infrastructure projects like hydrogen storage facilities require substantial financial investment. Securing the necessary funding can be a complex and time-consuming process, potentially impacting the project timeline.
- Mature and efficient pathway through regulations and permitting: navigating the regulatory landscape and obtaining the necessary permits can be a significant hurdle. A streamlined and efficient planning and permitting process is crucial to avoid unnecessary delays. Clear guidelines and coordination between regulatory agencies are essential.

This study has determined a lower-end resource potential of 22 TWh of hydrogen storage capacity within the East Coast region, assuming a uniform cavern radius of 20 m and a cavern-to-cavern pillar width of 5 × cavern radius. Due primarily to geological constraints, specifically the morphology of the bedded halite formations, achieving this 22 TWh capacity requires the construction of approximately 1000 caverns. Increasing the storage capacity to 48 TWh would necessitate approximately 2200 caverns (Table 5). These estimates are consistent with previous literature, such as the work by Williams *et al.* (2022) and The Royal Society (2024), which suggest that approximately 3000 caverns would be required to achieve up to 100 TWh of storage capacity (Table 9).

Based on these findings, achieving an additional 22 TWh of salt cavern storage capacity by 2050 would require the construction of approximately 50 facilities, each comprising 20 caverns. Critically, many of these facilities would need to be developed concurrently to meet this ambitious target. This presents a significant logistical and project management challenge. The challenge is further amplified when considering larger storage capacity targets, given the typical 15 year development timescale for a single cavern facility (e.g. HyUnder 2013). Therefore, accelerating the development process, through innovation in construction techniques, streamlining regulatory processes and securing necessary resources, will be crucial to realizing the full potential of salt cavern hydrogen storage in the UK (Daniels *et al.* 2023).

Theoretical storage capacity – a site-selection tool for hydrogen in salt caverns

This study has co-developed an interactive site-selection tool for the development of a salt cavern hydrogen storage facility. The tool is designed to facilitate informed decision-making in the early stages of project development, and is publicly accessible and hosted on the GitHub repository: https://github.com/christian-garvey/idric-salt-cavern-hydrogen-storage.git. The open-source nature of this tool promotes transparency and collaborative development, allowing stakeholders to engage with the site-selection process.

The interactive tool allows users to explore the potential capacity of a given site and to conduct sensitivity analyses by adjusting key design parameters. Specifically, the tool enables exploration of the impact of the following variables on the overall storage capacity:

- Cavern radius: the radius of the individual salt caverns is a critical parameter influencing the storage volume. Increasing the cavern radius and height generally leads to a larger storage capacity but is constrained by geomechanical stability limits, engineering design envelope and the specific geological characteristics of the salt formation (Bérest and Brouard 2003; Bérest 2011). The tool allows users to input different cavern radii and observe the corresponding changes in storage potential, enabling an assessment of the trade-offs between cavern size and stability.
- Cavern pillar width: the pillar width, defined as the distance between adjacent caverns, is essential for maintaining the long-term geomechanical integrity of the storage facility. An insufficient pillar width can lead to stress concentrations and potential cavern instability (Yu *et al.* 2022; Cyran and Kowalski 2024). The tool allows users to vary the pillar width and examine its influence on the overall number of caverns that can be safely accommodated within a given site, directly affecting the total storage capacity. This allows for the optimization of the cavern layout to maximize storage while ensuring long-term stability.
- Withdrawal rate: the rate at which hydrogen can be withdrawn from the caverns is a crucial operational parameter. The tool allows users to adjust the withdrawal rate and observe its impact on the long-term pressure dynamics within the caverns. This is important for ensuring efficient injection and withdrawal cycles, and for maintaining the deliverability of the stored hydrogen. Furthermore,

the withdrawal rate can influence the overall energy efficiency of the storage facility.

By providing this interactive platform, stakeholders can gain a better understanding of the complex interplay between design parameters and storage capacity. This tool serves as a valuable resource for the preliminary site assessment and can inform more detailed feasibility studies. Future development of the tool could include the integration of additional site-specific data, such as geological surveys and geotechnical investigations, to further enhance its predictive capabilities and support more robust decision-making. Furthermore, the incorporation of economic parameters would enable users to conduct cost–benefit analyses of different design scenarios and generate necessary engineering inputs to building a viable business case.

Conclusion

The presented study shows a unique cluster-specific assessment for underground hydrogen storage capacity for the east coast of England with a replicable methodology that may be applied to any halite-bearing region. Salt cavern storage for hydrogen is a mature technology that has existed in the UK for more than 50 years, albeit at a relatively small scale compared to future requirements by 2035 and 2050. Current rhetoric from national policy documents and published literature assumes that large-scale hydrogen storage in salt caverns is readily available within the timescales for the net zero pathway and can meet the UK's hydrogen storage demand of up to 100 TWh by 2050; however, increasingly these assertions are being challenged.

The presented study revises the estimate of theoretical storage potential for the east coast of England. It proposes to call this an estimate of the *reserve potential*, which was found to be between 22 and 48 TWh. This is based on the following assumptions:

- Development is specific to the halite member of the Fordon Evaporite (FoE) Formation only.
- Caverns are modelled as a simple cylindrical form with constant volume corrections for bulking, insoluble fraction and to account for an imperfect mined shape. The estimates are based on a uniform horizontal cavern radius of 20 m.
- Each cavern is developed as part of a cluster of many caverns within a 2.5 km^2 development site.
- Development cannot occur within any defined surface criterion boundary.

It is important to stress that the modelled caverns and storage capacity estimates are theoretical, and more refined estimations of reserve potential will require site-specific geological investigations, in addition to site-specific consideration of technical feasibility and social and economic viability. This is beyond the scope of this study but is recommended for future research. Through further refinement, opportunities could be identified to develop hydrogen storage in salt caverns in techno-socio-economically challenging locations, which would unlock unconsidered development areas.

This study has reinforced that, outside of economic feasibility, the development of salt cavern storage is strongly limited by:

- Geographical and geological limitations of the halite-bearing strata, and obstructions to development on the surface.
- The location of suitable salt deposits in relation to protected sites and areas, the existing land use, natural heritage, landscape and historical designations, and the availability of land of sufficient size to develop a salt cavern storage facility.
- The time required to develop at scale, including inefficiencies of a nascent supply chain.

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