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Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt cavern storage potential of bedded halite formations

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ABSTRACT

Hydrogen can be used to enable decarbonisation of challenging applications such as provision of heat, and as a fuel for heavy transport. The UK has set out a strategy for developing a new low carbon hydrogen sector by 2030. Underground storage will be a key component of any regional or national hydrogen network because of the variability of both supply and demand across different end-use applications. For storage of pure hydrogen, salt caverns currently remain the only commercially proven subsurface storage technology implemented at scale. A new network of hydrogen storage caverns will therefore be required to service a low carbon hydrogen network. To facilitate planning for such systems, this study presents a modelling approach used to evaluate the UK's theoretical hydrogen storage capacity in new salt caverns in bedded rock salt. The findings suggest an upper bound potential for hydrogen storage exceeding 64 million tonnes, providing 2150 TWh of storage capacity, distributed in three discrete salt basins in the UK. The modelled cavern capacity has been interrogated to identify the practical inter-seasonal storage capacity suitable for integration in a hydrogen transmission system. Depending on cavern spacing, a peak load deliverability of between 957 and 1876 GW is technically possible with over 70% of the potential found in the East Yorkshire and Humber region. The range of geologic uncertainty affecting the estimates is approximately ±36%. In principle, the peak domestic heating demand of approximately 170 GW across the UK can be met using the hydrogen withdrawn from caverns alone, albeit in practice the storage potential is unevenly distributed. The analysis indicates that the availability of salt cavern storage potential does not present a limiting constraint for the development of a low-carbon hydrogen network in the UK. The general framework presented in this paper can be applied to other regions to estimate region-specific hydrogen storage potential in salt caverns.

1. Introduction

Decarbonised energy systems require clean fuels to compensate for curtailment and intermittency associated with fluctuations in renewable energy generation [1,2]. Hydrogen can serve as a near carbon-free energy vector when generated by electrolysis (powered by renewable energy), or through methane reformation fitted with Carbon Capture and Storage (CCS) technology [3,4]. It can be used to decarbonise challenging applications such as providing low-carbon power, heat for industrial processes, heating commercial buildings and homes during cold periods, and also as a fuel for heavy transport. The United Kingdom (UK) has developed a hydrogen strategy in which it is recognised that low-carbon hydrogen will be critical for meeting the UK's legally binding commitment to achieve net zero greenhouse gas emissions by 2050 [5–7]. The strategy aims to deliver 5 GW of hydrogen production capacity by 2030 for use across the economy [7]. Displacing natural gas consumption by use of hydrogen to generate low-carbon heat is considered a particularly attractive option for industrial, commercial, and domestic applications [8]. Current industry roadmaps for hydrogen production in the UK assume the majority of hydrogen in the near-term

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will be generated from natural gas by methane reformation with CCS, and offshore geological storage of the captured carbon dioxide [9,10]. Sunny et al. [4] show that such technologies can provide the UK with a cost-effective and low-carbon hydrogen-based heat supply when combined with negative emissions technologies. Storage of hydrogen will be a key component of any regional or national hydrogen network because of the variability of both supply and demand across different end-use applications. For example, gas demand for domestic heating is strongly affected by seasonality. Surface storage facilities such as pipelines and tanks, provide some limited storage capacity, however the requirements for inter-seasonal storage are most efficiently delivered by underground storage [11].

Underground storage of gas and liquid petroleum products is typically undertaken either in depleted oil and gas reservoirs, saline aquifer formations or engineered subsurface cavities such as mine workings or salt caverns [12]. Some studies have identified a significant potential for hydrogen storage in depleted UK gas fields [13,14]. However, storage of pure hydrogen in porous reservoir rocks is currently considered to be a low maturity technology with no commercially operating precedent. More fundamental research is therefore required to address the remaining challenges and to prove the feasibility for porous-rock hydrogen storage at scale [2,15]. Conversely, salt caverns have been used to store hydrogen for use in industrial processes over several decades. Salt caverns are artificially generated cavities in underground rock salt (halite) formations created by the solution mining process where halite is dissolved and removed in a controlled manner by injection of water [16]. Halite is both tight and inert to liquid and gaseous hydrocarbons and to other gases including hydrogen. The physical and behavioural properties of halite enable the construction and operation of very large (several hundred-thousand m^3) unlined stores that are stable for long periods of time, with many facilities successfully operating for several decades [16,17]. Unlike porous reservoirs, salt caverns are completely open cavities, enabling very high flow rates and providing significant operating flexibility. Abandoned brine-production salt caverns were first used to store natural gas at Hutchinson, Kansas in 1962 [18], while the first two purpose-built gas storage caverns were constructed at the Eminence Dome, Mississippi in 1970 [19,20]. Although existing brine caverns can be repurposed for gas storage where conditions allow, new specifically designed caverns are normally used in modern large-scale gas storage schemes.

Historically, underground storage of hydrogen has mostly comprised storage of town gas, a gas mixture containing 40–60% hydrogen together with carbon monoxide, methane and other volatile hydrocarbons, commonly used during the mid-20th Century [16,21,22]. To date, there are only a small number of underground storage facilities for pure hydrogen in operation worldwide, including salt caverns at three locations in Texas, USA, and a single facility comprising three caverns at Teesside in the north-east of England, UK [17,21,23,24]. These projects have demonstrated the commercial feasibility for salt cavern hydrogen storage over several decades. In this context, several studies have sought to evaluate the potential for hydrogen storage on a large-scale to support decarbonisation efforts in the UK. The potential for hydrogen infrastructure development was assessed in a study for the Department of Trade and Industry which included an assessment of storage potential in onshore salt caverns [25]. The Energy Technologies Institute subsequently undertook several detailed assessments of the potential role of hydrogen, including an assessment of salt cavern storage potential [24,26,27]. These studies concluded that the UK's salt bed resource could provide significant storage potential for hydrogen, including the re-use of existing natural gas storage caverns and the construction of new purpose-built facilities. However, an estimate of the total storage resource available was not provided. Significant potential for hydrogen storage in salt caverns has also been identified in several other European countries, notably Poland, Romania and Germany [28–30]. For Europe as a whole, the hydrogen storage potential, including offshore and onshore salt deposits, is estimated as 84.8 PWh [3].

If there is to be continued usage of natural gas in the UK economy, and indeed considering its vital role as a feedstock for hydrogen production, it is unlikely that a significant proportion of existing caverns can be made available for hydrogen storage in the near-term. Therefore, it is expected that the construction of new storage caverns will be required to enable the development of a UK hydrogen network [31]. New purpose-built storage caverns could potentially be developed in parts of the UK where thick and massive bedded halite sequences are present. Sedimentary basins where suitably thick halite formations are present include parts of East Yorkshire and the Humber, the North Sea, and the Cheshire, East Irish Sea and Wessex Basins [24,32,33]. This paper estimates the hydrogen storage potential of selected regions onshore UK by adapting the methodology of Parkes et al. [34], which evaluated the potential for Compressed Air Energy Storage (CAES) in the Cheshire Basin. Parkes et al. [34] developed a novel methodology to model a potential distribution of new storage cavern locations and to estimate the physical volumes that might be available for storage. A similar method was subsequently applied to estimate the potential for hydrogen storage in salt caverns across Europe [3]. Both studies estimate the usable volume of salt by modelling the placement of an idealised cavern design configuration. Whereas previous efforts to model the regional distribution of hydrogen storage capacity assume a standard cavern depth and volume, this study enhances the method by calculating the salt volumes available for cavern construction at each individual site. Operational pressure ranges are then estimated for each potential cavern location based on depth, and used to determine the storage volume and corresponding energy storage potential. The advantage of this approach is an enhanced accuracy of storage capacity estimates. The results can therefore be used to support infrastructure planning processes and to target detailed site appraisal studies. Theoretical cavern storage estimates are presented first to provide an upper-bound estimate of the available storage resource, followed by a sensitivity analysis. The outputs are then scrutinised to inform the storage capacity needed to support the transition towards a low-carbon heat network for the UK. The results can inform energy systems models seeking to establish optimal deployment pathways for new hydrogen networks.

2. Geology and salt cavern characteristics

2.1. Geology and salt distribution

Massive, thick-bedded halite formations of both Permian and Triassic age are present in a number of sedimentary basins onshore and offshore UK [35–42] (Fig. 1). A detailed account of their potential for underground gas storage is provided by Evans and Holloway [33] and Evans et al. [43]. Thick halite sequences with relatively homogenous and isotropic properties are generally favoured for hosting underground gas storage caverns. Host formations will need to be both aerially extensive and sufficiently thick to enable the construction of large numbers of caverns exceeding 100 m in height. Based on these criteria, together with UK gas storage experience [32,33], the present study therefore evaluates the potential for onshore hydrogen storage in the following formations:

- The Fordon Evaporite Formation of East Yorkshire, incorporating the Humber (Permian);
- The Northwich Halite Member of the Cheshire Basin (Triassic);
- The Dorset Halite Member of the Wessex Basin (Triassic).

Whilst the distribution of thick and continuous halite formations is spatially restricted, they may provide a storage option for several large industrial centres. The Fordon Evaporite is located conveniently to industrial clusters located along the northeast coast of England, including Teesside and the Humber, while the Cheshire Basin may provide an option for the industrialised northwest and North Wales.

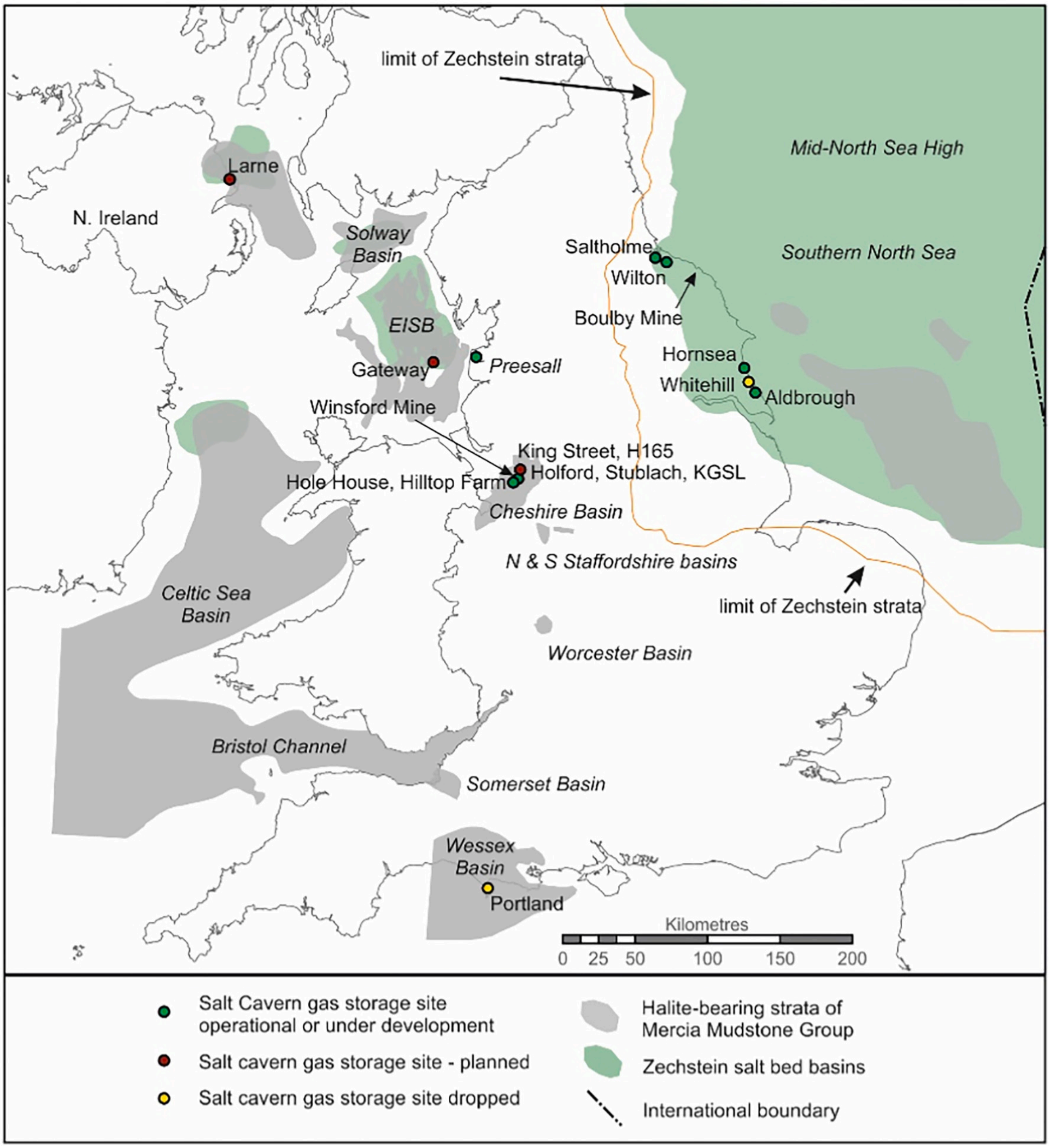

Fig. 1. Diagrammatic map of UK sedimentary basins containing massive, bedded halite deposits and the location of operational, planned and cancelled UK gas storage facilities (after [24]). Note that thin, aerially restricted onshore lateral equivalents of thick offshore Triassic halite formations are not shown. Abbreviations: EISB – East Irish Sea Basin; KGSL – Keuper Gas Storage Limited. Contains Ordnance Survey data © Crown copyright and database rights 2015. Ordnance Survey Licence no. 100021290.

Decarbonisation of industrial clusters forms a key component of current UK Government strategy [44].

2.2. Basin descriptions

2.2.1. East Yorkshire and Humber

The Southern Permian Basin (SPB) is a major sedimentary basin which extends for over 1000 km from eastern England and across Northern Europe to the eastern border of Poland [35]. During the Late Permian, a thick cyclic carbonate-evaporite sequence was deposited, ascribed to the Zechstein Group, which includes the Fordon Evaporite Formation (Figs. 2). The formation is present along a large part of the east coast of England, and extends beneath the southern part of the North Sea. The Permian (Z2) Fordon Evaporite Formation has already been developed for natural gas storage, and comprises the most extensive gas storage target in Eastern England. The formation hosts several large gas storage caverns at Hornsea and Aldbrough (Fig. 1) where it is found at >1600 m depth and is almost 300 m thick. Elsewhere, the formation is generally buried at depths exceeding 500 m and deepens towards the coast. Its thickness exceeds 300 m in some places. The current gas storage projects do not exploit the full thickness of available salt. Cavern diameter is typically equivalent to cavern height, in the order of 100 m, and caverns are operating at depths of between 1700 and 1800 m.

2.2.2. The Cheshire Basin

The Northwich Halite Member is one of two significant bedded halite formations present in the fault-bounded Cheshire Basin [36]. In difference to the Fordon Evaporite Formation, the Cheshire halites are Triassic in age. Triassic halite formations are considered as attractive options for

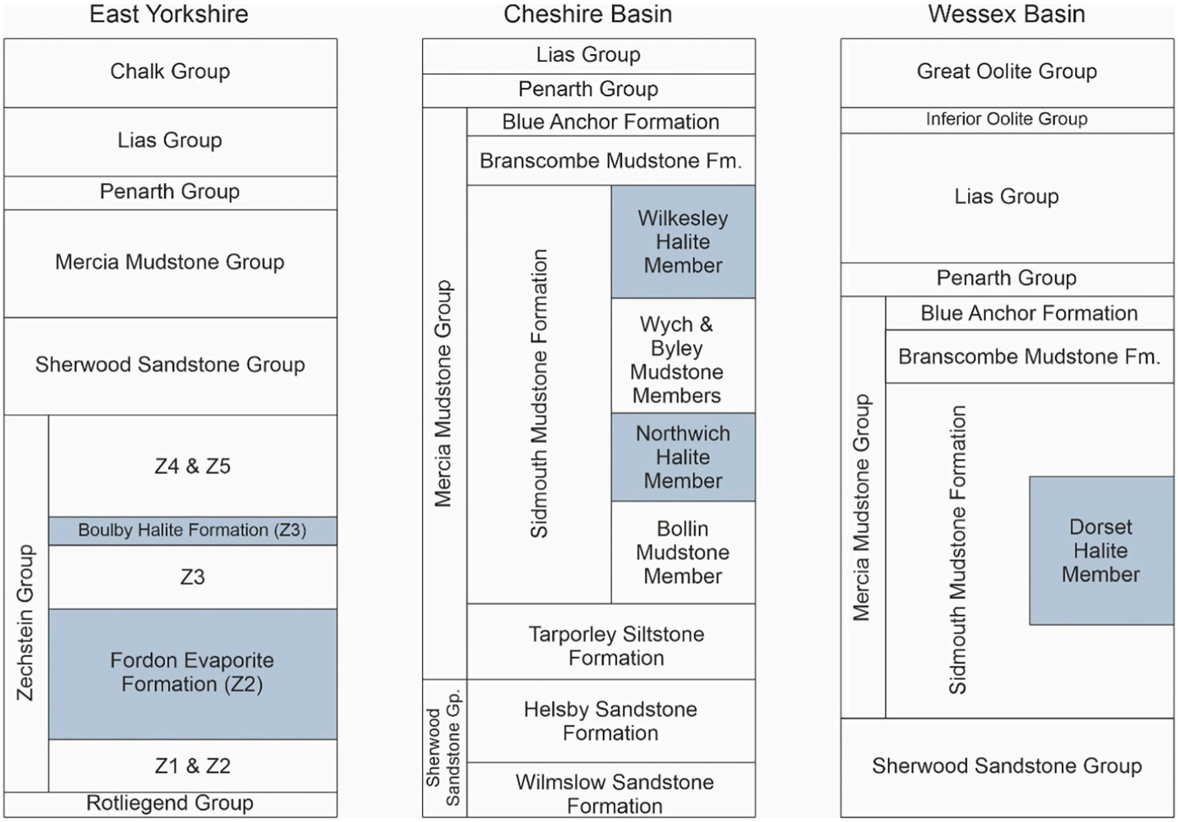

Fig. 2. Representative stratigraphic successions of the Cheshire Basin, East Yorkshire region and Wessex Basin showing principle halite-bearing units, after Evans and Holloway [33] and Howard et al. [45].

salt cavern development in the UK as they are commonly encountered at shallower depths relative to older Permian halite formations. The Northwich Halite Member of the Mercia Mudstone Group (Fig. 2) has been widely exploited for brine production and rock salt, and already hosts several natural gas storage cavern projects. The Cheshire Basin is the most developed region of the UK in terms of natural gas storage caverns, with at least 73 caverns in operation or planned for construction (refer [33,46]). Further gas storage projects are planned, signifying the capacity to develop multiple gas storage projects consisting of several individual caverns in the region. Halite is also extracted from the Winsford (Meadowbank) dry mine. At the eastern and northern parts of the basin the Northwich Halite Member is found at rockhead beneath Quaternary deposits, and generally deepens towards the basin-bounding Red Rock Fault and associated structures to the east. At depth, it is over- and underlain by the Byley and Bollin Mudstone members, respectively, and its maximum proven thickness is 283 m in the Byley Borehole [33]. The younger Wilkesley Halite Member is not generally considered for potential salt cavern development as it subcrops Quaternary deposits over much of the basin, although it may have some potential restricted to deeper parts of the basin.

2.2.3. *The Wessex Basin*

In the Wessex Basin of southern England, the Triassic Mercia Mudstone Group comprises a saliferous unit known as the Dorset Halite Member. The saliferous unit underlies much of Dorset, where it is concealed beneath an often-thick cover of Jurassic and younger rocks [33,39,41]. Consequently, the presence of salt remained undiscovered prior to oil and gas exploration activities during the 1970s. Despite the presence of salt being proven in a series of boreholes, the nature and lateral continuity of many of these accumulations are still relatively poorly defined. The structure of the region is relatively complex, with a series of sub-basins disrupting the continuity of the Dorset Halite Member. Consequently, wells in the region encounter significant variation in the thickness of individual halite units. The saliferous section is very impure in places and contains numerous mudstone beds, especially in the upper sections of the Dorset Halite. Consequently, wells in the region encounter significant variation in the thickness of individual halite units. The offshore limits are poorly constrained due to lack of borehole penetrations, but the lack of halite in boreholes on the Isle of Wight indicate that the eastern limit is located offshore beneath Bournemouth Bay. The halite is shallowest in the north of the basin where it is found at 422 m in the Marshwood borehole, although it reaches depths exceeding 2000 m to the south and offshore. An appraisal well, Portland 1, was drilled to prove the depth and thickness of the Dorset Halite Member for gas storage purposes on the Isle of Portland, proving a 470 m saliferous sequence with the main halite being 135 m thick [33]. Although planning permission for the Portland Gas Storage Project was granted in 2008, the project failed to raise sufficient capital and to date no gas storage caverns have been constructed in the region [32]. Given that the geological uncertainty remains significant and there is no operational precedent for underground gas storage in the region, the Wessex Basin is considered to be something of a frontier prospect for energy storage in salt caverns.

Careful site investigations are required prior to development of Triassic halites, as halite beds may be thin and of variable thickness. Additionally, they may also contain a high proportion of impurities and mudstone interbeds, particularly towards basin margins. Consequently, potential cavern dimensions and storage volumes may be reduced. This is particularly true in the Wessex Basin where the structure is relatively complex resulting in disruption to the continuity of the Dorset Halite. While hydrogen storage capacity estimates for the Wessex Basin are included in this study, they are subject to a greater degree of uncertainty relative to the Cheshire and East Yorkshire regions where salt cavern feasibility has been proven through many years of natural gas storage cavern operation.

2.2.4. Salt cavern potential of other regions

In addition to the three regions considered in this study, there may also be some potential for additional hydrogen storage in some of the less extensive UK halite formations. Although these regions may provide some storage potential for local applications, their storage potential is not considered likely to be significant. In the future there may also be significant potential for hydrogen storage offshore. The storage potential and limitations in these additional onshore and offshore halite formations is discussed further in Appendix A.

2.3. Storage cavern design and operational conditions

2.3.1. Hydrogen storage cavern experience

Commercial-scale hydrogen storage in salt caverns is currently undertaken in only a small number of locations, including Teesside in the UK (Fig. 1), as well as at three locations in Texas, USA. At Teesside, hydrogen is stored in three former brine caverns in the Saltholme Brinefield which is part of the larger Teesside salt field [47,48]. The caverns exploit thin eastwardly dipping Permian salt beds of the Boulby Halite Formation at relatively shallow depths of 350 to 450 m. The caverns are relatively small and are flat and elliptical in form, with each cavern storing around 70,000 cubic metres (m^3) of hydrogen for use in industrial processes. The caverns are operated in brine-compensated mode at pressures of 45 to 50 bar [2,17,23,49], and have a combined estimated energy storage potential of 25 gigawatt-hours (GWh) [50].

Hydrogen storage caverns have also been operated in Texas since the 1980s. The caverns are constructed in salt domes at depths exceeding 800 m [2,17,23,24,49]. They are generally much deeper and larger than the Teesside caverns, and therefore operate at greater pressures. Due to the exploitation of salt domes, the aspect ratio of these USA caverns differs markedly from typical gas storage cavern designs in UK bedded halite deposits. Existing hydrogen cavern properties are summarised in Table 1.

The designs of both the Teesside and Texas caverns are rather atypical of those that will be required to provide large-scale hydrogen storage onshore UK. Whilst small caverns such as those in Teesside may be useful for local end-use applications, their capacity would be insufficient to provide storage for a national hydrogen storage and distribution system. Conversely, caverns with the dimensions of those in the USA will rarely be possible onshore UK because the distribution of halokinetic structures such as salt domes is largely limited to offshore regions in the North Sea. Onshore caverns in the UK will therefore more closely resemble those currently in use for storage of natural gas. While operational requirements and rock mechanical properties will ultimately dictate cavern design, there are no significant differences in the general geotechnical requirements between hydrogen and natural gas storage caverns [2,29]. Current natural gas storage caverns therefore provide a useful indication of potential cavern geometries and the conditions under which new hydrogen storage caverns may be operated in UK settings [32,33]. As hydrogen storage caverns may need to be cycled rapidly, caverns may resemble modern fast-cycle natural-gas storage caverns. The most distinguishing characteristic of fast-cycle caverns is their deliverability capability, where caverns can be cycled rapidly several times throughout the year to meet fluctuating demands. One key issue of relevance to storage facility design, is that the volumetric energy density of methane gas exceeds that of hydrogen by a factor of 3.2, meaning a hydrogen storage cavern will store significantly less energy than an equivalent-sized natural gas storage cavern.

Table 1
Characteristics of existing salt cavern hydrogen storage projects (after [2,17,23,49,50]). m, metres. GWh, gigawatt-hours. NA, not applicable.

	UK	USA		
	Teesside	Clemens Dome	Moss Bluff	Spindletop
Depth to cavern top (m)	350–450	850	823	1128
Cavern height (m)	15–40	300	579	518
Cavern diameter (m)	70	49	60	76
Cavern volume (m^3)	70,000	580,000	566,000	NA
Operational pressure range (bar)	45–50	70–135	55–152	NA
Energy stored (GWh)	25	92	120	>120

2.3.2. Gas storage volumes – Definitions

Underground gas storage facilities generally operate by compressing the storage gas during injection and decompressing the gas during withdrawal. The total gas storage capacity or volume is the maximum volume of gas that can be stored at the storage facility. This is governed by physical factors, such as the reservoir volume, engineering, and operational procedures including minimum and maximum pressure ranges, temperature, and injection rates, which are determined from rock mechanical studies. The total storage volume comprises two elements:

- Working gas volume, which represents the available gas that can be used between the maximum and the minimum operating storage pressures, providing the usable energy storage;
- Cushion gas volume, representing the unavailable gas that is below the minimum operating pressure and which must remain permanently in the store to provide the required minimum pressure to maintain the geomechanical stability of the storage cavern. In the case of porous rock storage, it also provides some of the drive, but it is irretrievable, being effectively lost in the porosity. During salt cavern storage operations, it is irretrievable until final cavern emptying and abandonment, where caverns are typically stabilised by filling with a concentrated brine.

3. Estimation of cavern volumes and hydrogen storage potential

3.1. Modelling cavern volumes

A GIS-based methodology is used to identify potential locations for new underground storage caverns together with an estimation of the physical volumes available for storage. The approach was first established by Parkes et al. [34] to estimate the storage capacity for Compressed Air Energy Storage (CAES), and was subsequently applied to model the CAES exergy storage potential of the main halite-bearing sequences across the UK [46]. The methodology of Parkes et al. [34] was used to model initial cavern placement and to calculate raw cavern volumes, albeit using depth ranges and cavern size constraints suitable for natural gas storage schemes rather than CAES. The method was further developed here to enable computation of hydrogen storage capacity and deliverability of the modelled cavern volumes. The procedure is summarised by Fig. 3.

Previous efforts to estimate hydrogen storage capacity across large regions (i.e. [3]) have assumed constant depth and thickness across sedimentary basins. A key feature of the process employed here is the use of structural maps designating the variation in depth and thickness of the salt formations across the areas of interest. The maps were derived from structure contour maps and borehole data available to the British Geological Survey. For illustrative purposes, the Cheshire Basin maps are depicted in Fig. 4. Improved estimates of storage capacity are enabled by allowing for variation in the dimensions of the modelled cavern distribution based upon the subsurface disposition of the host-rock formations.

A theoretical placement of caverns is distributed by modelling a regular, close-packed hexagonal grid pattern within the selected regions. The cavern grid distribution was implemented in GIS using tools developed by Jenness [51] and optimises use of the available salt for cavern development. With this arrangement, approximately 15% more

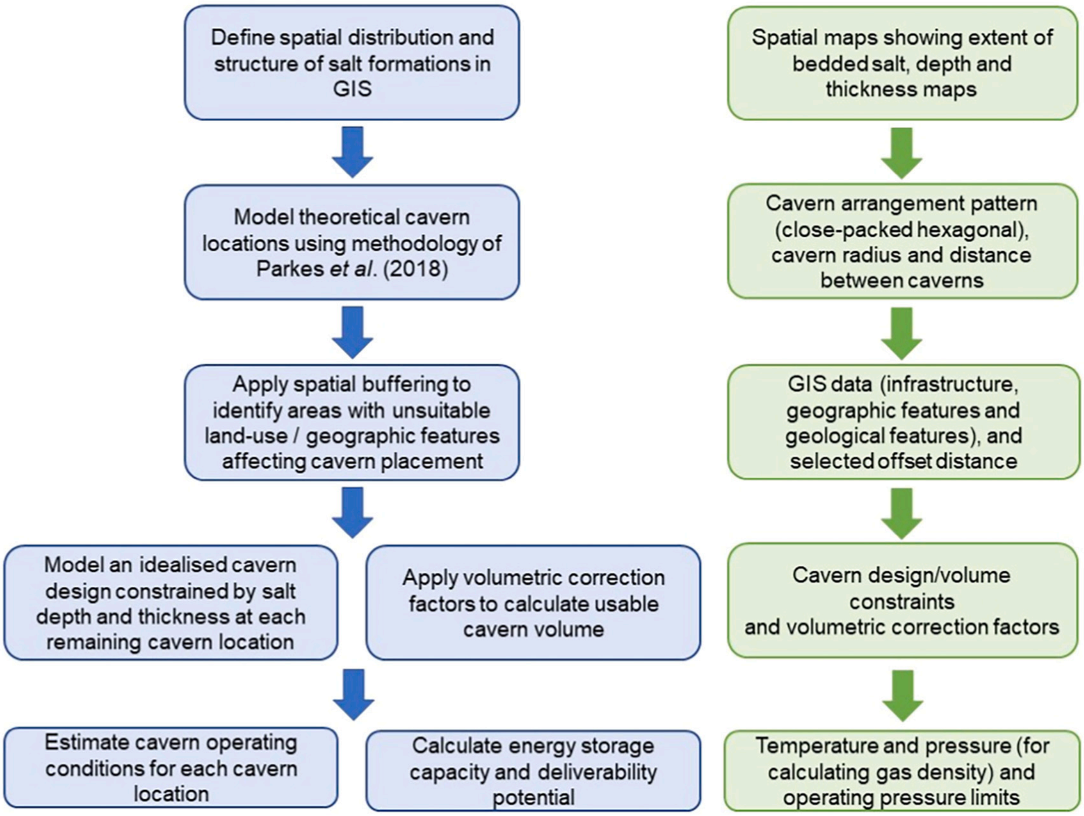

Fig. 3. Methodology for estimation of salt cavern storage capacity. Step-wise process shown on the left, with input data requirements shown on the right.

caverns can be placed relative to a rectangular grid layout. The distribution honours the following rules:

1. Caverns are of a uniform diameter of 100 m (50 m radius);
2. Distance between caverns is set at 150 m (3 × radius).

The cavern diameter of 100 m was selected based on the diameters of large salt caverns commonly employed for natural gas storage in the UK, while the fixed pillar width of 150 m is based on modelling work undertaken in support of the planning application for the Preesall Gas Storage Project [52]. Sensitivity to both cavern radius and pillar width is described in Section 4.3.

There are many areas where development of salt caverns may not be appropriate due to the presence of surface infrastructure, environmentally sensitive areas or geographical features such as waterways and coastlines. Issues may include difficulties in siting drilling and operating equipment, including brine disposal infrastructure, or protracted environmental assessments and planning considerations. There may also be safety concerns relating to cavern integrity and subsidence, necessitating appropriate stand-off distances from roads, railways or urban settings. Subsurface features of note include subsurface mine workings and existing gas storage and brine caverns. Detrimental geological conditions include areas where halite is present at rockhead (referred to as wet rockhead) and faults. Wang et al. [53] suggest that gas storage caverns should be offset from major tectonic faults by no less than twice the cavern diameter. Detailed assessments undertaken for the Preesall Gas Storage Project indicated that salt pillar width between caverns and major faults should be no less than three times the maximum cavern radius, decreasing to two times cavern radius for smaller intrabasinal faults [54].

A GIS buffer layer incorporating all of these features was generated to eliminate locations that would likely prove to be unfeasible or problematic to develop. An exclusion zone of 150 m (three times the cavern radius) was created around such features to be consistent with the pillar width used in the theoretical cavern placement. The process for modelling cavern locations is illustrated in Fig. 5.

Following spatial buffering, salt depth and thickness attributes were extracted for the remaining cavern locations for modelling of caverns and volume calculations. The modelled caverns are constrained by several geometrical restrictions that ensure consistency with common cavern designs, while also accounting for engineering safety requirements (Table 2). The constraints are based on the cavern design principles of the UK's operating and planned underground natural gas storage schemes. While some parameters are based on those used in the CAES assessment of Parkes et al. [34], others have been modified to reflect the differences between CAES and natural gas storage to provide a better indication of the likely geometries of future hydrogen storage caverns. Full descriptions of the parameters and rationale behind each of the selected values are detailed in Section 3.2.

Application of the geometrical constraints produces a distribution of caverns with variable heights, dependent on the depth and thickness of the salt at each location (Fig. 6). Where the depth and thickness of the salt at a given location do not allow for caverns within the constraints, the location is excluded from further analysis.

3.2. *Cavern volume constraints*

3.2.1. *Cavern depth*

The casing shoe depth is restricted to the range of 250 to 1800 m below ground surface level, as per current UK natural gas storage examples. Worldwide experience shows that caverns can be constructed at greater depths, and deeper caverns were previously planned in the UK at a depth of approximately 2400 m as part of the Portland Gas Storage Project [33]. The depth range selected for this study can therefore be considered to be globally conservative, but consistent with the current depth window used by operating gas storage facilities in the UK. Deeper

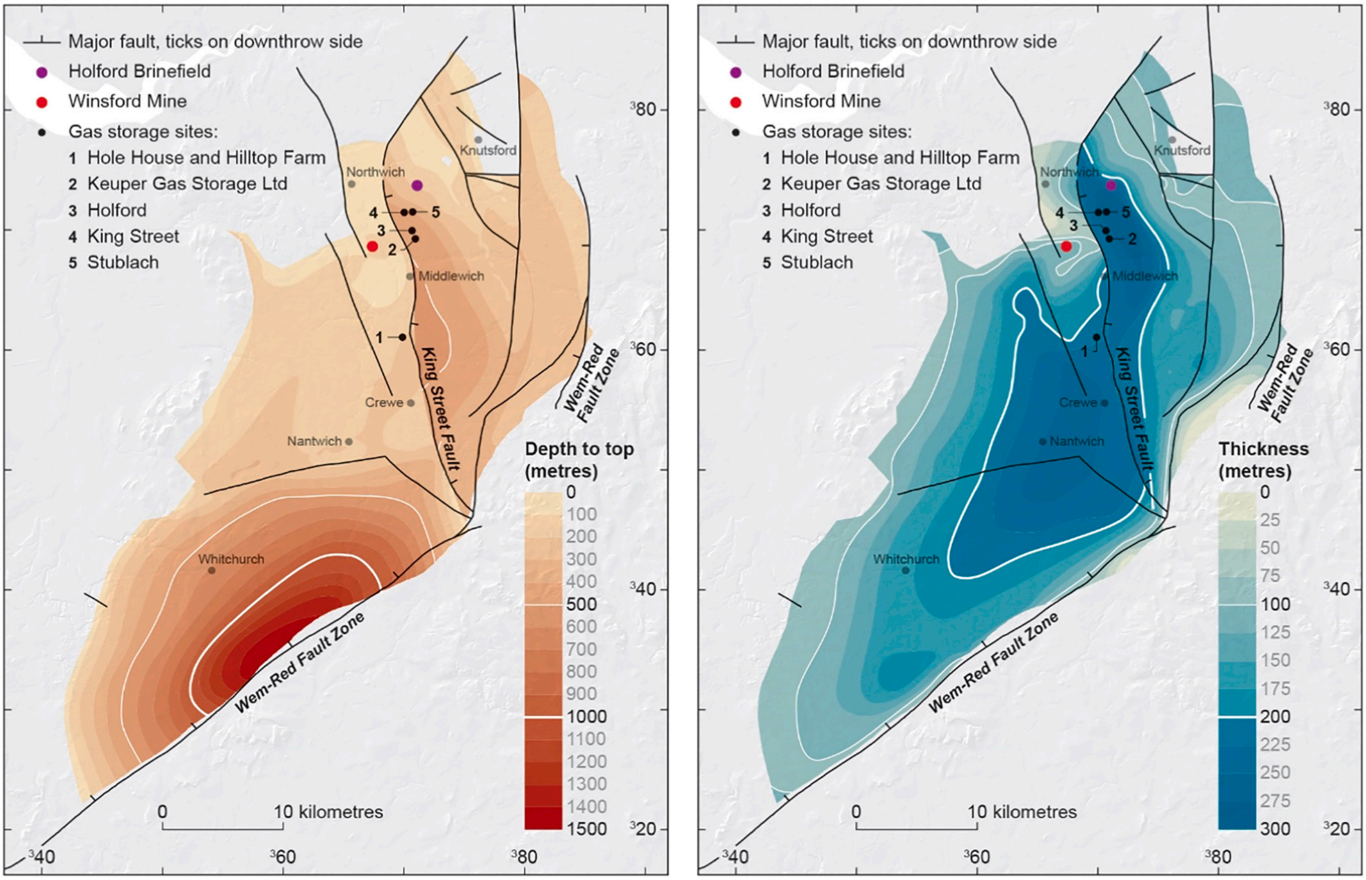

Fig. 4. Depth to top (left) and thickness (right) of the Northwich Halite Member of the Cheshire Basin. Depth units are metres (m) measured relative to ground surface. Surfaces derived from British Geological Survey models generated during the IMAGES (Integrated, Market-Fit and Affordable Grid-Scale Energy Storage) project. Contains Ordnance Survey data © Crown copyright and database rights 2015. Ordnance Survey Licence no. 100021290. NEXTMap Britain elevation data from Intermap Technologies.

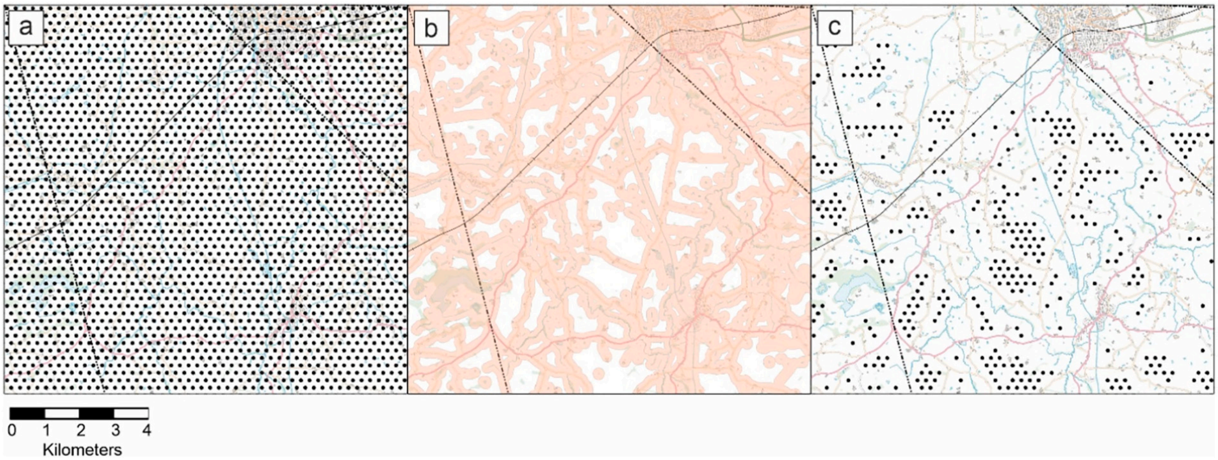

Fig. 5. Process for generating theoretical cavern locations. a) Initial cavern placement based on a close-packed hexagonal grid framework. b) Infrastructure buffer file. c) Final viable cavern locations. Contains Ordnance Survey data © Crown copyright and database rights 2015. Ordnance Survey Licence no. 100021290.

caverns may be beneficial in the context of hydrogen storage because greater pressures will enable increased storage volumes.

3.2.2. *Cavern height*

The minimum allowable storage cavern height used is 20 m, based on the dimensions of storage caverns operating in thinly bedded halite in the USA [55]. Currently, the height of natural gas storage caverns in the UK is commonly around 80 to 120 m [34]. The usable salt thickness is often limited by the presence of thicker mudstone interbeds or intervals with greater insoluble contents. Hydrogen storage operations would benefit from caverns with larger dimensions due to the lower volumetric energy density of hydrogen relative to natural gas. However, development of such caverns will be conditional on the local nature of the halite and large caverns would need to meet operational conditions and be

Table 2

Base case geometrical cavern constraints used to estimate theoretical hydrogen storage capacity.

Parameter	Value (m)
Minimum casing shoe depth	250
Maximum casing shoe depth	1800
Minimum cavern height	20
Maximum cavern height	300
Minimum salt roof thickness	20
Minimum salt floor thickness	10

capable of operating within the engineering envelope for a given project. Although maximum cavern heights are ultimately restricted by available salt thickness, a maximum cavern height of 300 m is adopted in this study after Ozarslan [1] for the calculation of theoretical storage capacity.

3.2.3. Minimum roof and floor salt thickness

To ensure structural integrity, an adequate thickness of roof salt above the cavern is required. The casing shoe was therefore set at least 10 m below the top of the halite. To further ensure cavern integrity and compliance with UK gas storage regulations, the cavern roof is set a further 10 m beneath the casing shoe. The Health and Safety Executive [56] require a minimum of 3 m of salt to be present between the casing shoe and cavern top, while a minimum of 10 m roof salt is suggested for caverns in thinly-bedded halite formations in the United States [57]. The parameters used here ensure that the roof salt comprises at least 20 m of halite above the cavern top which may be a conservative requirement. In practice, the required roof salt thickness will depend on the site-specific salt properties and required operational parameters such as cavern cycling rates, and will be informed on a project-basis through geomechanical modelling. A minimum floor salt thickness of 10 m was left beneath the base of the caverns. This is consistent with the 5 to 10 m floor salt thickness proposed by Geostock [54].

3.3. Modelling cavern volumes

Following Parkes et al. [34], cavern volumes were calculated assuming simple cylindrical caverns modified using correction factors to calculate the physical volumes available for storage. The correction factors account for reduction in usable cavern volume that results from deviation of cavern shape from idealised form, and the presence of insoluble materials within the salt which remains in the cavern following the solution mining process. The following correction factors were used to calculate bulk cavern volumes (V_{Bulk}):

1. A Shape Correction Factor (SCF) that accounts for deviation from the idealised form, and cavern wall roughness due to imperfect dissolution of halite beds. Based on modelling work by Mott MacDonald [52], a uniform SCF of 0.7 was applied.
2. An Insoluble Fraction (IF), that is the proportion of insoluble material within the salt at the cavern location. This may be supplied as maps of insoluble content, generally derived from wireline logging of nearby boreholes or as a representative constant. The IF accounts for non-halite lithologies interbedded with the salt, as well as the insoluble mineral content of the salt beds. A uniform value of 0.25

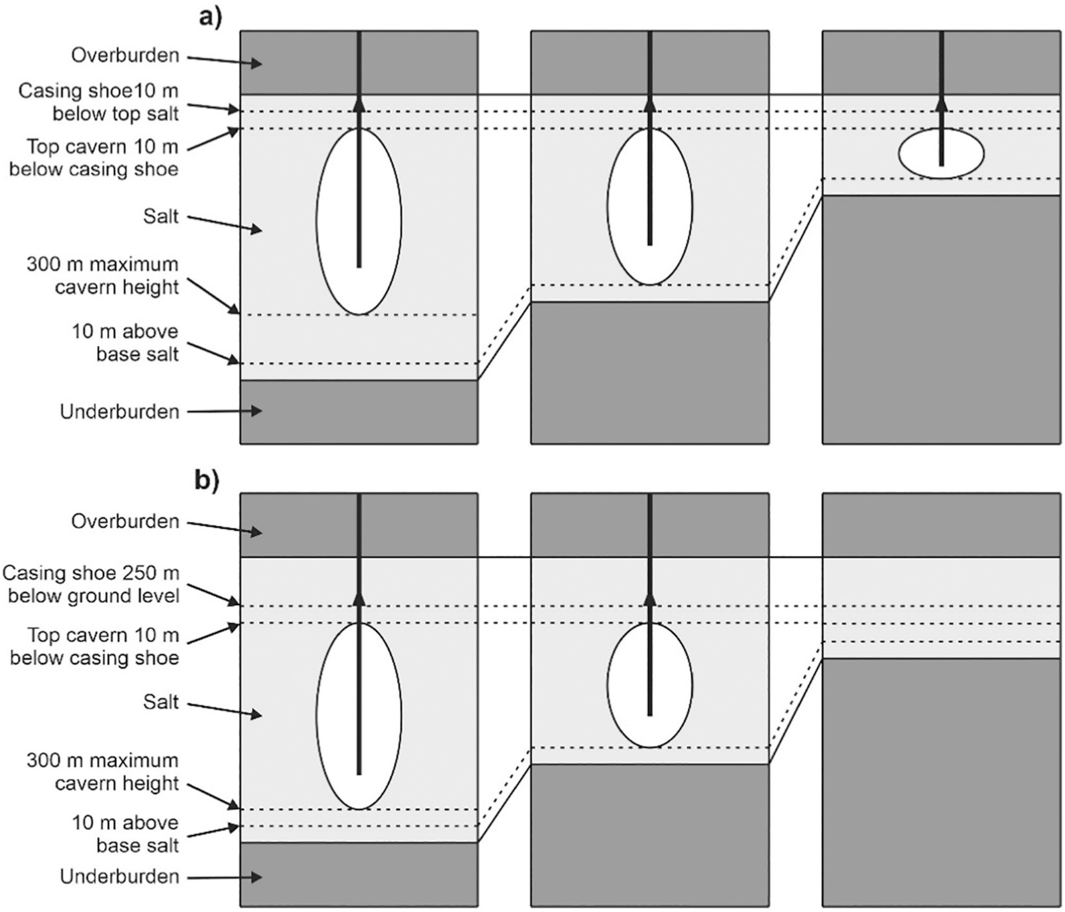

Fig. 6. Geometrical cavern design constraints for variable salt deposit thickness where a) top salt is deeper than 250 m depth and b) top salt is shallower than 250 m. Note that for a shallow and thin salt deposit the constraints do not allow cavern development due to the minimum cavern height stipulation of 20 m. Position of the casing shoe is shown as a triangle on the cavern construction borehole (black line). Image is for illustrative purposes only and dimensions are not to scale.

was used here after Earp et al. [36] based on UK brine cavern construction experience.

3. A correction for the fraction of insoluble material that remains in the cavern after mechanical sweeping (INSF). At Preesall it was estimated that 86.5% of the insoluble content would remain within the cavern due to sweep inefficiency. This material forms the cavern sump area [52].
4. A Bulking Factor (BF) to account for the uneven stacking of the INSF material within the cavern sump. Based on the Preesall work of Mott MacDonald [52], this was taken to be 1.46.

Applying the correction factors, the cavern volume that is available for storage (V_{Corr}) is evaluated as:

$$V_{Corr} = SCF \times (1 - IF \times INSF \times BF) \times V_{Bulk} \tag{1}$$

The resulting available volume V_{Corr} is 47% of V_{Bulk}. The correction factors selected are based on unpublished detailed modelling work undertaken for the Preesall Gas Storage Project. In practice these will vary between cavern locations and should be derived on an individual project basis. The insoluble content can be particularly variable across an individual basin and should be determined by analysis of geological logs and downhole samples.

3.4. *Estimation of hydrogen storage volumes*

3.4.1. *Cavern operating conditions*

Assuming that the hydrogen gas will be cooled following compression, it will be injected at near cavern temperature. Similarly, the hydrogen will cool as it expands during extraction, and will need to be heated before being fed to a turbine or chemical process. Whilst there is a thermal aspect, assuming storage at ambient cavern temperature is considered to be a reasonable approximation for calculation of storage capacity. For each cavern location, the temperature at the cavern midpoint ($T_{MidPoint}$) is therefore given by:

$$T_{MidPoint} = T_0 + \Delta_T \times \left(Z_{Casing} + 0.5 \times H_{Cavern}\right) \tag{2}$$

where T_0 is the mean annual surface temperature (10 °C), ΔT is the change in temperature with depth (geothermal gradient), Z_{Casing} is the casing shoe depth relative to ground surface and H_{Cavern} is the cavern height. The geothermal gradients used are 27 °C per kilometre for the Cheshire Basin, 31.9 °C per kilometre for East Yorkshire and 34.5 °C per kilometre for the Wessex Basin (after [58]). Measured temperatures in all regions are subject to considerable variation and are therefore subject to significant uncertainty [58].

The lithostatic pressure at the casing shoe (P_{Casing}) is dependent on the average density of the rock material between the casing shoe and the ground surface, which is always comprised of both overburden lithologies and salt, such that:

$$P_{Casing} = (\rho_{Overburden} \times t_{Overburden} + \rho_{Salt} \times t_{Salt}) \times g \tag{3}$$

where $\rho_{Overburden}$ is the density of the overburden, $t_{Overburden}$ is the thickness of the overburden (same as depth to top of salt), ρ_{Salt} is the density of salt, t_{Salt} is the thickness of salt above the casing shoe and g is the acceleration due to gravity (9.81 m/s^2). A density of 2400 kilogrammes per cubic metre (kg.m^{-3}) has been assumed for the overburden density, which is a typical value for Mercia Mudstone Group strata in the Cheshire Basin; the salt density of 2200 kg.m^{-3} is representative of pure halite. The calculated pressures are consistent with ranges reported for the north of England by Fellgett et al. [59]. During operation of a gas storage cavern, the range of allowable pressure is carefully controlled to maintain the cavern integrity. The upper operating pressure is kept below the lithostatic pressure to prevent opening of fractures and damage to the cavern walls. The lower operating pressure has to be sufficient to ensure deliverability during gas withdrawal and to prevent closure of the cavern through mechanical creep. The operational requirements of the facility (including cycle-rates), together with local rock mechanical properties will determine the optimal operational pressure range, which may be up to 0.83 and no lower than 0.3 of lithostatic pressure [52]. This analysis adopts maximum and minimum operating pressures of 0.8 and 0.3 of the lithostatic pressure at the casing shoe respectively, based on Kruck et al. [22]:

$$P_{MaxOperating} = 0.8 \times P_{Casing} \tag{4}$$

$$P_{MinOperating} = 0.3 \times P_{Casing}$$

3.4.2. *Energy storage capacity*

The minimum and maximum operating pressures are used to estimate the corresponding densities of hydrogen at cavern conditions using the equation of state of Bell et al. [60]. These densities are then multiplied by the corrected cavern volume to provide the stored mass of hydrogen at the maximum and minimum operating pressures:

$$m_{MaxOperating} = \rho_{H2Max} \times V_{Cavern} \tag{5}$$

$$m_{MinOperating} = \rho_{H2Min} \times V_{Cavern}$$

where $m_{MaxOperating}$ is the mass of hydrogen at the maximum operating pressure, ρ_{H2Max} is the density of hydrogen at the maximum operating pressure, V_{Cavern} is the cavern volume, $m_{MinOperating}$ is the mass of hydrogen at the minimum operating pressure and ρ_{H2Min} is the density of hydrogen at the minimum operating pressure. The working mass (kg) of hydrogen ($m_{Working}$) that can be stored in the cavern is the difference between these values:

$$m_{Working} = m_{MaxOperating} - m_{MinOperating} \tag{6}$$

The mass of hydrogen at the minimum operating pressure represents the cushion gas requirement. The energy storage capacity of the cavern in GWh is computed from the working hydrogen mass:

$$E = m_{Working} \times \frac{LHV}{3,600,000} \tag{7}$$

where *LHV* is the lower heating value of hydrogen in megajoules per kilogramme (119.96 MJ·kg^{-1}). Heat transfer by adiabatic processes are not considered in this work, while use of the *LHV* rather than the higher heating value means the reported energy storage estimates can be considered to be conservative.

3.4.3. *Cavern deliverability potential*

The storage capacities can also be considered in the context of cavern deliverability. The rate at which hydrogen can be extracted from a cavern is constrained by the requirement to maintain cavern stability through limiting the effects of extreme mechanical and thermal loading. Pressure drop rates in seasonal gas storage caverns are typically 0.8–1 MPa per day, although can be as high as 2 MPa per day [61,62]. Pressure rates are far greater in CAES operations, typically around 0.5 MPa per hour and possibly as high as 1.5 MPa per hour [61,63]. For a given extraction pressure rate (ΔP_{day}), the average delivery rate of a cavern can be approximated from the energy storage capacity and the operating pressure range. The number of days to deliver the working capacity of the cavern is approximated by:

$$n_{days} = \frac{P_{MaxOperating} - P_{MinOperating}}{\Delta P_{day}} \tag{8}$$

The daily energy delivery rate is then given by:

$$E_{day} = \frac{E}{n_{days}} \tag{9}$$

In practice the daily rate will vary throughout a delivery cycle due to changes in stored hydrogen density as the cavern is emptied and pressure decreases, impacting the mass of hydrogen remaining in the cavern and hence the amount of energy stored. The E_{day} value should therefore be considered to be an indicative average over the delivery period. The experience of operational natural gas storage caverns is that <10% of the working gas should be extracted in a single day, with a maximum of 10 turnovers per year [17]. The rationale behind this guidance is to minimise mechanical stress on the cavern walls, and would be equally applicable to hydrogen storage caverns. Maximum acceptable rates for filling and emptying caverns are governed by the maximum flow rates in the boreholes and the maximum pressure reduction rates permissible in the caverns. In practice these specifications are determined by the local geomechanical properties of the halite beds. The calculated deliverability estimates are controlled by the rate of pressure change within the caverns, and are independent of the number of working extraction wells.

4. Results

4.1. Total theoretical storage potential

For each basin, the total working hydrogen storage capacity can be calculated by summing the estimates from all modelled cavern locations (Table 3). The reported estimates provide static storage capacities, and do not account for cycling of working gas volumes or optimal extraction rates for any given application. Nevertheless, it is useful to quantify the total theoretical storage potential given the available geological storage resource and the adopted technical criteria in Table 2. The combined hydrogen storage capacity of all modelled caverns across the different regions exceeds 64 million tonnes, providing 2151 TWh of theoretical storage potential. The estimates are subject to significant sources of uncertainty which include the depth, thickness and physical properties of the salt formations. The sensitivity to these geological uncertainties is addressed in Section 4.3.

East Yorkshire has the greatest storage potential of the three regions considered, owing to the extensive and deep nature of the Fordon Evaporite. The deeper caverns permit storage of greater volumes due to the increased pressure and corresponding gas compression relative to shallower caverns of a comparable size and physical volume. The Dorset Halite of the Wessex Basin is also buried to a depth that provides for significant theoretical storage potential, while the storage potential of the Northwich Halite in the Cheshire Basin is lower owing to its shallower depth over much of its extent. In East Yorkshire more than six times the number of caverns are modelled than for the Cheshire Basin, and more than twice as many caverns than modelled in the Wessex Basin. For comparison with the results shown in Table 3, the UK's National Gas Transmission System (NTS) currently delivers 995 TWh of natural gas [64], whilst using approximately 16 to 30 TWh of dedicated storage [65].

Table 4 provides key geometrical and capacity parameter ranges for the modelled caverns in each region. Caverns are modelled in Cheshire at casing depths ranging from 261 to 1468 m. The thickness of the Northwich Halite constrains the maximum cavern height to 262 m. Shallower caverns are not possible in East Yorkshire as the minimum casing shoe depth is modelled at 747 m. The depth of the Dorset Halite in the Wessex Basin enables caverns to be modelled within the full depth range considered in the study (250–1800 m). Despite the lower storage potential in the Cheshire Basin relative to the other two regions, the theoretical energy storage potential is still significant. The large number of relatively shallower cavern locations may prove to be highly efficient in meeting more local, limited storage demands for particular end-uses.

Table 4
Key parameter ranges for modelled caverns in each region. Average values are provided in brackets.

	Cheshire Basin	East Yorkshire	Wessex Basin
Cavern casing shoe depth range (m)	261–1468 (699)	747–1800 (1524)	250–1800 (1240)
Cavern height range (m)	28–262 (137)	20–300 (130)	20–300 (145)
Physical cavern volume range (m^3)	106,934–986,482 (514,774)	75,315–1128,599 (488,178)	76,293–1128,599 (546,384)
Maximum cavern operating pressure range (MPa)	4.9–27.6 (13.2)	14–33.9 (28.7)	4.6–33.9 (23.3)
Working hydrogen mass range (tonne)	397–5577 (2981)	486–13,239 (5218)	310–10,632 (4944)
Equivalent energy storage range (GWh)	13–186 (99)	16–441 (174)	10–354 (165)

The distribution of total theoretical basin-wide storage capacity is shown by the energy storage capacity range of individual caverns along with the number of caverns within the corresponding capacity ranges in Fig. 7. There is generally a positive relationship between total basin-wide storage capacity and per cavern capacity range. This reflects the significant contribution of higher-capacity caverns to the overall storage capacity estimates. In the Cheshire Basin for example, 60% of the caverns have individual storage capacities below 120 GWh, representing 40% of the overall basin-wide storage potential.

For some end-use applications, it may be necessary to consider caverns of a certain size in order to provide optimally-designed storage facilities. While small caverns may be sufficient to provide storage for certain purposes, other end-use applications will require high-capacity caverns to balance storage demand and deliverability requirements. It is therefore useful to consider the theoretical storage capacity available in caverns of a given size. Fig. 8 shows the amount of total basin energy storage that is available in caverns of a given capacity or greater. For example, in the Cheshire Basin, the total amount of theoretical basin-wide energy storage capacity is 129 TWh, but the amount that is available in caverns with an individual energy storage capacity of 120 GWh or more is approximately 77 TWh. In each of the regions the overall storage capacity clearly reduces as the storage requirement for individual caverns is increased.

The spatial distribution of storage capacity across the study regions is

Table 3
Theoretical storage capacity for underground hydrogen storage in the UK. Note the modelled cavern size is not uniform, as cavern height is dependent on available salt thickness.

Region	Number of caverns	Combined cushion gas requriement of all caverns (kilotonnes)	Combined working hydrogen storage mass of all caverns (kilotonnes)	Combined theoretical energy storage capacity of all caverns (TWh)
Cheshire Basin	1297	2536	3867	129
East Yorkshire	8425	30,860	43,963	1465
Wessex Basin	3378	11,442	16,703	557
TOTAL	***13,100***	***44,838***	***64,533***	***2151***

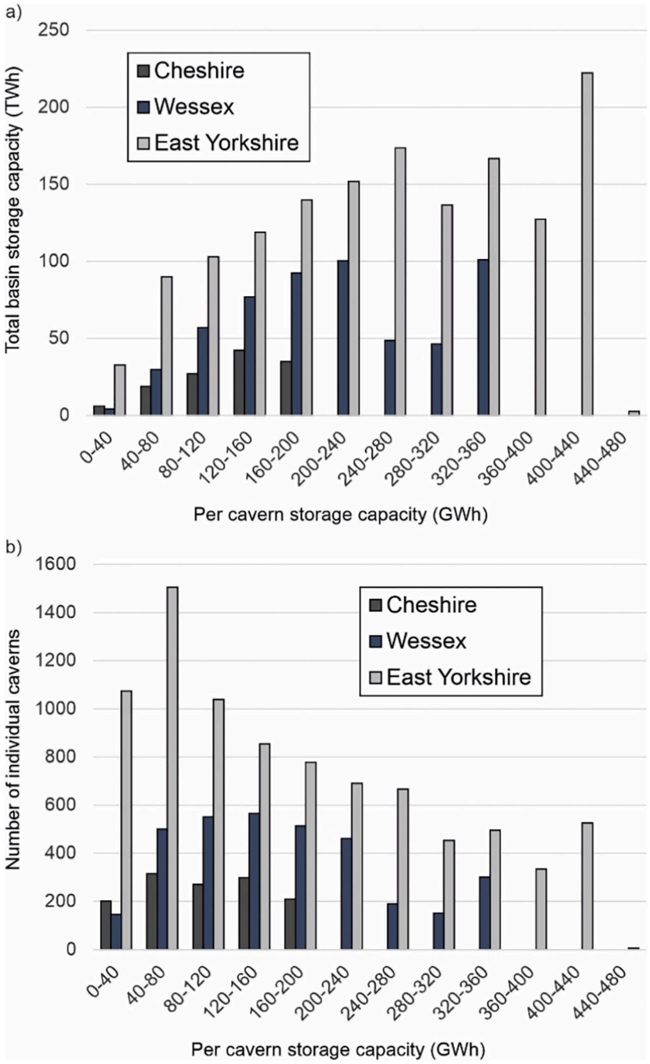

Fig. 7. a) Basin-wide energy storage for the three study regions, plotted against ranges of per-cavern energy storage capacity in gigawatt-hours (GWh). b) Number of caverns by per-cavern energy storage capacity.

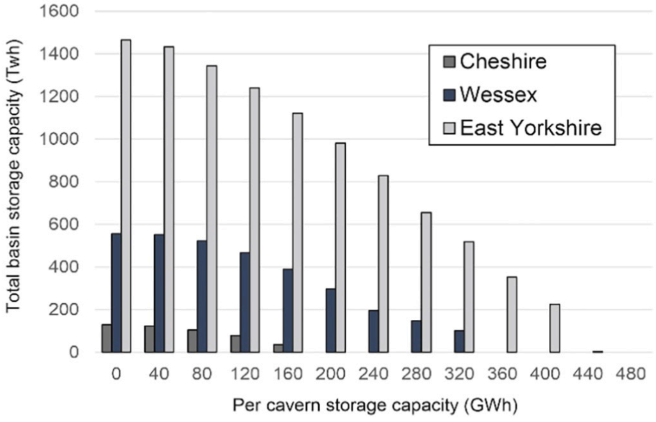

Fig. 8. Basin-wide energy storage potential in the three study regions. For each value on the horizontal axis, the height of the bar is the total amount of energy storage available in the basin in caverns of that capacity or greater.

illustrated in Fig. 9. Such maps are useful for identifying areas with the greatest potential for hydrogen storage, and can be used to target further exploratory, appraisal and feasibility studies. The data can also be interrogated to identify regions suitable for any given end-use application based upon specific storage capacities, operating pressure ranges and deliverability requirements.

4.2. Benchmarking against current gas storage sites

Physical volumes of individual modelled caverns range between approximately 75,000 and 1,129,000 m^3 (Table 4). Most current UK natural gas storage caverns have physical volumes <600,000 m^3, however some developments with larger caverns have been planned (e.g. [33,46]). The volumes of hydrogen storage caverns at Moss Bluff and Clemens Dome are also <600,000 m^3 (Table 1), so some of the caverns modelled here are very large compared to current facilities. Despite this, there are existing natural gas storage caverns elsewhere that do exceed 1 million cubic metres in volume [66], which provide a precedent for operating caverns of similar scale. In addition, larger hydrogen storage caverns may be desirable to account for the reduced volumetric energy density of hydrogen relative to natural gas.

The estimated energy storage volumes have been benchmarked against current UK storage caverns (Table 5). Currently, 25 GWh of energy is stored in the form of hydrogen at Teesside (e.g. [17,21,23,24]). Using the gas cavern dimensions reported by Parkes et al. [34], current existing natural gas storage caverns in the UK would be capable of storing approximately 4.7 TWh of hydrogen. There are several additional projects undergoing planning, which if developed, would be capable of storing an additional 8.5 TWh of hydrogen. The current and planned cavern stock are likely to be required for continued storage of natural gas, and will not necessarily be available for conversion to hydrogen. The estimated energy storage potential calculated here for new dedicated hydrogen storage caverns far exceeds the potential of the UK's current natural gas cavern stock. However, not all cavern locations will be available and competition for cavern locations and volume may also arise from other energy storage requirements such as for additional natural gas storage or CAES (e.g. [34,46]).

4.3. Sensitivity analysis

The sensitivity of the total theoretical storage capacity is evaluated for three principal groups of variables, including cavern radius and distance between caverns, geological variable uncertainty, and cavern height constraints.

4.3.1. Cavern radius and pillar thickness

The mass of hydrogen stored in a cavern depends on the volume of the cavern and hence on the square of the radius *r*. For any given change in cavern radius, the per cavern capacity (E_{new}) can be calculated such that:

$$E_{new} = E_{initial}\left(\frac{r_{new}}{r_{initial}}\right)^2 \tag{10}$$

The hexagonal close-packed cavern distribution used in the modelling assumes cavern wall thickness (the separation distance between caverns) to be directly proportional to cavern radius. The areal density of caverns, that is the number of caverns within a given area, is therefore inversely proportional to the square of the cavern radius. Reducing cavern radius reduces the required wall thickness, and therefore a greater number of caverns can be placed in a given area. The opposite would be true if cavern radius were to be increased. For a rectangular area *A*, the number of caverns *C* with radius *r* in that area and wall thickness *wr* approximates to:

$$C = \frac{2A}{\sqrt{3}}\,\frac{1}{(2+w)^2 r^2} \tag{11}$$

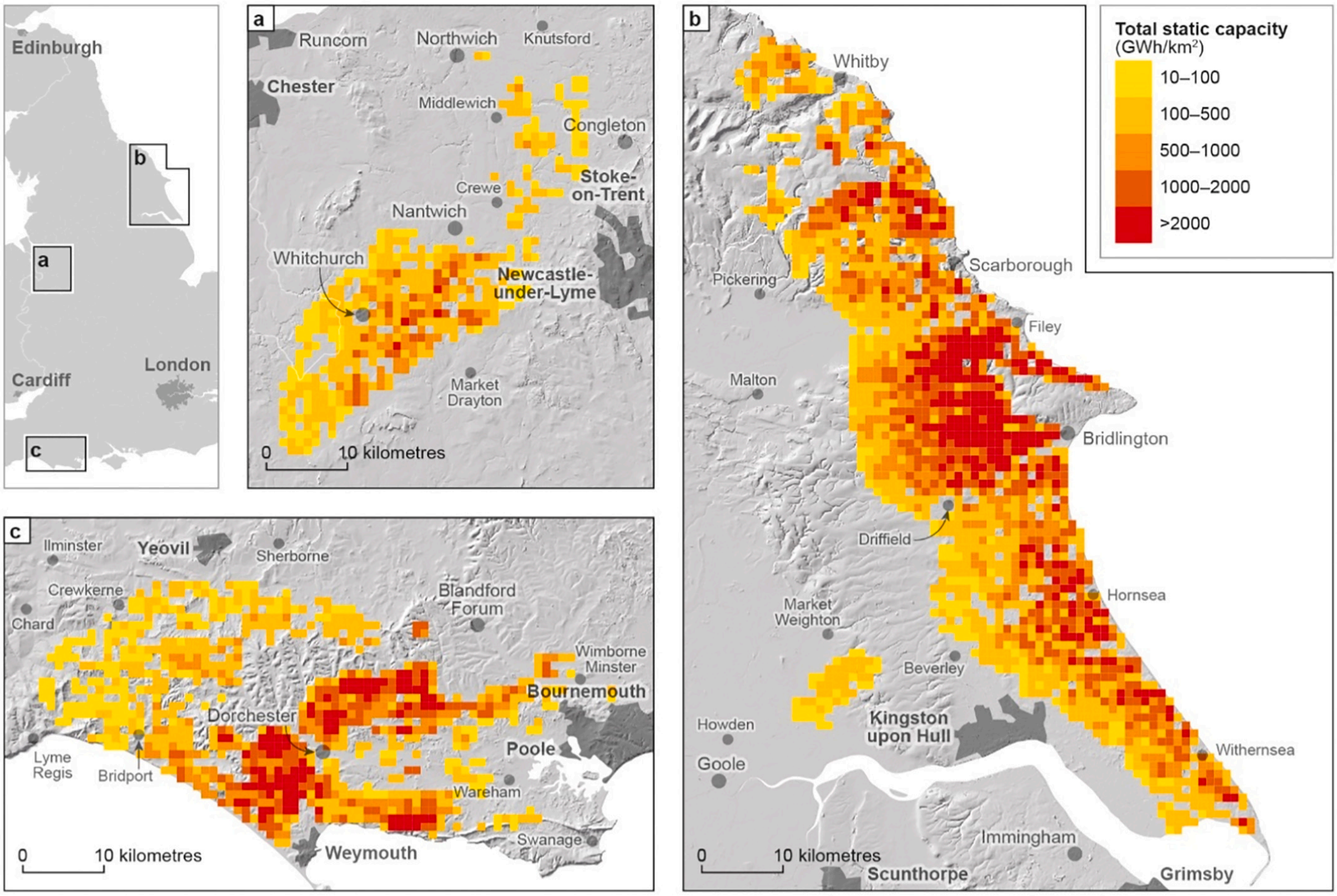

Fig. 9. Density distribution of energy storage capacity in units of GWh per km^2 in a) the Cheshire Basin, b) East Yorkshire and c) the Wessex Basin. Contains Ordnance Survey data © Crown copyright and database rights 2015. Ordnance Survey Licence no. 100021290. NEXTMap Britain elevation data from Intermap Technologies.

Table 5
Comparison of hydrogen storage potential of current UK hydrogen and natural gas salt caverns against theoretical storage potential as calculated in this study.

Current H_2 storage (GWh)	H_2 storage potential of current natural gas storage caverns (TWh)	H_2 storage potential of planned natural gas storage caverns (TWh)	Theoretical H_2 storage potential in new dedicated caverns – this study (TWh)		
			Cheshire	East Yorkshire	Wessex
25	4.7	8.5	128.8	1464.9	556.6

For wall thickness of *3r*, this simplifies to:

$$C = \frac{2A}{25\sqrt{3}}\,\frac{1}{r^2} \tag{12}$$

The energy stored per cavern varies as r^2, and the number of caverns varies as $1/r^2$, such that the total close-packed storage in a given area is not sensitive to changes in cavern radius. Therefore, if cavern radius is modified, the total capacity estimates would remain unchanged, although the number of caverns would differ relative to the initial calculations. The model results will however be sensitive to changes in cavern wall thickness. If the cavern wall thickness is increased, the number of caverns in a given area will be reduced, with the relationship depending on the square of the distance between cavern centres. With hexagonal close-packing, the number of caverns is approximately:

$$C = \frac{2A}{\sqrt{3}}\,\frac{1}{d^2} \tag{13}$$

Where d is the distance between cavern centres. Note that this distance is twice the cavern radius plus the wall thickness. The assumption of 3 × cavern radius used in the base case model is considered as a minimum cavern spacing after Evans [48], providing an upper bound to the theoretical storage capacity. To evaluate sensitivity to cavern wall thickness, a less aggressive scheme is considered by increasing cavern spacing to 5 × cavern radius. The increased wall thickness would minimise the mechanical integrity risk related to interference of far-field stresses between caverns. Increasing wall thickness from *3r* to *5r* corresponds to a separation of cavern centres (d) of *5r* and *7r*. A simple scaling relationship can therefore be used, such that the number of caverns, and therefore the storage capacity is reduced by a factor of:

$$\frac{5^2}{7^2} = \frac{25}{49} = 0.51 \tag{14}$$

Similarly, the equation can be scaled to provide a multiplier to determine the sensitivity to any theoretical increase or decrease in wall thickness as a function of cavern radius. In practice however, the depth and thickness of the available salt is non-uniform, and the distribution of caverns may be preferentially concentrated in certain areas. If the cavern distribution is clustered in deeper areas, the increase in pressure may offset any reduction in the number of shallower caverns elsewhere. To test the effectiveness of the scaling method, the full methodology described in Fig. 3 was applied to the Cheshire Basin using an increased cavern wall thickness of *5r*. Stand-off distances from infrastructure and other buffer features were maintained as per the initial calculations. In this scenario, the energy storage capacity was reduced to 64.3 TWh, within 2.5% of the value that would be estimated using the multiplier calculated by Eq. 14. This suggests that a simple scaling approach provides a robust means by which to evaluate the sensitivity to cavern spacing. Results for all three study regions are shown in Table 6.

The results indicate that the estimates are highly sensitive to the cavern wall thickness parameter, however the estimated energy storage potential remains significant. In practice, the appropriate cavern wall thickness will be determined through detailed geomechanical modelling for each individual storage scheme. A cavern wall thickness range of 3 to 5 × cavern radius is considered appropriate for the depth range considered here, although it is possible that greater cavern spacing may be required depending on site specific conditions and operational requirements.

4.3.2. *Sensitivity to geological variables*

The methodology employed to estimate the hydrogen storage potential of the three regions necessitates the simplification of certain parameters which, in reality, will vary depending on site-specific conditions. To account for the corresponding uncertainty, a sensitivity analysis was undertaken to establish the key factors affecting the storage capacity estimates (Fig. 10). The sensitivity analysis centred on the geological variables detailed in Table 7, with cavern design considerations maintained as per the initial calculations. The variables include the overburden density and geothermal gradients which are used to estimate the hydrogen density at cavern depths from the equation of state. In terms of overall storage capacity, varying the pressure-temperature relationships based on the parameter ranges given in Table 7 has a relatively minor impact on the estimated storage volumes. This indicates that the model is more sensitive to considerations that impact on physical cavern size and volume. Of the variables investigated, the results are most sensitive to variations in salt thickness, highlighting the importance of site characterisation and accurate geological models for estimating hydrogen storage capacity in salt caverns. Sensitivity to depth was investigated within a relatively narrow range (Table 7) to reflect common errors encountered in geological modelling based on seismic reflection data. The resulting sensitivity to depth is relatively limited because the top and base of the available salt are varied proportionally. Consequently, the raw cavern volume does not change, and the small depth-variation considered has only a minimal impact on hydrogen density. The insoluble content is subject to considerable uncertainty, as the volume of insoluble content within bedded halite can be highly variable across a basin [34]. By variation within the ranges given in Table 7, the insoluble content is the second most sensitive parameter with a change of 5% in insoluble content resulting in a 9% change in storage potential. In some regions, where interbedded mudstones form a major component of the halite formation, the insoluble content may even exceed the upper bound of 30% used in the sensitivity analysis.

Taken together, the sensitivity of the results to the geological variables considered may be as high as ±36%.

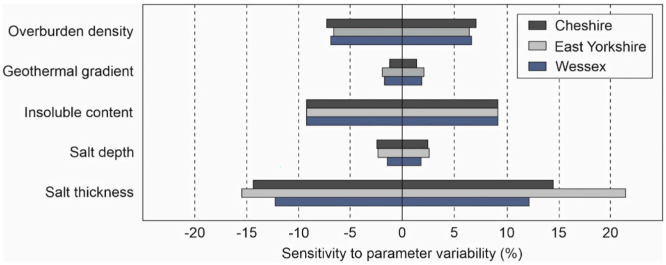

Fig. 10. Sensitivity of basin-wide theoretical storage potential estimates to the parameter variations outlined in Table 7.

Table 7
Parameter variation used in sensitivity analysis.

Variable	Base case parameter	Parameter variation
Overburden density	2400 kg·m^{-3}	+/−200 kg·m^{-3}
Geothermal gradient	27 °C km^{-1} (Cheshire) 31.9 °C km^{-1} (East Yorkshire) 34.5 °C km^{-1} (Wessex)	+/−5 °C km^{-1}
Insoluble content	0.25	+/−0.05
Depth of salt deposit	Variable as per geological models	+/−20 m
Thickness of salt deposit	Variable as per geological models	+/−20 m

4.3.3. *Cavern height sensitivity*

While a maximum cavern height of 300 m has been adopted for estimation of an upper bound theoretical storage capacity, caverns at current natural gas storage facilities in the UK rarely exceed 100 m in height. While the larger caverns may be viable where the disposition and properties of the halite allows, the presence of thicker mudstone interbeds and intervals of salt with high insoluble content may limit cavern dimensions in practice. The optimal cavern dimensions at a given site will ultimately be dictated by a combination of geological, engineering and techno-economic considerations specific to the desired storage application. The sensitivity of the results to cavern height was investigated by modifying the maximum permissible cavern height relative to the theoretical maximum of 300 m used in the initial estimates (Fig. 11). The cavern radius of 50 m remains constant in these calculations. Limiting maximum cavern height to 100 m, which reflects the dimensions of most current natural gas caverns in the UK, reduces basin-wide storage capacity by 31 to 40% depending on the basin. The reduction is greatest in East Yorkshire, and lowest in the Cheshire Basin due to the differences in the proportion of larger caverns modelled in the different basins as a function of halite thickness. Allowing for larger caverns of up to 140 m height, decreases the reduction in storage capacity to between 11 and 26% between the three regions. For large-scale hydrogen storage, it may therefore be beneficial to consider caverns with dimensions greater than those commonly employed for natural gas storage in the UK. Caverns between 100 and 200 m in height may be optimal for large-scale hydrogen storage developments in the UK setting.

4.4. *Hydrogen storage for heating applications*

The calculations presented previously represent the theoretical

Table 6
Sensitivity of theoretical storage capacity to increased cavern spacing, from 3 × cavern radius to 5 × cavern radius. Wall thickness range after Evans [48].

Region	Theoretical energy storage capacity (TWh) assuming wall thickness of 3 × cavern radius	Theoretical energy storage capacity (TWh) assuming wall thickness of 5 × cavern radius
Cheshire Basin	129	66
East Yorkshire	1465	747
Wessex Basin	557	284
TOTAL	***2151***	***1097***

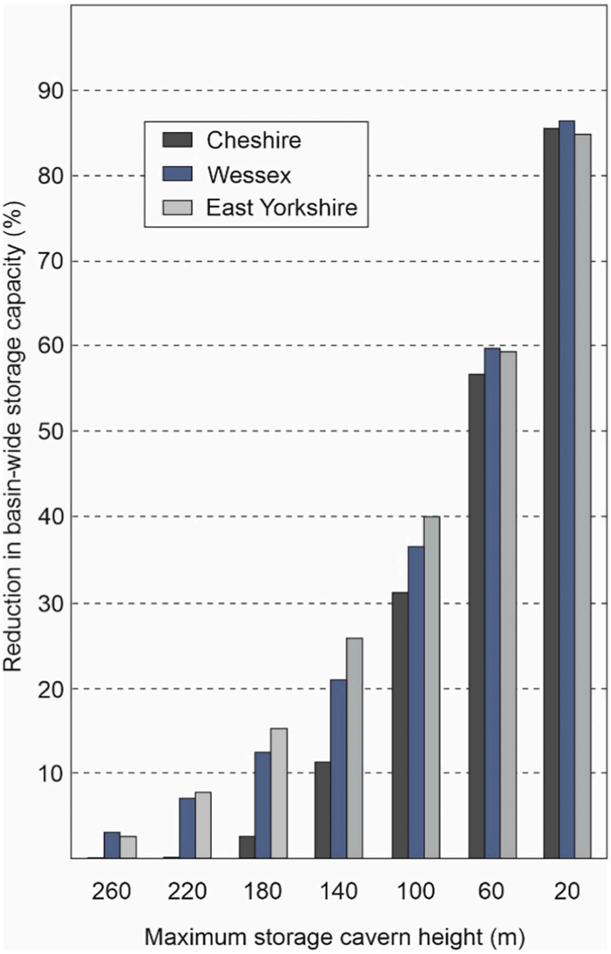

Fig. 11. Sensitivity of total basin theoretical storage capacity to a reduction in maximum cavern height relative to the base case maximum cavern height restriction of 300 m (m). While widespread development of 20 m height caverns with 50 m radius is unlikely, the data are shown here for completeness.

single-fill storage capacities of each basin considered. The results provide an upper bound to the amount of energy that may be stored at a given time, based on the available bedded salt resource. In practice, working gas volumes will be cycled multiple times throughout the year. For practical applications, it is also necessary to consider cavern deliverability rates in addition to storage capacity. The optimal balance between cavern capacity and extraction rate will vary depending on the regional hydrogen consumption profile. Different regions may prove conducive for development of caverns of a particular size, capable of delivering hydrogen at the specific rates required by certain end-use applications. The storage capacity is discussed here in the context of inter-seasonal hydrogen storage for provision of low-carbon heat.

To establish the potential practical contribution of salt cavern storage for a future hydrogen transmission system, a number of criteria have been applied to identify the proportion of the theoretical storage capacity that may be available for inter-seasonal storage purposes:

- A minimum energy storage capacity of 120 GWh per cavern;
- A cavern withdrawal rate of 0.8 MPa per day, which is at the lower end of the typical range given for inter-seasonal gas storage caverns by Bérest et al. [61];
- Daily extraction rate is limited to a maximum of 10% of the working gas to ensure the caverns are not subjected to excessive mechanical and thermal loads during rapid withdrawal;
- Cavern height is restricted to a range of 80–120 m, based on the dimensions of typical natural gas storage caverns in the UK. Available cavern volumes range from approximately 300,000 to 450,000 m^3;
- The cavern operating pressures must be compatible with the pressure in the hydrogen transmission system to avoid additional re-compression costs following hydrogen withdrawal from the caverns. A minimum operating pressure of 8.5 MPa is selected after the Northern Gas Networks [10] study.

Table 8 shows the daily energy deliverability of the modelled caverns in the three regions investigated. In principle, a peak domestic heating demand of approximately 170 GW across the UK (after [67]) can be met using the hydrogen withdrawn from caverns alone, although in practice this is unlikely to be tenable given that the demand for heat is dispersed across the country, and the required geology for salt caverns is geographically limited. On average the modelled caverns deliver around 5% of their stored energy per day under these assumptions, comparable to the natural gas caverns operating at Hornsea (based on data presented by [68]).

Table 8 also provides a summary of the cavern depth and operating pressure ranges for the caverns that meet the criteria described above. The operating pressure ranges are broadly within the ranges given for operating and planned natural gas storage caverns in the UK by Evans & Holloway [33] and Parkes et al. [34]. In the Cheshire Basin however, current natural gas storage caverns are found at relatively shallow depths (240–700 m) and operate within a pressure range of around 3 to 10 MPa [34]. As a result of the low density and therefore low energy per unit volume of hydrogen relative to natural gas, deeper caverns capable of storing greater volumes would be required to meet seasonal hydrogen storage demands. The maximum modelled cavern pressures provided in Table 8 are therefore somewhat higher than those reported for operational natural gas storage caverns in Cheshire. In East Yorkshire, the Aldbrough and Hornsea gas storage facilities operate at pressures of 12–27 MPa. The now moribund Whitehill project (Fig. 1) was intended to operate with a wider cavern pressure range of 10–34.5 MPa [34], comparable to the modelled pressure ranges in both East Yorkshire and the Wessex Basin.

Fig. 12 illustrates the spatial distribution of energy deliverability potential of inter-seasonal storage caverns across the studied regions. In comparison to the theoretical capacity distribution shown in Fig. 9, areas suited for seasonal storage based on the criteria described above are more geographically constrained. It is evident that in the Cheshire Basin, seasonal hydrogen storage will be limited to the very deepest parts of the basin, whereas current natural gas storage developments are located in the northern part of the basin (Fig. 4). While the data presented illustrate the deliverability potential of caverns suitable for provision of inter-seasonal hydrogen storage for low-carbon heating, the theoretical capacity results can be similarly interrogated to generate comparable distributions for other applications such as power-to-hydrogen and mobility, which will have different criteria for optimal cavern dimensions, capacity, and withdrawal rates. Such data may provide a rigorous basis for informing planning and development of hydrogen distribution and storage networks to decarbonise a range of applications in the UK. In particular, these data can be used to provide an upper limit on the cavern storage potential for modelling and optimisation of energy systems.

Conceptual designs from two recent gas industry feasibility studies are used to provide context for the results. The H21 Leeds City Gate project developed a concept for conversion of the existing natural gas network to hydrogen in the city of Leeds, England's fourth largest city [69]. Seven caverns with a working capacity of 122.1 GWh each would be required to provide the inter-seasonal storage demands of the project along with two smaller intra-day storage caverns. The more ambitious H21 North of England study would require 56 caverns located in the East Yorkshire region to provide 8052 GWh inter-seasonal storage to supply the entire North of England study region [10]. The study region accounts for 12.5% of the UK's net population. It is clear that the available storage

Table 8
Storage cavern characteristics and potential peak load deliverability of UK bedded halite formations suitable for providing inter-seasonal storage for a hydrogen transmission system.

Region	Number of caverns	Cavern casing shoe depth range (m below ground level)	Maximum individual cavern capacity (GWh)	Number of days to deliver working volumes	Daily energy delivered from indiviudal caverns (GWh)	Caverns operating within pressure range (MPa)	Total basin peak load deliverability (GW)
Cheshire	120	1205–1468	158	18–22	6.2–7.7	8.5–27.6	37
East Yorkshire	4789	1217–1800	178	18–26	4.7–7.6	8.6–33.9	1358
Wessex	1662	1205–1800	176	18–26	4.9–7.6	8.5–33.9	481

resource is more than sufficient to meet these storage requirements. Only around 0.02% of the modelled cavern capacity of East Yorkshire would be required to provide the peak day demand of 659 GWh reported for northern England by Northern Gas Networks [10].

Although there are no immediate plans to discontinue natural gas use, Scafidi et al. [14] estimate the volume of hydrogen storage that would be required to displace UK natural gas consumption with hydrogen at 150 TWh. Assuming a median cavern size of 150 GWh, almost 1000 caverns would be required to meet this capacity requirement. The development of larger caverns in areas of East Yorkshire and the Wessex Basin where the salt formations are deep and sufficiently thick, may significantly reduce the number of caverns required. In East Yorkshire, increasing the maximum cavern height to 150 m, would reduce the number of caverns required to around 770. This number could be further reduced if even larger caverns were considered where geological conditions allow. It is clear however that there may be a potential trade-off between cavern dimensions and the number of individual caverns required to provide sufficient storage for a given application. In comparison, 155 natural gas storage caverns are currently operational, under construction or consented across the UK to date [34], indicating the scale of the deployment challenge. Brine processing and disposal will also need to be included in any economic evaluation given the large number of new cavern developments that may be required.

5. Discussion

Hydrogen forms a key component of current decarbonisation roadmaps in the UK, particularly through displacement of natural gas consumption for space heating in private homes and business buildings [6–8]. However, unlike natural gas, the use of hydrogen is currently limited to industrial sites with very limited network infrastructure. The scale-up of both hydrogen supply and demand across the energy system is contingent on access to cost-effective network infrastructure that can be used to provide security of supply to consumers. In this context, studies have shown that integration of large-scale storage can considerably reduce the cost of hydrogen supply by providing flexibility and resilience to the network [4]. Yet, the overall theoretical potential for cost-effective subsurface hydrogen storage accounting for region-specific variations is poorly understood. In addressing this knowledge gap, this study estimates the total theoretical storage capacity of new hydrogen storage caverns in bedded halite formations onshore UK to be 2150 TWh. Although this should be considered as an upper bound to the storage capacity, the potential significantly exceeds the storage requirement to replace the UK's natural gas consumption, despite the significant uncertainty associated with the estimates. Sunny et al. [4] indicates economic benefits from large-scale integration of hydrogen storage in salt caverns for the supply of heat in the UK using approximately 85 TWh of storage in the system by 2050. The present study shows that there is an abundance of geological resource to meet the storage requirements for heating, albeit geographically constrained to those areas underlain by thick and continuous bedded halite formations. Furthermore, the storage potential will likely be sufficient for an increased uptake of hydrogen across the energy system for other applications, including but not limited to power-to-hydrogen, mobility, or industrial applications, where the infrastructure provides crucial load-balancing services.

Caglayan et al. [3] presented estimates of the hydrogen storage potential of salt caverns across Europe, estimating the hydrogen storage capacity of the UK to be 10,400 TWh including offshore potential. In lieu of basin-wide geological models, the Caglayan et al. [3] study assumed highly idealised salt deposits with uniform depth and thickness across the entire extent of each deposit. The use of regional geological models accounting for depth and thickness distributions in this study significantly enhances the reliability of the estimated onshore storage volumes but did not consider the offshore potential. Caglayan et al. [3] highlights

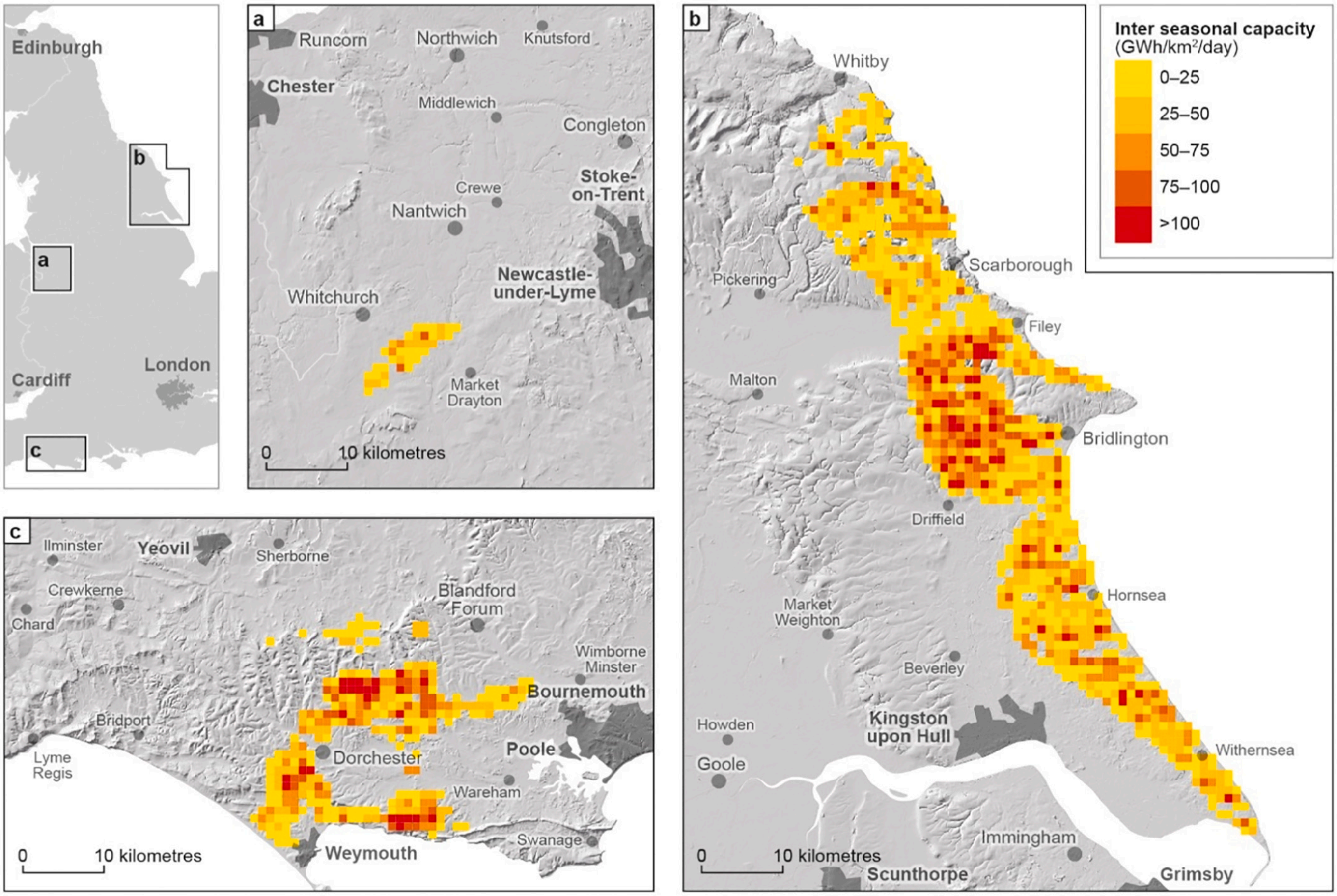

Fig. 12. Density distribution of potential daily energy deliverability (GWh/km^2/day) in a) the Cheshire Basin, b) East Yorkshire and c) the Wessex Basin. Contains Ordnance Survey data © Crown copyright and database rights 2015. Ordnance Survey Licence no. 100021290. NEXTMap Britain elevation data from Intermap Technologies.

the considerable additional storage capacity potentially available in offshore salt structures and bedded salt formations within the East Irish Sea Basin, Southern North Sea and offshore extension of the Wessex Basin.

The hydrogen storage capacity estimates provided in this study are based on the theoretical capacity to construct new salt caverns, and use regional geological data to characterise the target salt formations. It is important to note that development of any new underground gas storage development must be preceded by detailed site-specific geological and geotechnical evaluations, together with comprehensive risk assessment [70]. Detailed screening, based on assessments of local structure and the characterisation and assessment of salt properties is required to validate the suitability of any given locality for cavern development. This requires detailed exploration programmes, including the review and appraisal of legacy datasets, acquisition of new seismic reflection data, and the drilling of salt exploration wells and retrieval and testing of salt cores. It is likely that in many areas, detailed site evaluations would identify localised geological features such as faulting or thick interbedded mudstone horizons. If present, these features may locally constrain cavern design and may prove to be detrimental to the construction and safe operation of gas storage caverns altogether at some localities. As a result, a significant proportion of the modelled caverns may not be practical to develop. Future studies will also need to optimise the cavern dimensions/volumes and identify optimal cavern localities to meet future hydrogen network requirements. Proximity to other infrastructure, such as hydrogen generation plants, CO_2 storage transport and storage infrastructure, and gas transmission hubs, will need to be considered. A proportion of the modelled caverns may not be sufficiently co-located with such infrastructure. Applications for gas storage projects are also subject to extensive environmental impact assessments and planning application processes, which may further restrict cavern development in certain areas (further details on the UK consenting process are provided in Appendix B).

The storage capacities presented here should therefore be considered as a theoretical indication of the maximum storage resource available, with the expectation that only a proportion of the modelled capacity will be required or feasible to develop in practice. Further appraisal will be a prerequisite prior to recommending any particular region for salt cavern developments. This is perhaps particularly pertinent to the Wessex Basin where fewer detailed evaluations have been undertaken to determine the suitability of the Dorset Halite Member [33]. Despite this, the modelled storage capacity is very significant, and only a small proportion of the modelled caverns would be required to provide significant storage capacity [4]. The H21 North of England project estimates that 8 TWh of inter-seasonal hydrogen storage would be required to support an 85 TWh hydrogen transmission system servicing the North of England, including the major conurbations of Leeds, Bradford, Wakefield, Huddersfield, Hull, Liverpool, Manchester, Teesside, Tyneside and York. This hydrogen storage requirement represents only a very small fraction of the storage capacity of modelled inter-seasonal storage caverns in East Yorkshire. Bedded onshore halite formations therefore possess sufficient capacity to host a network of new gas storage caverns to provide the UK with the inter-seasonal storage capacities required to service hydrogen networks at scale.

Another potential application for hydrogen storage is to provide large-scale electricity storage. Modelling carried out as part of an ongoing study by The Royal Society, considered an ambitious case where all of Great Britain's future electricity demand is met entirely by wind and solar energy, provided directly or via hydrogen storage. It was found that with an electricity demand of 570 TWh/year (net of demand for electrolysis to produce hydrogen for other purposes, and pre-transmission and distribution losses), the storage infrastructure would need to be capable of storing 130 TWh (including 20% contingency) if filled by 85 GW of electrolysers (C. Llewellyn Smith, private communication). With more/less electrolyser power, the storage volume would be smaller or larger: 85 GW/135 TWh is the cheapest solution with the costs that were assumed. For an electricity demand of 440/700 TWh, the optimal storage volume (including contingency) would be some 100/185 TWh. It is clear from the theoretical capacity estimates presented here that UK storage potential significantly exceeds the requirement of the above scenario in addition to the requirement of 150 TWh of seasonal storage required to displace natural gas [14].

6. Conclusions

Previous studies have assessed the potential for salt cavern hydrogen storage in the UK [24,27], however, this study presents the first provision of a geological resource-based hydrogen storage capacity estimate. The overall theoretical single-fill storage capacity, which is the total sum of the storage resource available is presented, followed by an assessment of the sub-set of this capacity suitable for meeting inter-seasonal storage demand for heat. A consistent approach is presented that enables the identification of specific regions which may be particularly suitable for development of hydrogen storage caverns for a given end-use application such as to meet seasonal heating demands. Conversely, areas where potential underground hydrogen storage provision might be problematic, for example if the given application requires caverns to operate strictly within certain pressure ranges, can also be identified using the modelling approach.

The theoretical hydrogen storage capacity of three onshore UK regions has been evaluated based on the distribution of bedded halite formations suitable for the development of new gas storage caverns. The Fordon Evaporite Formation of East Yorkshire provides the greatest potential, with over 8400 potential cavern locations providing a combined 1465 TWh of hydrogen storage capacity. In the Cheshire Basin, 1297 potential cavern locations provide a combined 129 TWh of hydrogen storage potential in the Northwich Halite. Although significant uncertainty remains regarding the suitability of the Dorset Halite Member for underground gas storage, the Wessex Basin provides a theoretical hydrogen storage capacity of 557 TWh, divided between 3378 potential cavern locations. Although the estimates are subject to considerable uncertainty, the potential significantly exceeds the UK's 25 GWh of hydrogen storage capacity currently operating in small, relatively shallow salt caverns at Teesside.

The storage capacity of each potential cavern location is calculated individually, based on the cavern dimensions and volume that can be accommodated by the host rock formation at the specific site. The theoretical hydrogen storage capacities include individual caverns ranging in size from 10 to 441 GWh. For some applications, such as for intra-day or inter-seasonal storage for heating purposes, it may be more useful to consider only caverns with operational pressure ranges suitable for the desired cycling and withdrawal rates. For inter-seasonal storage caverns with working capacity of at least 120 GWh, an upper bound of 6571 individual caverns could deliver over 45 TWh of hydrogen in a single day across the three regions compared to an annual UK heating demand of around 450–500 TWh/year (after [71]). With wider cavern spacing, and accounting for geologic uncertainties, a conservative lower-bound estimate of at least 612 GW could be delivered by hydrogen storage caverns, well in excess of the UK's peak demand for heat.

Gas industry feasibility projects have estimated the hydrogen storage requirements for conversion of parts of the existing national gas transmission system to hydrogen. The estimated theoretical hydrogen storage capacities significantly exceed the projected storage requirements for these projects, even if sensitivity to the key geological variables is considered. Only a small proportion of the modelled caverns would therefore be required to support a hydrogen-based low-carbon heat network in the UK, although a significant uplift in the number of caverns relative to the existing natural gas cavern stock will be required.

Some limitations of the study include:

- The modelled caverns and storage capacity estimates are theoretical. Detailed geological, engineering and techno-economic evaluations have not been undertaken to validate the practicality of developing caverns at any given location;
- A significant proportion of the estimated storage capacity is located in regions where few studies have evaluated the halite for purposes of salt cavern development at the relevant locations and depths;
- The assessment is based on legacy geological models and data that were not specifically acquired and interpreted for purposes of estimating hydrogen storage capacity;
- Caverns are modelled with a simple cylindrical form, with constant volume correction factors to account for imperfect cavern shape and the impact of insoluble content;
- The study is limited to onshore regions and excludes some smaller salt basins.

It is important to note that comprehensive subsurface characterisation studies are required to validate the suitability of any particular location for underground gas storage cavern development. At present, large-scale natural gas storage caverns are predominantly located in selected parts of the Cheshire Basin and East Yorkshire. Additional geological studies are therefore required to investigate the feasibility for developments in new regions such as the Wessex Basin, deeper parts of the Cheshire Basin and the northern and in-land parts of East Yorkshire. Because detailed screening will likely preclude many of the modelled cavern locations, reducing the overall storage capacity estimates, it is recommended that those regions with the greatest theoretical capacity are prioritised for geological characterisation and validation. Inclusion of additional infrastructural and economic criteria would be required to converge on a realistic and practical storage capacity for any given application.

Despite these limitations, the estimated storage capacities suggest that the available resource is sufficient to enable significant hydrogen storage in addition to further CAES or natural gas storage caverns. Depending on cavern size, up to around 1000 new cavern developments may be required to meet the capacity requirements for replacing the UK's natural gas consumption, while additional caverns may be required to provide storage infrastructure for other end-uses. It remains to be seen whether the development of new storage cavern infrastructure at such a scale would be deemed socially or politically acceptable.

The distribution of suitable salt formations is not distributed evenly across the UK, and not all prospective users of hydrogen will be conveniently co-located with potential storage sites. For example, London and the southeast, and industrial centres in Scotland and South Wales, will not have access to nearby onshore storage caverns. The distribution of halite may therefore limit the degree to which hydrogen network infrastructure can be developed to service particular sectors in some areas, which may have implications for planning towards a future hydrogen economy. Some options for additional storage do exist, although they may be less technologically mature. The offshore potential of the East Irish Sea, Southern North Sea and Wessex basins, which have not been evaluated here, may provide significant additional storage capacity. Some offshore salt formations may have a role in providing hydrogen storage for regions lacking onshore storage resources, for example London and the southeast. The co-location of offshore salt formations with significant wind resources, may also favour the development of renewably-powered hydrogen production and storage. Such a proposition may establish opportunities to export low-carbon hydrogen to European markets. Ongoing research is also seeking to establish the potential for hydrogen storage in porous reservoir rocks such as saline aquifers and depleted gas fields. While further work is required to prove the technological feasibility at scale, porous reservoir rock storage may support the development of future hydrogen network infrastructure in areas lacking suitable bedded salt resources.

CRediT authorship contribution statement

We confirm that all authors have read and approved the manuscript. **John Williams:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Visualization. **Paul Williamson:** Methodology, Software, Validation, Writing - Original Draft. **Dan Parkes:** Conceptualization, Methodology, Investigation, Writing - Original Draft. **David Evans:** Writing - Review & Editing, Supervision. **Karen Kirk:** Methodology, Software, Writing - Review & Editing, Visualization. **Nixon Sunny:** Writing - Original Draft, Writing - Review & Editing. **Ed Hough:** Writing - Review & Editing, Supervision. **Hayley Vosper:** Validation, Formal analysis. **Maxine Akhurst:** Writing - Review & Editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Additional halite formations and storage potential

The current study focusses on thick and aerially extensive onshore halite formations which may be suitable for large-scale gas storage developments at numerous sites comprising multiple caverns. Some additional storage potential may exist in other halite units which are described here.

A.1. Onshore salt basins

A.1.1. Teesside

The Boulby Halite in the Teesside salt field lies at depths between 274 and 366 m, and is up to 45 m thick [72]. Several former brine caverns and purpose-built caverns in the region have been used to store nitrogen, natural gas and other liquid hydrocarbons in the Teesside area, including at Saltholme and Wilton [33,68]. Town gas (which has a considerable hydrogen content) has been stored in solution-mined storage caverns in Teesside since at least as early as 1959 [72], while hydrogen has been stored in three former brine caverns since the early 1970s for industrial purposes [16,21,23,47,68,73]. The limited halite thickness imposes limitations to cavern size, resulting in elliptical caverns 15 to 40 m in height with diameters in the region of 70 m.

For purposes of this study, the Boulby Halite is not identified as a major gas storage opportunity due to uncertainties over rapid variations in lateral thickness and lithology, although it may well offer some additional potential for hydrogen storage locally. The large number of caverns leached for brine production in the Billingham, Saltholme, Greatham and Wilton brinefields means there may be little opportunity to develop significant numbers of new multi-cavern storage developments specifically for hydrogen storage. Despite this there may be some potential to construct new caverns and some existing caverns may also be converted to provide new hydrogen storage capacity in some cases. The use of former brine caverns for hydrogen in Teesside demonstrates the potential for re-using existing caverns in the region for relatively small-scale hydrogen storage.

A.1.2. Northern Ireland

Relatively thin halite deposits of Permian age are preserved locally at depth in the East Irish Sea Basin and in the Larne area of Northern Ireland [33,40,42]. The Permian halite beds near Larne have previously been evaluated for the construction of caverns for both gas storage and CAES [33,43]. Triassic halite formations are also present in both the south and north of Northern Ireland. In the southern part of Northern Ireland, the halite formations are exploited through both brine solution and mechanical mining of rock salt [37]. The halite formations in the Larne area are buried at greater depths and are also present in a series of restricted basins extending offshore to the east [42]. At this stage, more research is required to identify if there may be sufficient volumes of sufficiently buried, thick and continuous halite that is yet to be exploited, and which may be available for future large-scale hydrogen storage.

A.1.3. Staffordshire, Worcestershire and Somerset

Several small Triassic salt basins are present in central and western parts of England. They include the Staffordshire, Worcestershire and Somerset basins. To date, gas storage caverns of any kind have not been developed in these areas. Storage cavern potential in these regions is considered likely to be restricted by a number of factors. The halite formations are of limited extent or have uncertain distributions. They are also relatively shallow, which will impact their suitability for cavern development. It is also likely that the insoluble content of the halite beds may be excessive. Furthermore, there is a high density of previous workings for rock salt and/or brine over much of the known salt distributions. Further geological assessments will be required to ascertain if there is any potential for developing salt caverns for energy storage purposes.

A.1.4. Preesall

The Triassic Mercia Mudstone Group contains halite units on the margins of the East Irish Sea Basin. In Lancashire, the Preesall salt field was first developed for brine by the Preesall Salt Company in the 1880s, later merging with other companies to form the Imperial Chemical Industries Limited (ICI) in 1926 [33]. The company mined rock salt and following mine closure, continued to extract brine until the early 1990s, playing a significant role in developing controlled brine pumping techniques in the UK [74]. While several thin and sometimes impersistent halite beds are present in the Mercia Mudstone Group, often correlating with thicker salt units present offshore in the East Irish Sea, the Preesall Halite Member has been considered for natural gas storage. The Preesall Halite is the equivalent of the Northwich Halite of the Cheshire Basin, and attains thicknesses of more than a hundred metres in some areas. The halite is generally encountered at depths of around 200 to 400 m below ground surface level. Brine has been extracted from nearly a hundred boreholes penetrating the formation [33]. A natural gas storage project was proposed in the early 2000s, with the intention of developing salt caverns exploiting the deeper part of the salt field where salt thickness exceeds 200 m. Despite appraisal drilling and analysis, the project was not developed, having encountered significant public opposition and planning issues. The Preesall Halite has been extensively worked over much of its area, while potentially suitable areas have already been earmarked for natural gas storage. While the Preesall Halite might offer some local potential for hydrogen storage, it is unlikely that there will be sufficient undisturbed halite available for large-scale hydrogen storage.

A.2. Offshore salt basins

Significant deposits of both massively bedded halite and halokinetic structures (salt swells, domes and walls) are present in offshore regions. These include the East Irish Sea Basin, where up to five halite-dominated units are identified in the Mercia Mudstone Group [38,75], and in the North Sea where the Zechstein Group evaporites have been significantly affected by halokinesis [76]. Up to three halite members are also present in Upper Triassic strata of the Southern North Sea. Consequently, significant additional storage cavern potential may be available offshore.

Both the Fordon Evaporite Formation and Dorset Halite Member, also extend offshore where they are generally encountered at deeper depths. The Northwich Halite Member correlates with the Preesall Halite Member of the East Irish Sea Basin [77]. The Gateway Gas Storage Project planned to develop offshore storage caverns for natural gas in the East Irish Sea, however despite the undertaking of detailed technical studies, the project is yet to be developed.

Onshore salt cavern development is technically simpler and less costly relative to offshore developments, and in general may be better co-located with existing gas distribution networks. Conversely, offshore development may be subject to fewer planning and social acceptance constraints. Existing oil and gas infrastructure may also potentially be re-purposed to facilitate storage offshore [14]. Offshore hydrogen storage may become progressively more attractive in the future, particularly if co-located with large-scale windfarms and floating electrolyser facilities, or as part of integrated gas production, reforming and carbon sequestration projects. The combination of offshore oil and gas, wind, carbon storage and halite resources, suggest that the UK Continental Shelf may be particularly suitable for such schemes.

Offshore gas storage caverns are not currently employed in the UK, and worldwide there is no operational experience in offshore storage of pure hydrogen. The potential for development of offshore hydrogen storage caverns should be evaluated in future studies to elucidate the technical, environmental and commercial considerations.

Appendix B. UK gas storage consenting process

Applications for gas storage projects are subject to extensive environmental impact assessments and planning application processes. Several applications to commission new underground natural gas storage projects in the UK have undergone numerous and lengthy planning and consenting processes. In addition, local communities have strenuously opposed some developments leading to significant delays and ultimately to cancellation of several projects [12,32]. Since 2011, natural gas storage planning applications (Preesall, Lancashire and Keuper Gas Storage, Cheshire) have proceeded under the Planning Act 2008 and relevant National Policy Statements. The Act established that large, nationally significant infrastructure projects (NSIPs) are now considered separately by the Planning Inspectorate (originally the Infrastructure Planning Commission). The Act created a new Development Consent regime (with the application for, and issue of, Development Consent Orders) for NSIPs in the sectors of energy, transport, water, wastewater and waste. It includes associated developments, which in the case of underground gas storage facilities comprises both surface works such as pumping/compressor stations, boreholes and pipelines, storage facilities and monitoring boreholes. Notably, the application for a proposed CAES facility at Islandmagee near Larne in Northern Ireland, proceeded under the Planning Act (Northern Ireland) 2011, which is the primary planning legislation and equivalent to the Planning Act 2008 (plus amendments) in England. Applications for the development of a salt cavern-based hydrogen storage facility will therefore be considered by the Planning Inspectorate under the Planning Act 2008 and related legislation, potentially alleviating some of the difficulties experienced by previous underground gas storage projects.

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