ARUP

Salt cavern development & capacity tool | UK onshore East Coast region

User manual

Version 1.0

February 2024

Contents

Tool Pages

Home/ Landing Page

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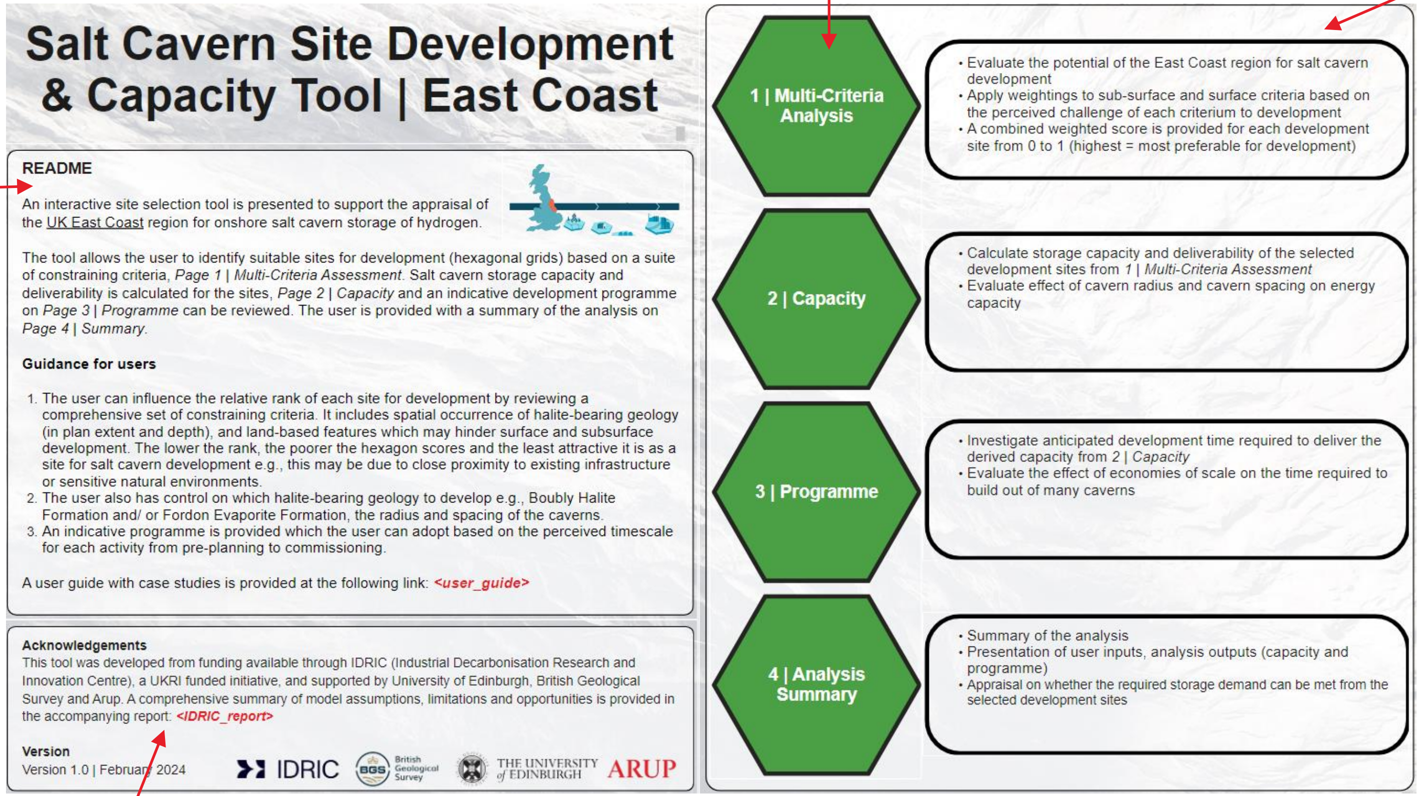
Click me to go to relevant page

README
This outlines the context and ambition of the tool, providing information on how it is envisaged to be used and by who.

Assumptions, limitation and opportunities associated with the development of the tool are provided in the associated, co-funded report *“Assessing the Regional Demand for Geological Hydrogen Storage - Building a Strategic Case for Investment in the East Coast Cluster” (February 2024)*



Acknowledgements
The development of the tool has been supported by several institutions provided here.
Version
The current version of the tool is provided in this section, along with relevant contact details.

Pages
Each page of the tool is described along with actions the user is expected to undertake and a link to each page is provided by clicking on the relevant green hexagon.

Page 1: Multi-Criteria Analysis. On this page the user will set weightings to each sub-surface and surface criteria. The effect of this is to exclude or evaluate each hexagon (development site) based on the impact of the criteria to any potential cavern development e.g., a salt cavern cannot be developed in the Fordon Evaporite Formation where Fordon thickness is 0 m, hence any hexagons where this is true will be eliminated. However if a hexagon is close (but does not intersect) with a Hydrogen Project, then the hexagon will be scored well.

Page 2: Capacity. On this page the user will firstly see the remaining hexagons from Page 1. The user will then define the geometrical and operational constraints for cavern development. The hexagons will be refined based on the feasibility to site caverns of selected radius in the given halite formations. and an estimate of energy capacity will be provided.

Page 3: Programme. An estimate of the programme timescale for cavern development is provided. Default values are provided based on industry knowledge and stakeholder engagement. The user can choose whether to model the time required to develop all the caverns as output from Page 2 Capacity, or override this number. Options also exist to define time-saving efficiencies based on optimal phasing of development activities and also due to construction of many caverns.

Page 4: Analysis summary. A summary page is provided which defines the user inputs, analysis outputs in terms of capacity and programme. The user has the option to define a “required storage capacity” which is compared against the analysis output. A maps of selected potential development sites is also provided.

Page 1. Multi-Criteria Analysis

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This title block presents the title of the tool WP2 MCA, Standing for Work Package 2 Multi-Criteria Analysis. It also provides interactive button which the user can click on to the right-hand side of the page, this includes links back to the landing page, WP2 scenarios, Capacity and programme tabs. Additionally, the number of hexagons presented on the right-hand side of the page is presented here

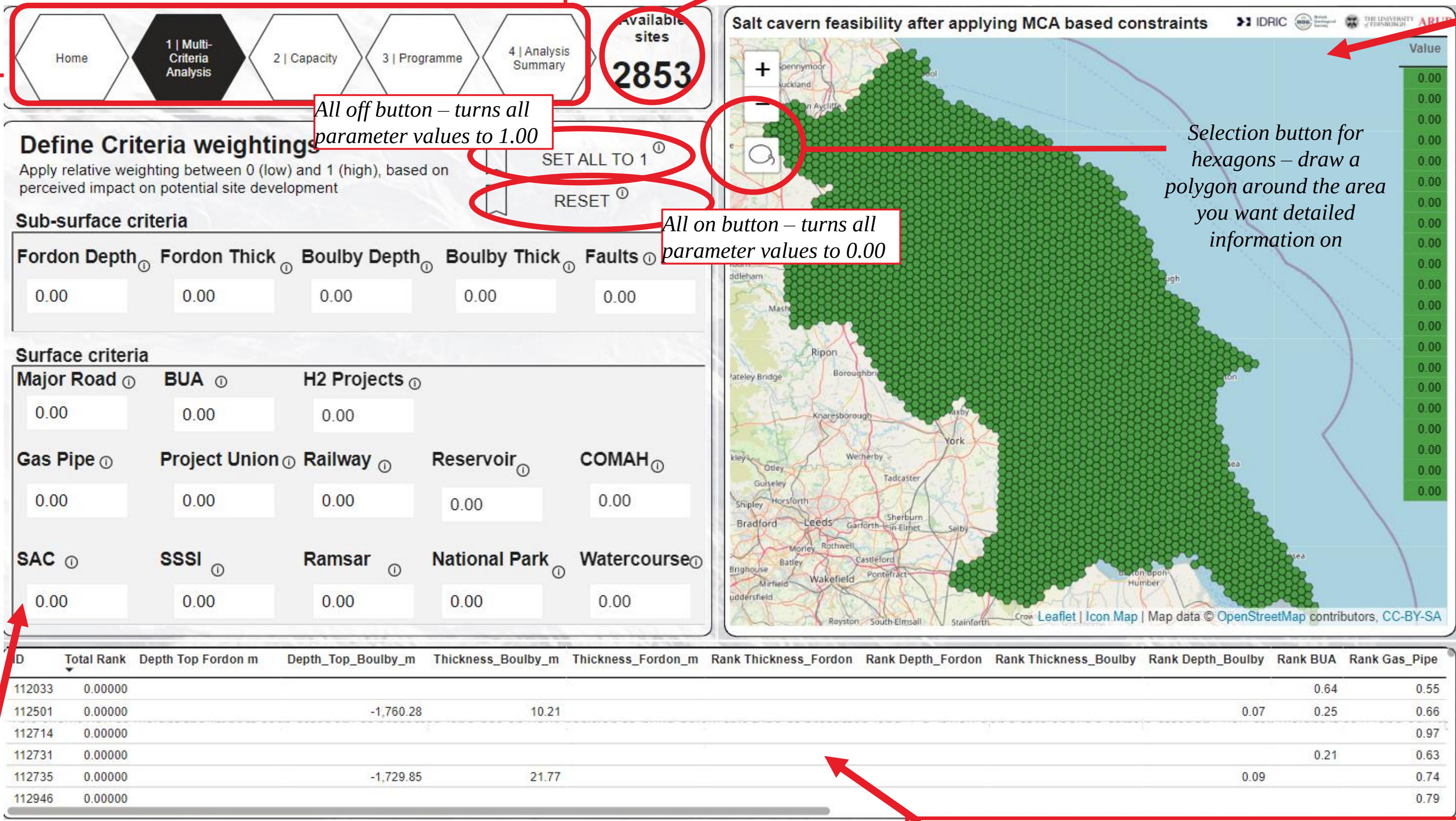
This number will change depending on the MCA applied

Press on these buttons to automatically travel to other tabs

Number presents the number of hexagonal areas presented in right hand side figure

This section of the tool defines the MCA. It contains the parameters that will go into the Hydrogen capacity assessment. These parameters are defined below:

- Depth to FEH – Depth to **top of** halite-bearing Fordon Evaporite Formation
- Thickness of FEH – Thickness of halite-bearing Fordon Evaporite Formation
- Reservoir – Water reservoir – opportunity to use for solution mining
- H2 Projects – Existing and proposed hydrogen production projects
- Depth to BHF - Depth to **top of** Boulby Halite Formation
- Thickness of BHF - Thickness of halite-bearing Boulby Halite Formation
- Major Road – Proximity to a major road – opportunity to utilise for construction works
- Built-up Area – Proximity from built up areas (does not include rural communities)
- Gas Pipelines – Proximity to gas pipeline infrastructure
- Project Union – Proximity to proposed Project Union (national hydrogen delivery) infrastructure
- Railway – Proximity to a railway line
- Geological Faults – Proximity to major faults
- COMAH – Proximity to site under Control of Major Accident Hazards (COMAH) regulations
- SAC – Proximity to a Special Area of Conservation (SAC) site
- SSSI – Proximity to a Site of Special Scientific Interest (SSSI)
- Ramsar – Proximity to a wetland site of importance under the Ramsar Convention
- National Park - Proximity to a National Park area
- Watercourse – Proximity to a major watercourse



All off button – turns all parameter values to 1.00

All on button – turns all parameter values to 0.00

Selection button for hexagons – draw a polygon around the area you want detailed information on

This view port of the tool presents the areas that are 'feasible' for salt cavern development based on your MCA criteria input on the left-hand side. This is a great visual aid for understanding the extent of feasibility based on your input.

Not only does this tool filter out non-feasible areas based on your input it will also rank the remaining hexagons from least favourable to most favourable. If you change the input criteria on your tool you will see that the value column on the right handside of this viewer portal will change, values will be ranked from 1.00 to 0.00.

The most favourable areas for development based on the input MCA being classed as 1.00 and coloured bright green and least favourable being ranked 0.00 and coloured white.

You will notice that each parameter has an interactive box underneath, this box automatically contains a number. This number informs the weighting of that parameter in terms of the MCA.

In the case presented in this guide all numbers are presented as 0.00. The numbers in the box can be assigned from 0 to 1. 1 being the most important and 0 being the least important. This means that all the criteria have a 'value of 0', as a result there are no limitations on the salt cavern feasibility results, and no hexagons will be excluded from the analysis.

This is why the entire area with salt present in the northeast appears as green! This is an interactive function of the tool and allows the user to define which criteria they find most important / least important / irrelevant etc.

If you change the numbers in your toolbox, you will see how this impacts the presentation on the areas considered feasible for salt cavern development on the right-hand side section of the tool. Try to change the numbers and see what happens, the map shown on the right-hand side should become more restricted, and the colours of the hexagons will start to change. This reason for this will be discussed in the next section.

A summary table is present at the base of the page, this will present information on each of the hexagons that appear in the viewer. It includes the ranking of each hexagon (ID), for each criteria (e.g., Rank Thickness_Fordon) and also a combined rank (Total Rank) which describes the favourability (0 (low) to l (high)) based on the MCA input.

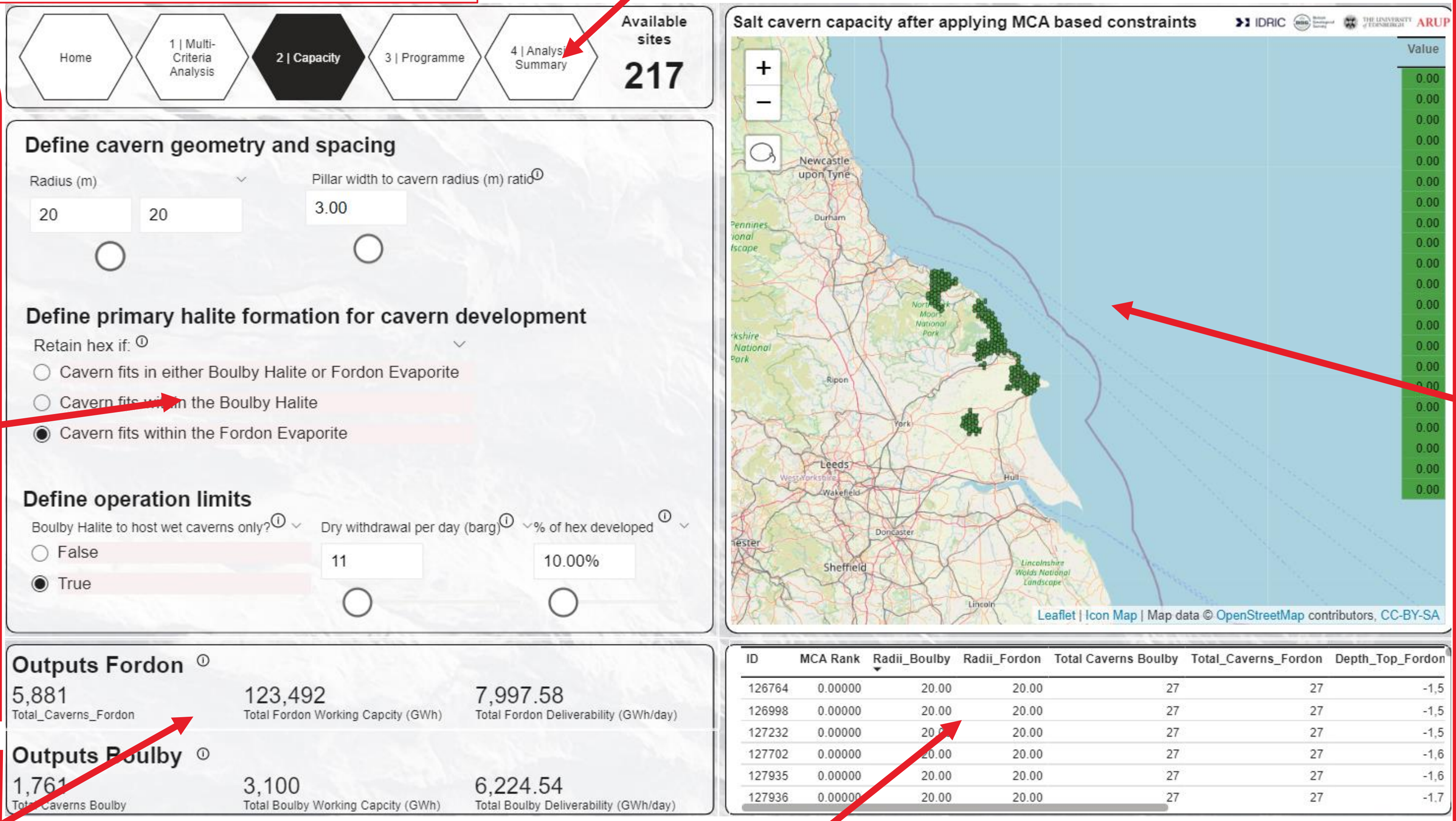
It will include a breakdown summary of the geology of each hexagon. The other MCA criteria will also have a ranking – this allows you to understand the favourability of each hexagon and where the overall ranking status comes from. This table also has an interactive function, by selecting hexagons from the right-hand side window you can pick out the areas that you want informed detail on in the table – rather than having all the hexagons which are present in the right-hand side viewer.

Page 2. Capacity Assessment

Page 2: Capacity. On this page the user will firstly see the remaining hexagons from Page 1. The user will then define the geometrical and operational constraints for cavern development. The hexagons will be refined based on the feasibility to site caverns of selected radius in the given halite formations. and an estimate of energy capacity will be provided.

This title block is similar to that presented on the WP2 MCA page. The only notable differences between the two title blocks is the title and the number on the right-hand side of the block describes the number of hexagons that are relevant to the capacity assessment, which is based on the desired input radius for the cavern, cavern spacing and the with drawl rate. All of which are determined in the box below.

This section defines the nature of the proposed cavern development including the cavern radius, the separation distance (as a function of cavern radius), the percentage of the hexagonal area that you want to develop and the withdrawal rate per day. This is important as only certain types of geologies will allow for the development of certain cavern sizes, spacing and pressure allowances (which influences with drawl rates). It also gives you the option to model the Boulby Halite Formation for wet or dry storage. Change the cavern components to reflect what you consider the ideal cavern size, spacing , withdrawal rates and area size. You will see how the map on the righthand side changes – reflecting the areas that are suitable to your proposed cavern design!



ID	MCA Rank	Radii_Boulby	Radii_Fordon	Total Caverns Boulby	Total_Caverns_Fordon	Depth_Top_Fordon
126764	0.00000	20.00	20.00	27	27	-1,5
126998	0.00000	20.00	20.00	27	27	-1,5
127232	0.00000	20.00	20.00	27	27	-1,5
127702	0.00000	20.00	20.00	27	27	-1,6
127935	0.00000	20.00	20.00	27	27	-1,6
127936	0.00000	20.00	20.00	27	27	-1,7

This figure presents the remaining hexagons suitable for your salt cavern development through a combination of the MCA selected on the last page and the cavern design selected on this page.

These hexagons are interactive you can click and select them for more information.

If you click on a hexagon a pop up will appear, this pop up will show a summary of the cavern design trace including a breakdown of the radius and the depth of the cavern.

Once a hexagon is clicked the summary tables below present the detailed information, including the total no. of caverns, the working capacity and the deliverability of that hexagon.

This section of the tool presents the cavern capacity outputs based on the inputs from cavern design coupled with the MCA.
In this section the outputs from both the Fordon evaporite horizon and the Boulby halite Formation are presented. The number of caverns, the total working capacity (GWh) and the total deliverability (GWh / day) are all presented. These are directly related to the inputs above, if you change your input, you will notice these values change. Additionally, you can click on specific hexagons on the righthand side image and a detailed output analysis for that specific hexagon will be produced in this tab.

This table presents a summary of the hexagons presented on the righthand side figure. It includes the radius of the proposed caverns within the Boulby halite and the Fordon Evaporite , total no. of caverns, a summary of the geology including depth and thickness of the Halite horizons. If you click on specific caverns in the figure above, the table will filter your selection and give a detailed analysis of those caverns only.

Page 3. Development Programme

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Page 3: Programme. An estimate of the programme timescale for cavern development is provided. Default values are provided based on industry knowledge and stakeholder engagement. The user can choose whether to model the time required to develop all the caverns as output from Page 2 Capacity, or override this number. Options also exist to define time-saving efficiencies based on optimal phasing of development activities and also due to construction of many caverns.

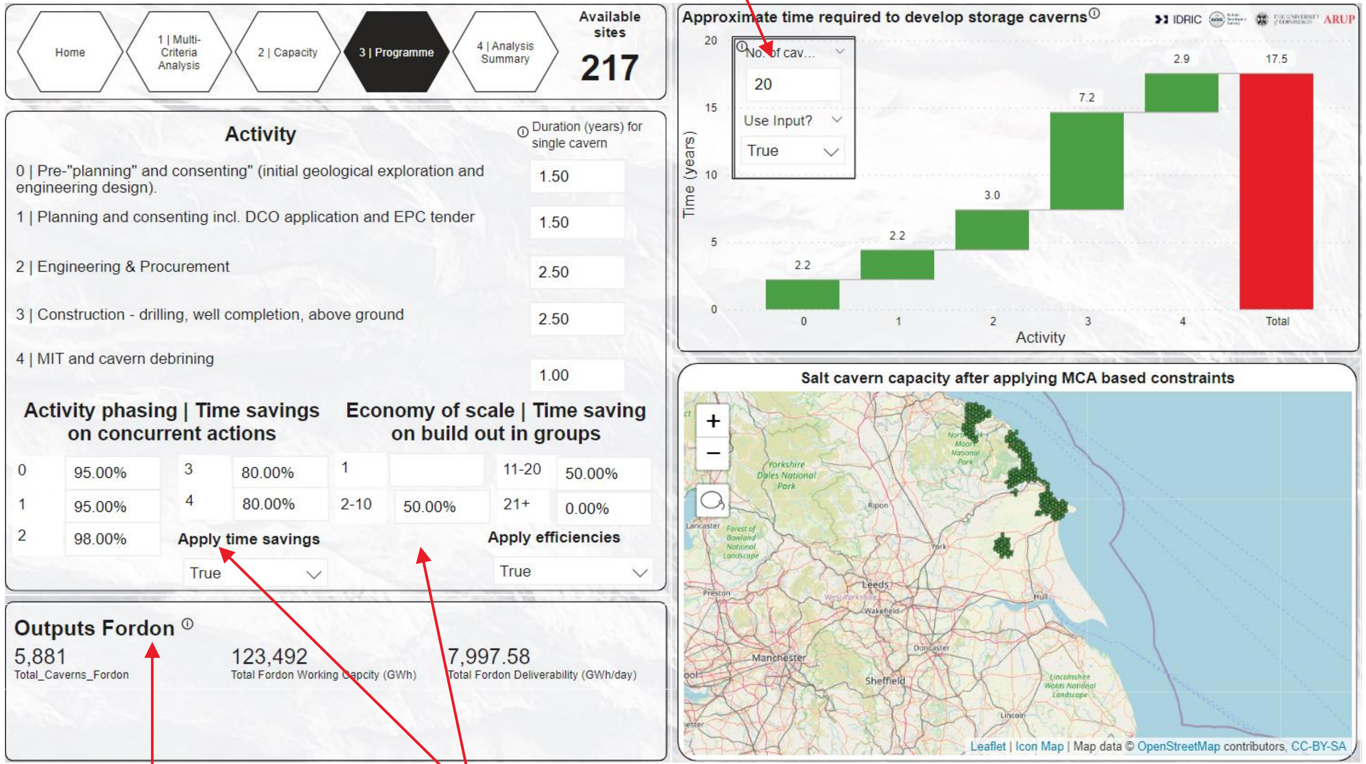
This is a dynamic chart which provides the total required time for the development of salt caverns. The number of caverns used to derive this chart is either the total from the analysis, or it can be overridden by the user (e.g., to model the time required for developing a cavern cluster) by selected TRUE and providing the number of caverns to model.

Activities

An indicative programme is developed from the key activities outlined here. They represent five key stages of salt cavern development, from pre-planning through to commissioning.

Fields are provided for the duration of each activity to develop a single salt cavern. These can be modified by the user however defaults are provided to inform the user of industry guidance/ rule-of-thumb.

1. Pre-planning. This activity includes community engagement, engagement with stakeholders, initial site investigation and site selection and the development of a preliminary/ indicative engineering design.
2. Planning & Consenting. Includes activities associated with submission of Development Consent Order (DCO) and those associated with tendering for the proposed works.
3. Engineering & Procurement. This activity includes detailed engineering design and procurement. It is dependent upon the supply chain to deliver skills and resources including people, solution mining equipment and fabrication of topside infrastructure.
4. Construction. This activity includes well drilling, installation of casing, solution mining, discharging of brine, changeover of well from brine to hydrogen, construction of topside facilities including dehydrators, compressors.
5. MIT & Commissioning. This activity includes mechanical integrity testing (MIT) to ensure the cavern is gas tight, and commissioning of the storage cavern for operational use.



Outputs are carried forward from Page 2 Capacity

Sources of information

The following sources have been used to derive recommended default values for the duration of activities and time-savings for the development of many caverns.

- HyUnder, 2013. D(4) - Overview on all Known Underground Storage Technologies for Hydrogen.
- Energy Technology Institute (ETI) & Foster-Wheeler, 2013. Hydrogen Turbines - Hydrogen Storage and Flexible Turbine Systems WP2 Report - Hydrogen Storage.
- INEOS, 2014. The Keuper Gas Storage Project newsletter April 2014.
- H21 , 2018. H21 North of England. H21 NoE Report/2018.
- Hydrogen UK, 2022. Hydrogen Storage: Delivering on the UK's Energy Needs.
- INEOS, 2024. Keuper Gas Storage Project Plans. Accessed February 2024. Available online: "https://www.kgsp.co.uk/the-plans/".
- INEOS, 2024. Verbal communication with Richard Stevenson regarding HyKeuper project. 22 February 2024.
- H2eart for Europe, 2024. The role of underground hydrogen storage in Europe.
- Energy Technology Institute (ETI), 2018. Hydrogen Turbines Follow On – Salt Cavern Appraisal for Hydrogen and Gas Storage.
- Hydrogen TCP-Task 42, 2023. Underground Hydrogen Storage: Technology Monitor Report. 153 pages including appendices.

Time-savings on activities & cavern scale

The time required to develop many caverns compared to a single cavern is not linear i.e., time is saved largely through i) optimal development phasing, and ii) economies of scale. Both of these are captured in this section. Select TRUE to model the programme with the time-savings.

Time-savings on activities. Time is saved through optimal phasing of activities such as concurrent activities taking place. Most saving will be made during 2. Engineering design and procurement, 3. Construction, and 4. MIT and cavern debrining, e.g., if a development of 20 caverns is built out in phases of 5 caverns, resources can be deployed along the development chain as the first caverns approach commissioning.

Default values are provided to inform the user of industry guidance.

Economy of scale. Comparing against a linear increase in time for additional development of storage cavern, efficiencies in the development system for each subsequent cavern can be made. Note that industry recommends that currently caverns are developed in clusters of no more than 20. This is largely due to supply chain bottlenecks hence the default values do not indicate any savings beyond 20 caverns built out as part of the same development.

Default values are provided to inform the user of industry guidance.

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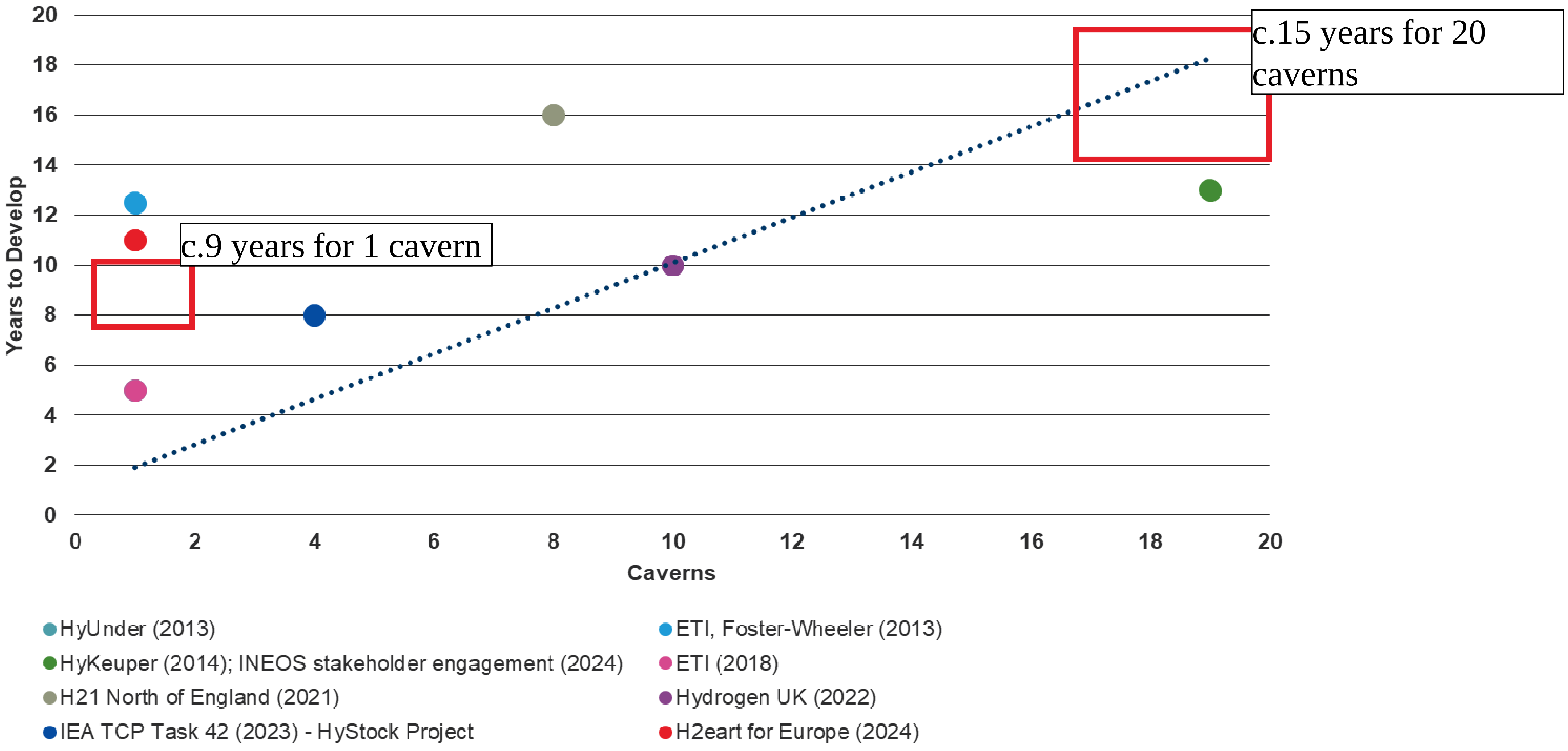
Cavern programme development

Indicative timescales from public sources



Programme Activities

Activity	1 cavern	20 caverns
0 - Pre-"planning" and consenting" (initial geological exploration and engineering design).	1.5	2.0
1 - Planning and consenting incl. DCO application and EPC tender	1.5	2.0
2 - Engineering & Procurement	2.5	3.0
3 - Construction - drilling, well completion, above ground	2.5	6.0
4 - MIT and cavern debrining	1.0	2.0
	9 years	*c.15 years*

- Time saving on each activity as already deployed skills and materials
  - Less applicable to Construction and Post-construction activities (#3 and #4)
- Time saving from building out many groups of caverns simultaneously
  - Efficiencies up to a point, then will reach ceiling of supply chain
  - E.g., able to concurrently develop 2 groups of 10 caverns, but supply chain constraints limits any efficiencies beyond developing more than 20 for any single project site

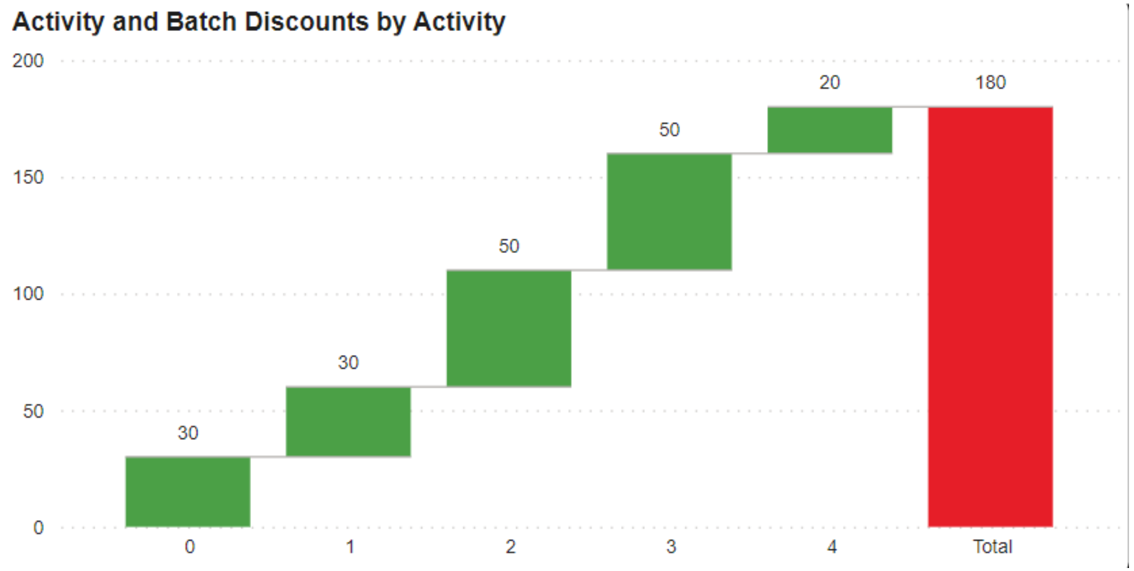
Programme Activities

Modelling time savings

No time savings on activities or simultaneous cavern development

1 cavern

20 caverns



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Programme Activities

Modelling time savings | Default Settings

1. Time saving on each activity for subsequent caverns as already deployed skills and materials
Efficiency from concurrent running of activities (phased cavern development).
Activities become more efficient for each additional cavern.

Activity savings on consecutive caverns (concurrent actions)

0	95.00%	1	95.00%
2	98.00%	3	80.00%
4	80.00%		

Discount Activities: True

2. Time saving from building out many groups of caverns simultaneously.
Optimised deployment of materials and skills for multiple cavern development.
Known limit of supply chain and brine disposal systems for a site greater than 20 caverns – no saving on additional caverns (0%).

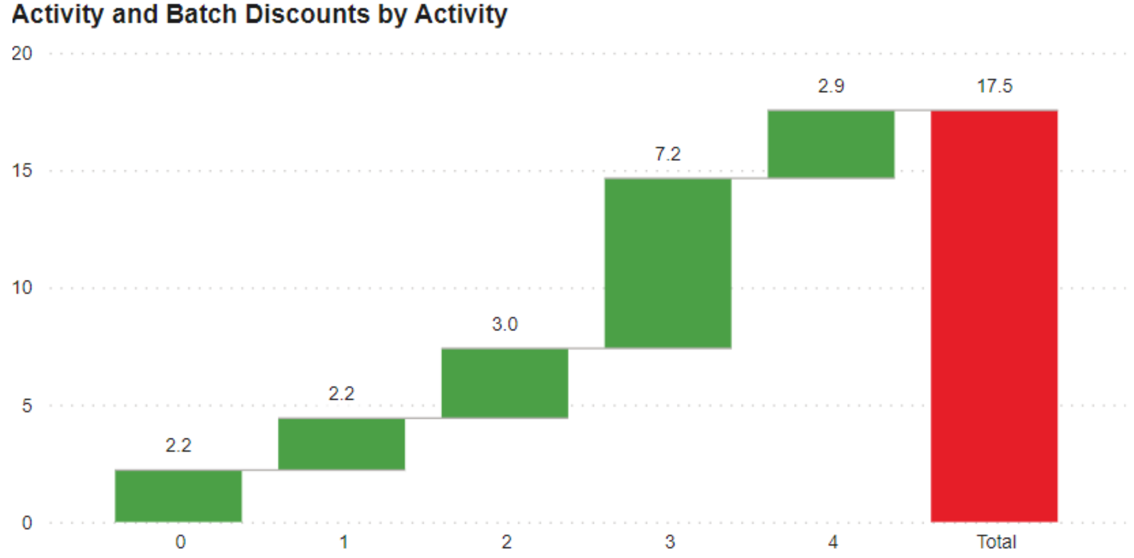
Discount on batches of caverns (assumes build out in groups)

1		2-10	50.00%
11-20	50.00%	21+	0.00%

Discount Batches: True

1 cavern

20 caverns



Page 4. Summary Report

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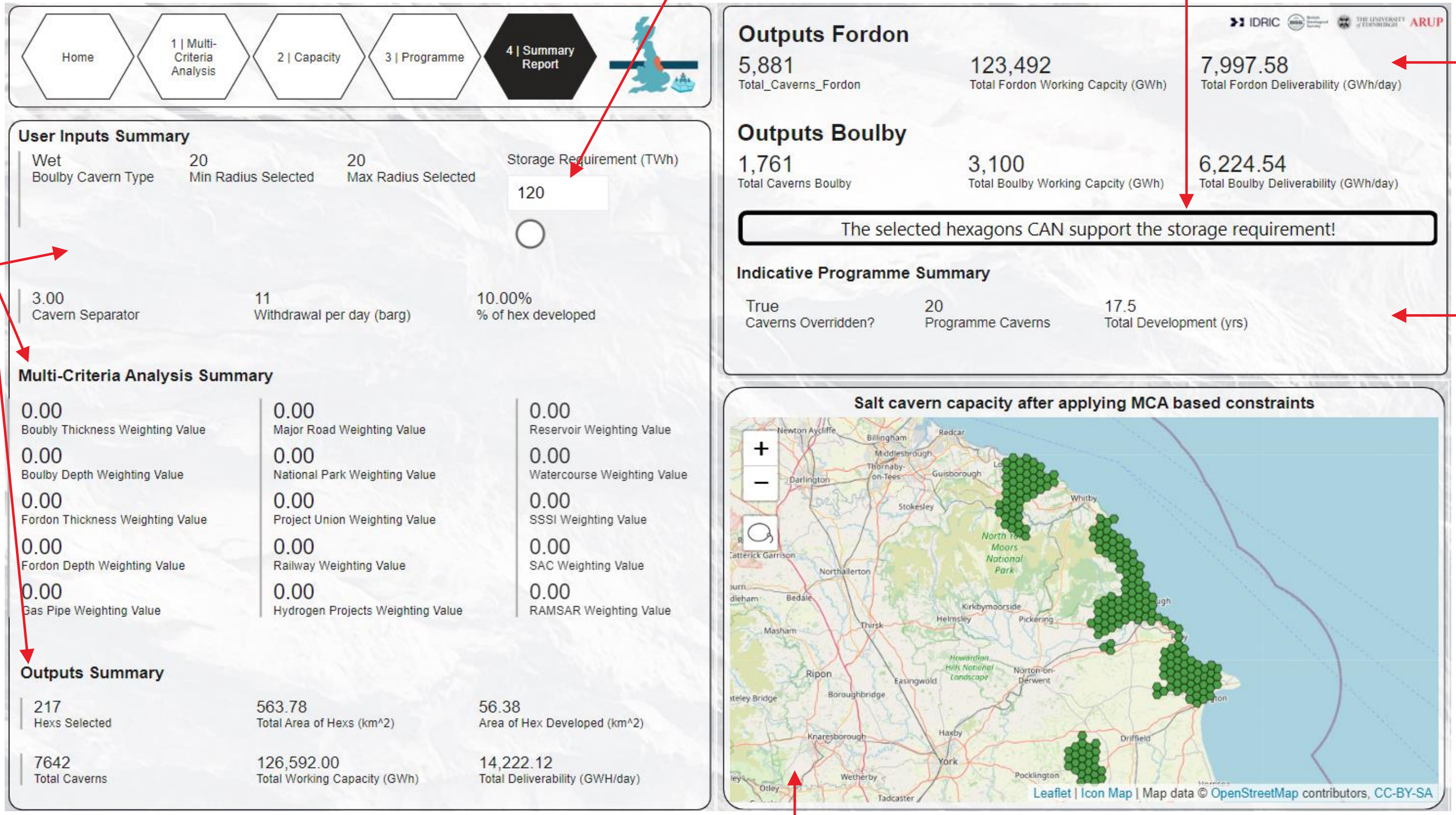
A summary page is provided which defines the user inputs, analysis outputs in terms of capacity and programme. The user has the option to define a “required storage capacity” which is compared against the analysis output. A maps of selected potential development sites is also provided.

The user can choose to provide a storage capacity requirement here. This is compared to the output of the analysis and a summary statement indicates whether the storage demand can be met through the user-defined scenario formed in Page 1 to Page 3.

User defined inputs from Page 1 Multi-Criteria Analysis and Page 2 Capacity (Cavern geometry and operational limits) are defined and provided here.

The output from the analysis is summarised, which includes number of caverns, total storage capacity, deliverability, programme estimate, development area.



A summary of the capacity and deliverability potential of the Fordon Evaporite and Boulby Halite formations is provided here.

A summary of the indicative development programme from Page 3 Programme is provided here.
Note that the number of caverns modelled for the programme may have been overwritten, so the programme timescale may not be specific to the total number of caverns derived from the analysis!

A summary of the selected hexagons for development is provided in this interactive map. Note that the map is carried through from Page 2 and Page 3, so the initial hexagons available will be the same as seen on those pages.
The map is also interactive on this page, hence if a hex is selected, the Outputs Summary and Programme Summary (if number of caverns has not been overridden) will update accordingly.

Case Studies

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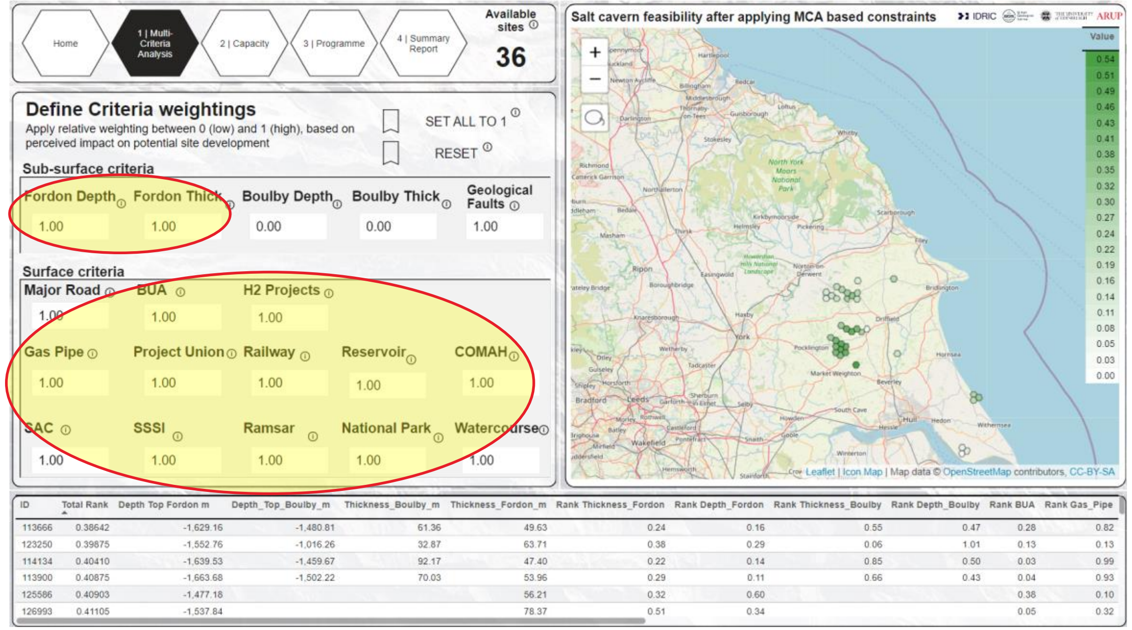
Case Study 1 – Capacity in the Fordon Evaporite Formation

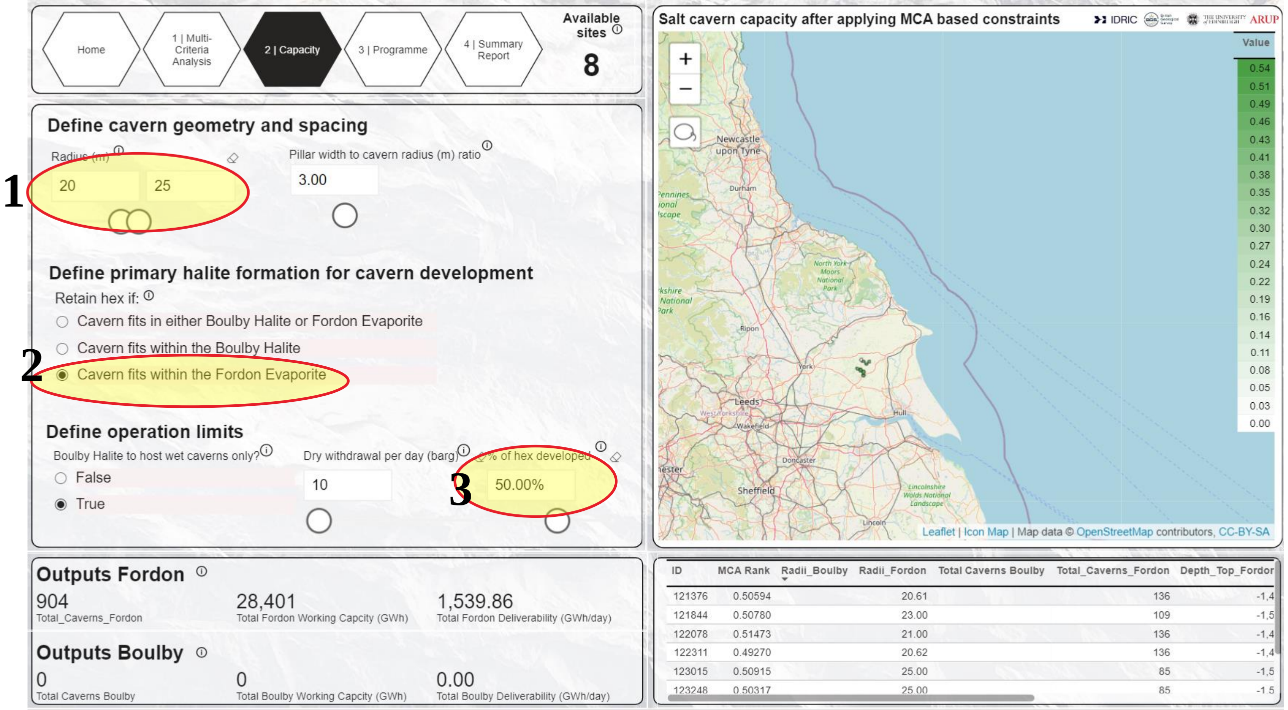
1. Set relative criteria



1. Fordon set to 1 will show sites where the Fordon Evaporite is present

2. Surface Criteria all equal to 1, therefore sites which interact with these criteria are excluded.

2. Set design criteria



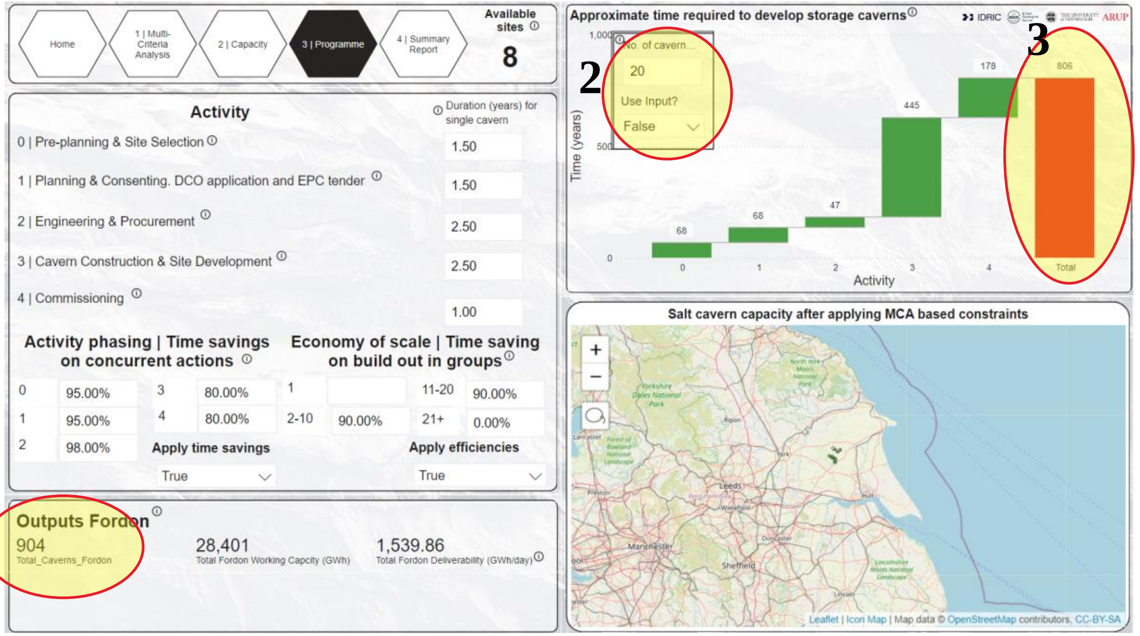
1. Cavern radius set between 20 and 25 m.

2. Only caverns within Fordon are modelled.

3.Only 50% of each site is developed for caverns.

Case Study 1 – Capacity in the Fordon Evaporite Formation

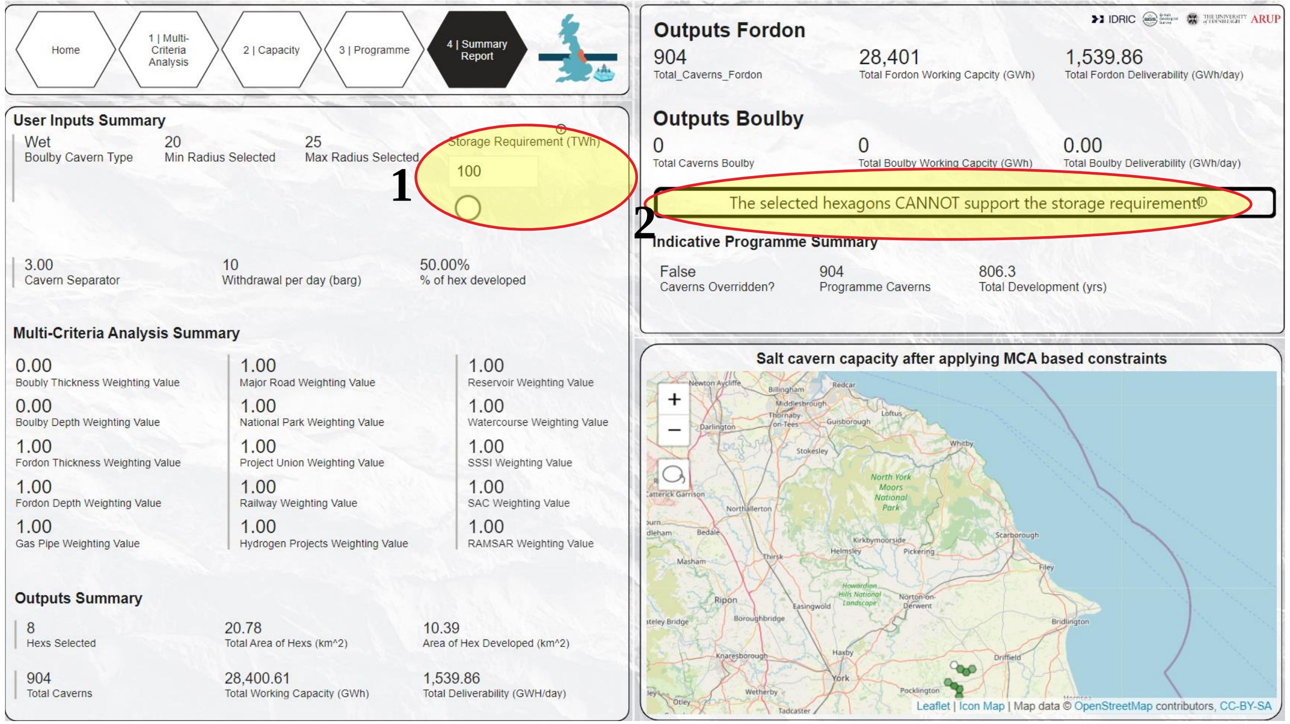
3. Estimate development time



1. To use the data from your specific study i.e., as shown in "Outputs Fordon" (in this case 904 caverns)…
2. …set the time calculator to "False"

3. The total time required to develop 904 caverns is approximately 800 years.
This is equivalent to around 45 sites of 20 caverns being developed concurrently, if each site takes 17.5 years to develop.

4. Summary



1. The storage requirement is set to 100 TWh

2. The requirement is compared to the capacity derived from your specific study. In this case the storage requirement CANNOT be met by storage caverns in the Fordon Evaporite Fm under the set conditions.

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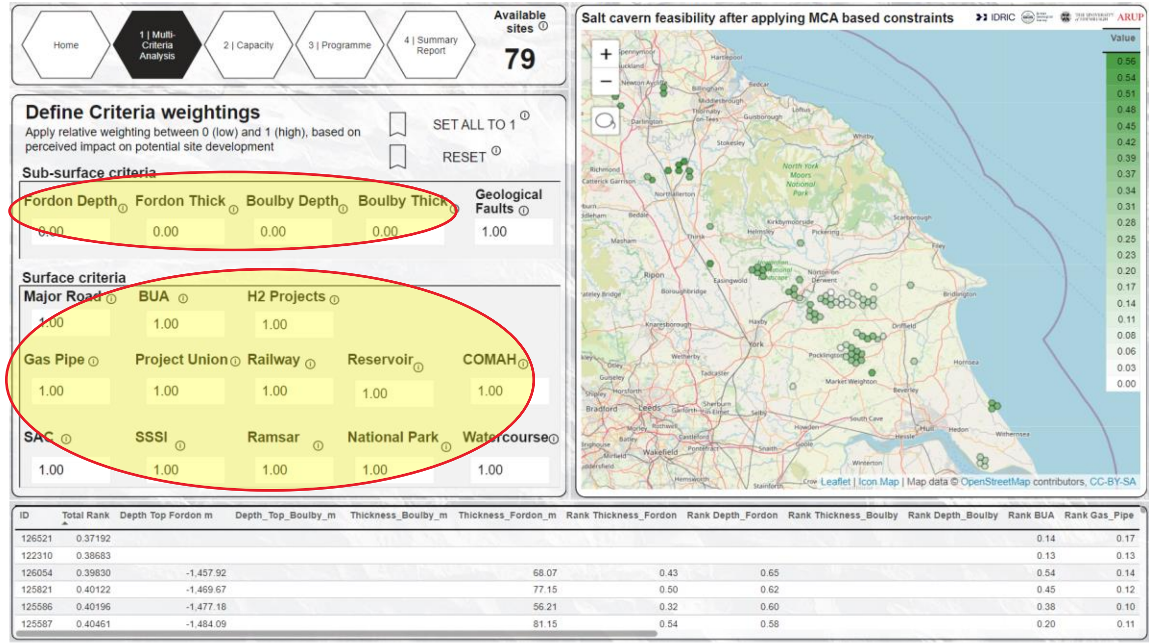
Case Study 2 – Capacity in the Boulby Halite & Fordon Evaporite Formation

1. Set relative criteria

1

2

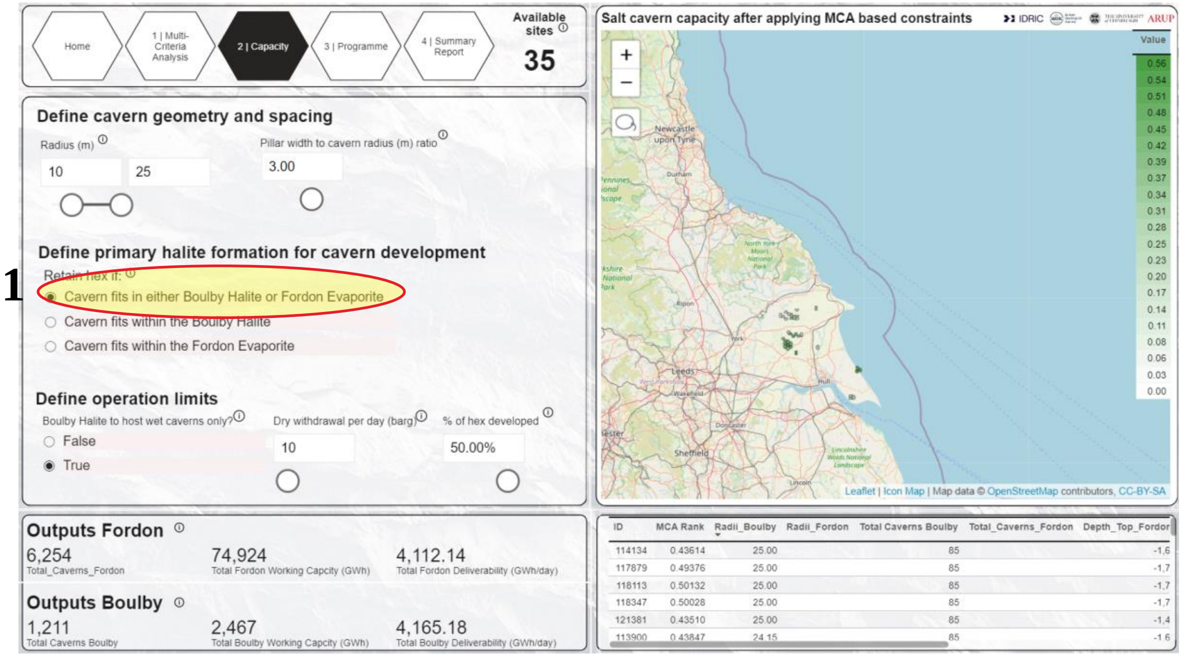


1. Fordon and Boulby properties are set to 0. The next page will identify sites which contain either Fordon or Boulby halite.

2. Surface Criteria all equal to 1, therefore sites which interact with these criteria are excluded.

2. Set design criteria

1



1. Caverns in both Boulby and Fordon are modlled. This setting filters out sites which do not contain halite and leaves only those that do.

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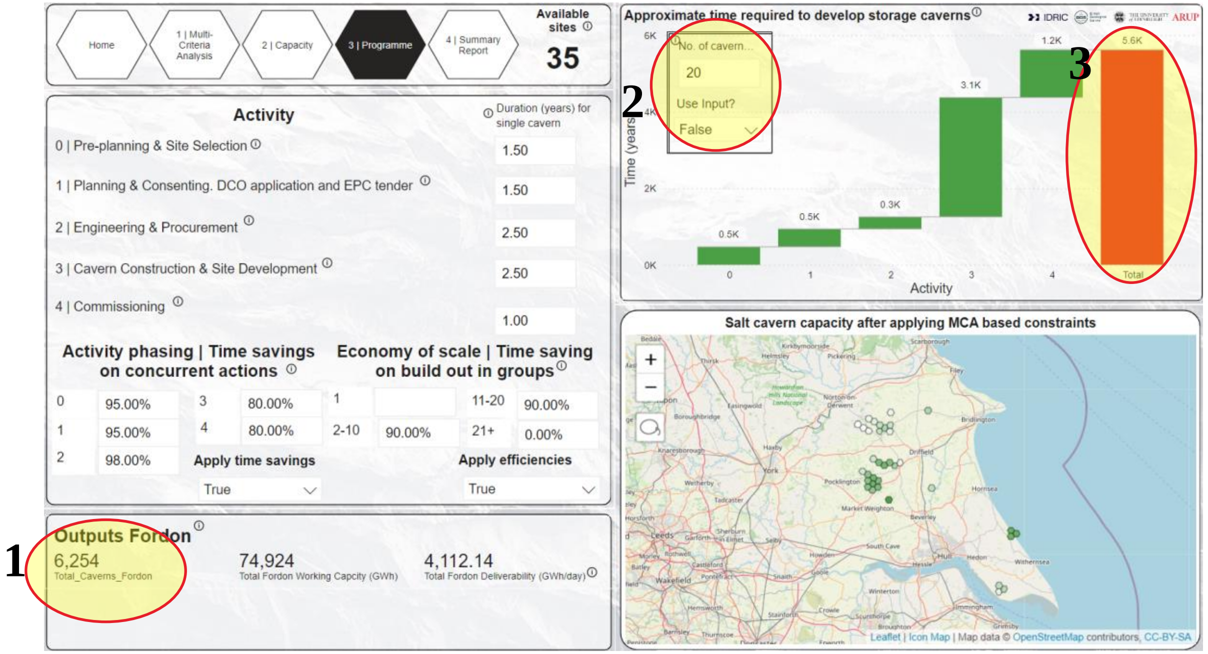
Case Study 2 – Capacity in the Boulby Halite & Fordon Evaporite Formation

3. Estimate development time

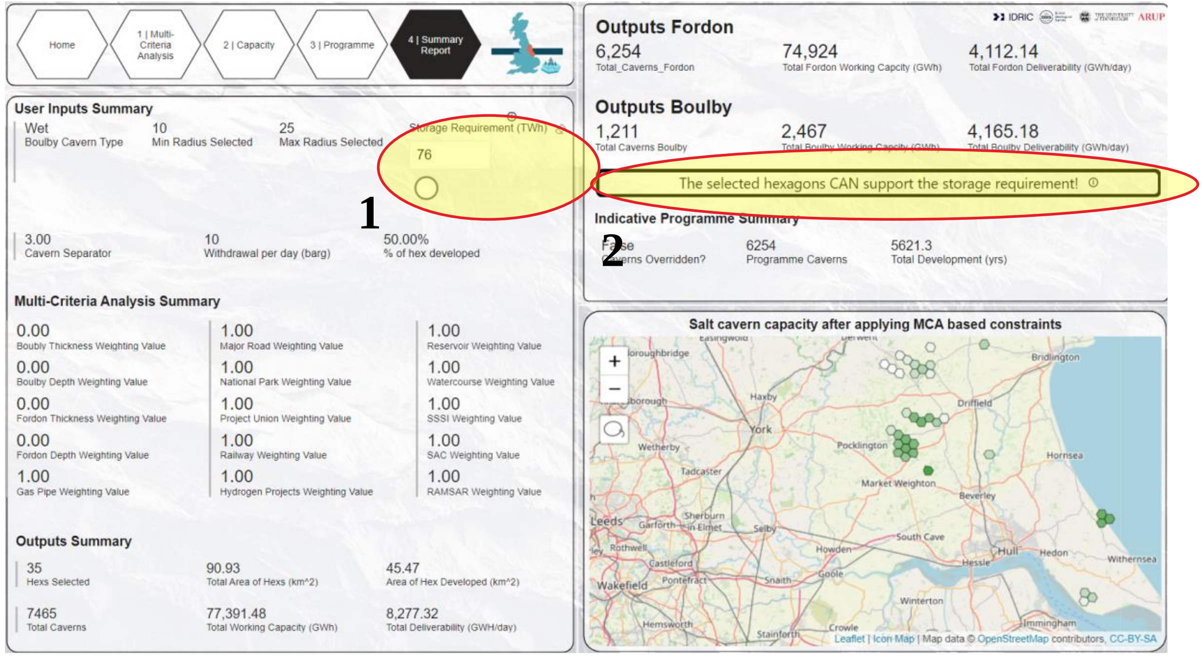


1. To use the data from your specific study i.e., as shown in "Outputs Fordon" (in this case 6254 caverns)…
2. …set the time calculator to "False"

3. The total time required to develop 6254 caverns is approximately 5600 years.
This is equivalent to around 300 sites of 20 caverns being developed concurrently, if each site takes 17.5 years to develop.

Note that only development time of caverns in the Fordon are modelled.

4. Summary



1. The storage requirement is set to 76 TWh

2. The requirement is compared to the capacity derived from your specific study. In this case the storage capacity is 75 TWh + 2.5 TWh, from Fordon and Boulby respectively, totalling 77.5 TWh. Therefore, the requirement CAN be met!

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Design Assumptions & Limitations

Extracts from co-funded report *“Assessing the Regional Demand for Geological Hydrogen Storage - Building a Strategic Case for Investment in the East Coast Cluster” (February 2024)*

Sub-surface and Surface Constraints: Defining Exclusion and Evaluation Criteria

Development potential of sites across the East Coast region is evaluated based on a suite of defined criteria.

19 spatial datasets are considered in determining the storage capacity in the East Coast region (Table B2). The datasets comprise 6 sub-surface constraints and 13 surface constraints.

Sub-surface constraints are:

- Depth and thickness of BHF and FEH
- Geothermal gradient and temperature at depth
- Major faults

Surface constraints are:

- Proximity to restricted development area (SSSI, SAC, RAMSAR, watercourses, National Parks)
- Proximity to built-up areas
- Proximity to reservoirs
- Proximity to railways and major roads
- Proximity to major pipeline networks/ corridors including Project Union pipeline.
- Proximity to COMAH sites
- Proximity to current and potential offtakers

Each constraint is appraised on its impact on the development potential of a site. Sites are typically excluded where they do not meet the criteria e.g., directly intersect the constraint or lie outside of the allowable range. Sites which have not been excluded are evaluated on the criteria of a sub-surface or surface constraint such as, the further from a built-up area the better, and they are ranked accordingly, so the further a site is from a built-up area, the higher the rank.

Relevance	Constraint	Allowable range/ criteria	Reference	Comment	Data sources
Sub-surface	Subsurface temperature	Below 80 degC. Excludes temperature above 80degC. Based on geothermal gradient of 30degC/ km	[11]	Exclusion criteria only	n/a
Sub-surface	Depth to top of salt	Above 300 m. Closer to Goldilocks zone (600 m – 1200 m) the better.	[12][13][14][15]	Exclusion & evaluation criteria	[43]
Sub-surface	Salt thickness	Above 30 m	Previous work considers a site if salt thickness is greater than 50 m (cavern height of 20m + roof and floor thickness of 30m) [2]	Exclusion & evaluation criteria	[43][7]
Sub-surface	Proximity to major fault	Above 200 m or 3 x cavern radius (whichever is greater). No grading.	[10][16]	Exclusion & evaluation criteria	[44][45]
Surface	Proximity to restricted development area (SSSI, SAC, RAMSAR, watercourses, National Parks)	Above 0 m from boundary. Further the better	Assumption based on [1]	Exclusion & evaluation criteria. Does not account for minor watercourses.	[46][48][49][50][51]
Surface	Proximity to built-up areas	Above 2500 m or 3 x cavern radius (whichever is greater). Further the better.	Assumption based on [1]	Exclusion & evaluation criteria	[58]
Surface	Proximity to reservoirs	Above 200 m or 3 x cavern radius (whichever is greater). Closer the better.	Assumption based on [13]	Exclusion & evaluation criteria	[52]
Surface	Proximity to railways and major roads	Above 200 m or 3 x cavern radius (whichever is greater). Closer the better.	Assumption based on [1][13]	Exclusion & evaluation criteria	[53][54]
Surface	Proximity to major pipeline networks/ corridors including Project Union pipeline.	Above 200 m or 3 x cavern radius (whichever is greater). Closer the better.	Assumption based on [1][13]	Exclusion & evaluation criteria	[47][55]
Surface	Proximity to COMAH sites	Above 1000 m or 3 x cavern radius (whichever is greater). Further the better.	Assumption	Exclusion & evaluation criteria. Does not represent site-specific COMAH requirements.	[57]
Surface	Proximity to planned hydrogen projects (i.e., offtakers)	Closer the better	Assumption	Evaluation criteria only	[59]

Design Assumptions: Dry and Wet Caverns

Key design assumptions in cavern design to minimise geomechanical instability of the salt cavern and adequately evaluate net cavern volume potential.

Relevance	Parameter	Assumption	Reference
Sub-surface	Cavern floor thickness	Floor allowance = 0.2 x cavern diameter	[1][10]
Sub-surface	Cavern roof thickness	Roof allowance = 0.75 x cavern diameter	[1][10]
Sub-surface	Cavern shape factor	Apply volume reduction of 0.7 based on irregular shape formation from leaching and allowance for creep closure over time, reducing the intended usable volume.	[1][2][9][17]
Sub-surface	Non-salt content	“Industry standard" of 25%	[2][17]
Sub-surface	Insoluble bulking factor	Factor of 1.46 to on the percentage of insolubles to account for bulking in the sump.	[2]
Sub-surface	Sump volume factor	Leached volume reduction factor from non-halite content and bulking: V_net = %impurities * V_leached * shape factor * bulking factor	Assumption based on [2]
Sub-surface	Temperature/ Geothermal gradient	30degC/ km depth.	[18][9]
Sub-surface	Temperature at surface	10degC assumed mean surface temperature	Assumption
Sub-surface	Cavern separation (pillar width)	Pillar width: 3*cavern radius (5x cavern radius centre to centre)	[17]
General	Lower Heating Value	Use Lower Heating Value (net calorific value) to convert between tonnage and power.	[9][19]
Sub-surface	Lithostatic pressure calculation	Internal lithostatic pressure of the cavern is computed from vertical stress only. No consideration of horizontal stresses.	Assumption
Sub-surface	Overburden density	Overburden assumed to be 0.0225 MN/m3, in line project experience in the UK salt fields (aligns to the overburden density used in Cheshire salt fields).	[9][20]

Table B3. Design assumption relevant for storage capacity calculations in dry and wet caverns in East Coast region

Design Assumptions: Dry Cavern Specific

Key design assumptions in cavern design of dry operated caverns to minimise geomechanical instability of the salt cavern.

Relevance	Parameter	Assumption	Reference
Sub-surface	Cavern height	Cavern is modelled as a flat-topped cylinder. Max cavern height is calculated by salt thickness - roof thickness - floor thickness. Max ratio with diameter = 2D:H	[17]
Sub-surface	Cavern operation	Capacity calculations will allow for dry caverns to be modelling in the Boulby Halite Formation and Fordon Evaporite Formation. This study only models capacity in the Fordon Evaporite Formation from dry caverns.	n/a
Sub-surface	Cavern radius	Cavern is modelled as a flat topped cylinder. Max cavern height is calculated by salt thickness - roof thickness - floor thickness. Max ratio height with diameter = 2D:H Minimum radius set at 5 m. Therefore minimum salt thickness required for caverns to be constructed: (cavern height = 20 m + roof thickness + floor thickness = 10 m) = 30 m.	[1][10][17][21]
Sub-surface	Operating pressure limits	Pmin set at 24% lithostatic. Pmax set at 80% lithostatic.	[1] (Note that [22] assumes Pmin = 0.2 x lithostatic)

Table B4. Design assumption specific to dry cavern storage, relevant for storage capacity calculations

Design Assumptions: Wet Cavern Specific

Key design assumptions in cavern design of wet operated (brine-compensated) caverns to minimise geomechanical instability of the salt cavern.

Relevance	Parameter	Assumption	Reference
Sub-surface	Cavern height	Cavern is modelled as a spinning top. Max cavern height is calculated by salt thickness - roof thickness - floor thickness. Max ratio with diameter = H:0.5D	[23]
Sub-surface	Cavern operation	Wet operated caverns will only be applied to Boulby Halite Formation (BHF). The site selection tool allows the user to choose to model caverns in Boulby (BHF) as either wet or dry operated caverns.	[23]
Sub-surface	Cavern radius	Cavern is modelled as a spinning top. Max cavern height = salt thickness - roof thickness - floor thickness. Diameter at widest point is approximately twice the length of cavern height (2D:H) [23]. This is to maximise storage volume given the thin halite bed. Minimum cavern radius is set at 10 m, therefore caverns can only be sited in salt equal to or greater than 30 m thick (cavern height = 10 m; roof allowance = 15 m; floor allowance = 5 m).	[23]
Sub-surface	Operating pressure limits	Constant internal pressure at halmostatic pressure (full-head of brine). Brine assumed to have unit weight of 0.0118 MN/m3.	[23]

Table B5. Design assumption specific to wet cavern storage, relevant for storage capacity calculations

Limitations & Opportunities

To enable further development of the research presented in this work package, key limitations are presented. Additionally, there exists many opportunities to further refine the theoretical storage capacity in salt caverns towards a "realisable potential".

Limitations

- Development sites are predefined on a 2.5 km^2 hexagonal footprint. The area is considered to be appropriate and similar to other development sites in the UK, such as Keuper Gas Storage Project. If a hexagon intersects with any surface constraint, the entire hexagon will be removed from the analysis. A smaller hexagonal grid size could be considered to better optimise the available land for development.
- The geological model has been informed from publicly available dataset from UK Onshore Geophysical Library (UKOGL) and onshore mapping published by British Geological Survey (BGS). Additional datasets such as seismic sections and intrusive data should be considered at any future stage.
- For the scope of this study, a region-wide appraisal, the granularity of the ground data used to develop the geological model is considered to be appropriate. It is worth noting that as the input data is generally at a much lower resolution than the size of a hexagon, significant geological uncertainty exists for each hexagon.
- Site-specific geological models should be developed to assist more rigorous development opportunities on a local basis.
- Ultimately, this is a regional study and all assumptions should be tested and refined on a site-specific basis with site-specific data.

Opportunities

- Refine geological model. Incorporate additional ground data such as BGS GeoIndex boreholes and geophysics sections to better constrain the extent, depth and thickness of salt horizons.
- Refine workable volume insoluble content. A uniform value of 25% of non-halite geology is considered for the workable volume of Boulby Halite Formation and Fordon Evaporite Formation. This should be refined to capture lithological and mineralogical heterogeneity.
- Communicate uncertainty in the geological model. This could be through statistical analysis of ground data and/or incorporation of an uncertainty factor.
- Refine topography model to reflect true land elevations. Currently the regional topography is defined as constant 0 mOD. This can result in over-conservative estimates of capacity where there is significant positive elevation.
- Refine potential capacity model. Incorporate extents of existing subsurface developments e.g., historical mining (e.g., coal), mine extraction limits (underground storage sites, Boulby Mine and Woodsmith Mine extraction limits), and underground infrastructure (Boulby Mine shafts and associated developments and Woodsmith Mineral Transport System and other associated developments)
- Industry engagement. Refine and develop the tool based on industry requirements. This will set the scene for subsequent revisions.
- An adequate estimation of realisable potential will require additional consideration of technical, social and economic viability, and is beyond the scope of this study and should be considered at the next stage.
- Understand the geomechanical viability of hydrogen storage. This will include geological modelling for cavern responsiveness to hydrogen cycling.
- Extend methodology to refine offshore storage estimates in the Fordon Evaporite Formation and Boulby Halite Formation.
- Economic analysis of CAPEX required to meet UK's hydrogen storage demand.

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