Geological storage of Hydrogen for Net Zero

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Hydrogen is necessary to meet UK Net Zero targets

Current (2024) UK energy mix

80% Fossil Fuels

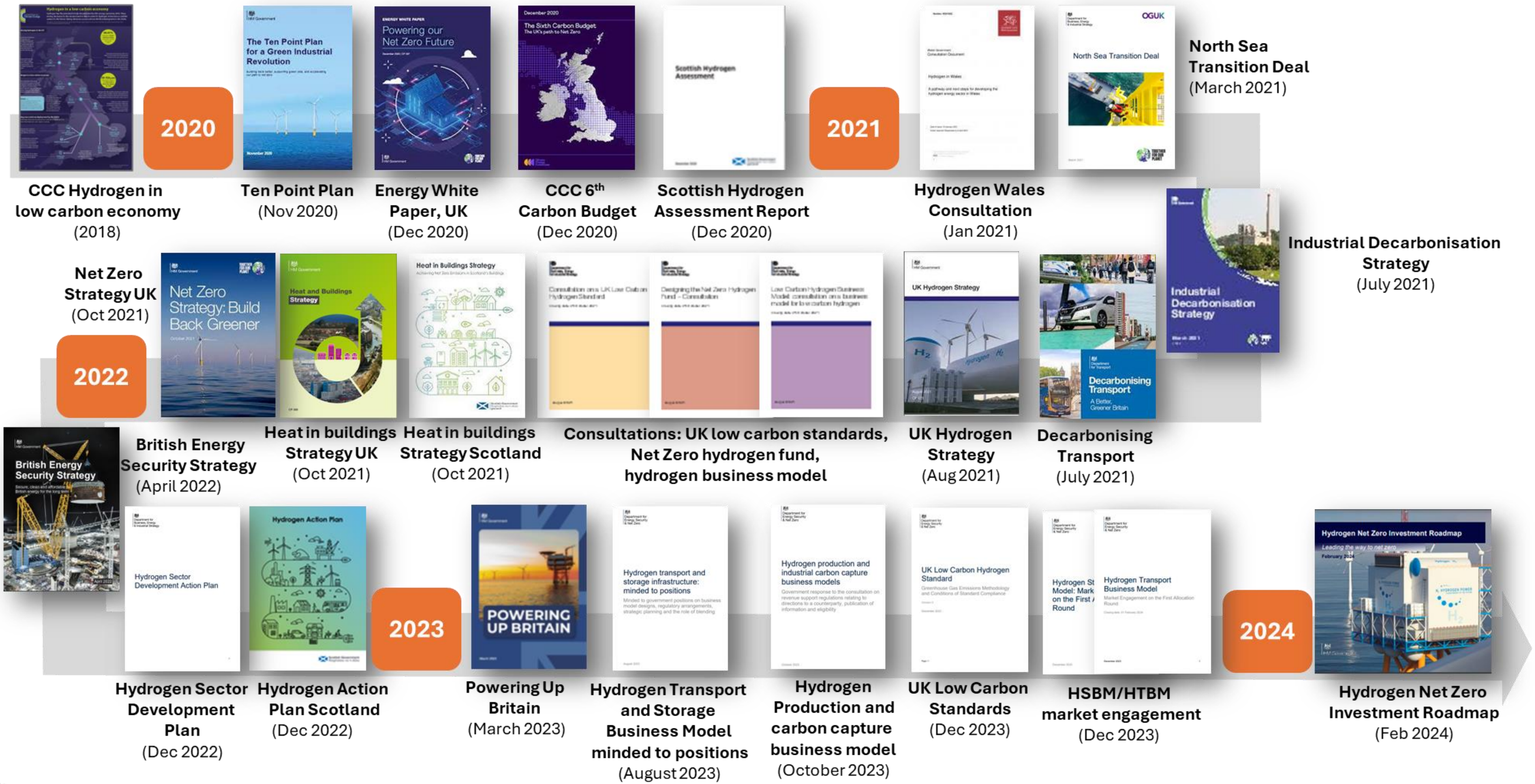
20% Electricity (~10% Renewable)

2050 UK Net Zero energy mix (CCC recommended path)

~15-22% Fossil Fuels

~60-70% Renewable Electricity

~15-25% Hydrogen (comparable to existing electricity)



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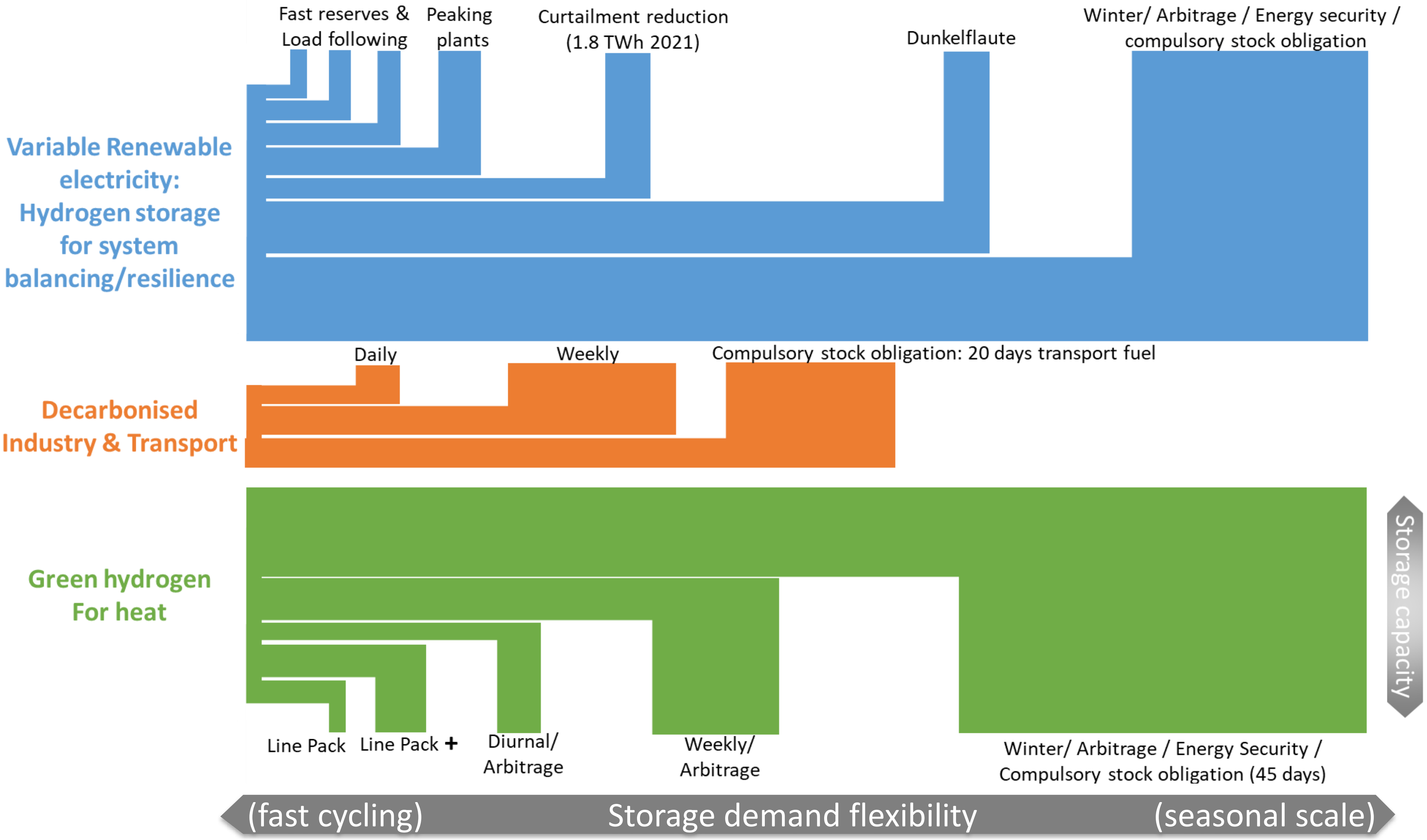
Why do we need hydrogen energy storage?



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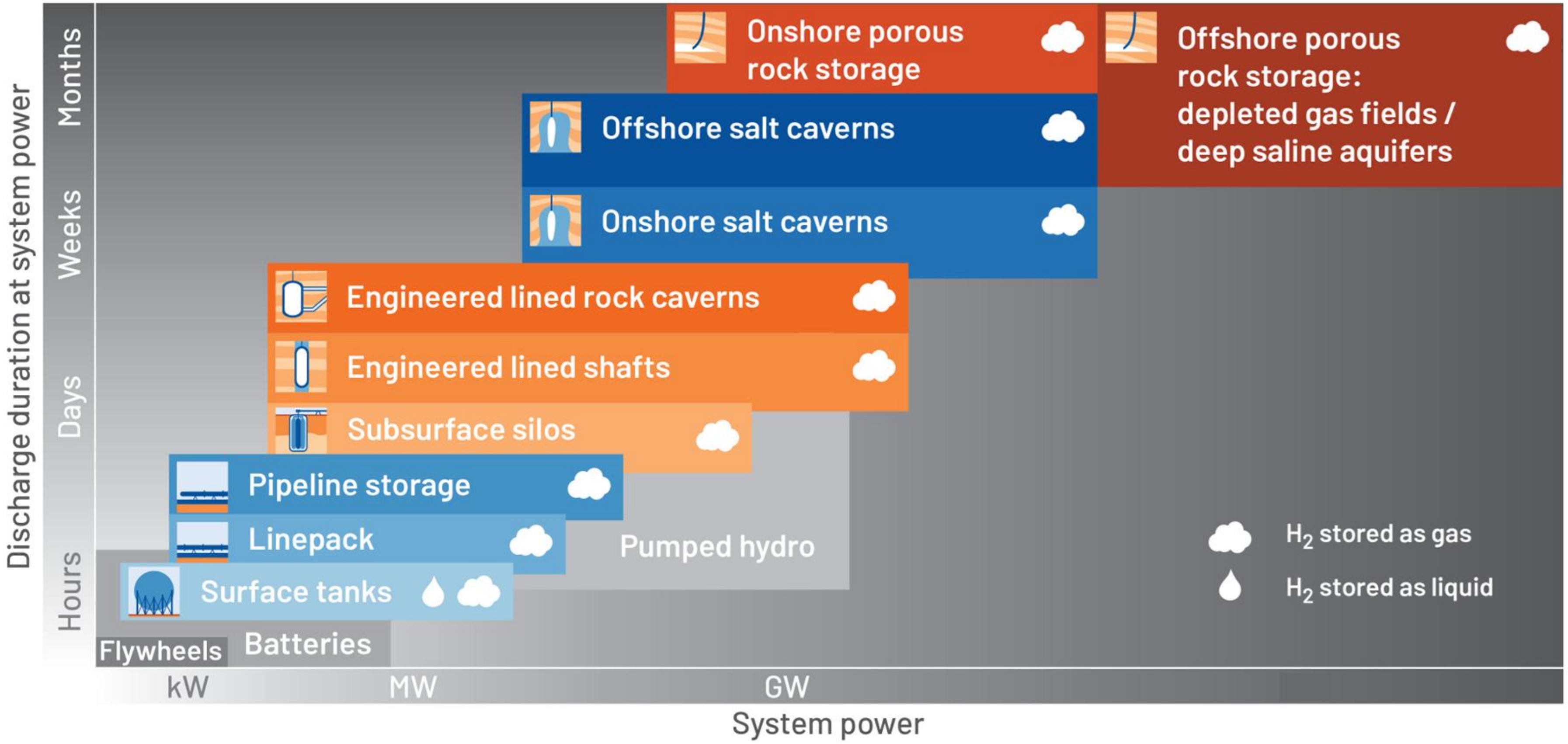
How much hydrogen energy storage will we need?

✓ The **UK** National Grid Future Energy Scenarios anticipate that 56 TWh/year of hydrogen energy storage is required by 2050 for their system transformation scenario.

Only the storage of hydrogen gas in suitable geological formations can deliver the required TWh capacity of energy storage with delivery over weeks to months that will be necessary for a renewable-heavy grid.



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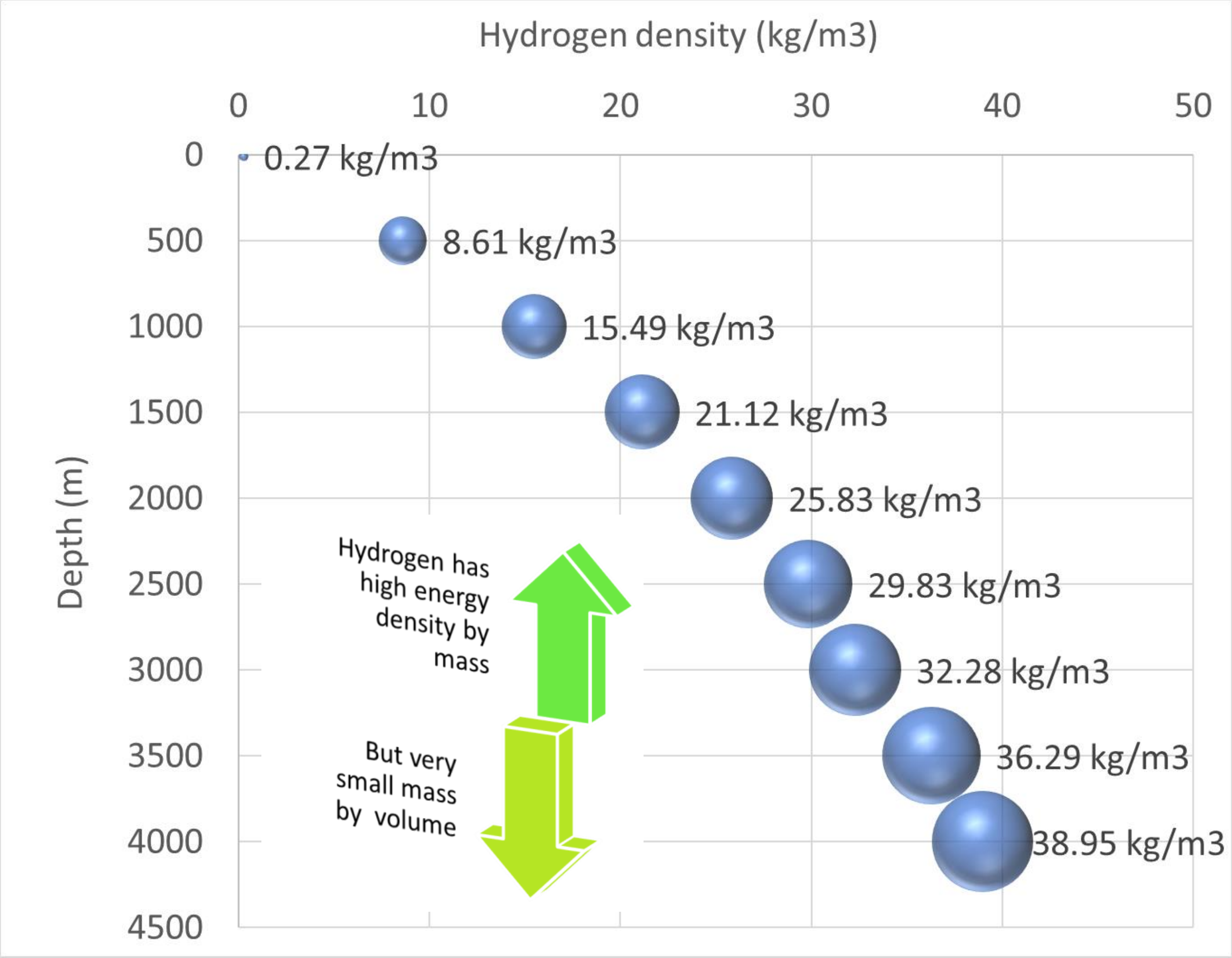
Why geological storage?

- While hydrogen has a very high energy density by mass, it's extremely small mass means that for the storage of hydrogen to be economically viable, its storage density must be increased.
- Geological storage of hydrogen is recognised as the cheapest option for large scale energy storage.
- Geological storage of hydrogen benefits from:
  - Increased temperatures and pressures with depth
  - Very large volumes of storage
  - Hydrogen can be stored in gas phase avoiding the additional costs associated with material-based hydrogen storage



Each circle represents the hydrogen density (kg/m3) at that given depth (= P/T)

- Pressure calculated from 0.0226 MPa/m average gradient
- Temperature from 25 oC/1000 meters average geothermal gradient and average surface temp of 15 oC

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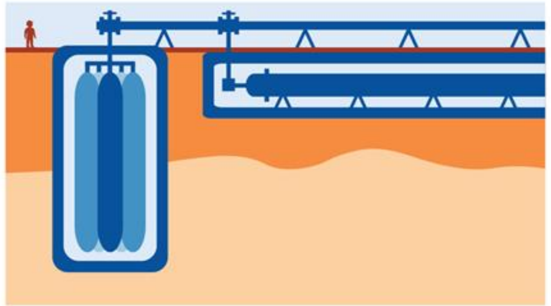
Geological hydrogen storage technologies…

Above ground pipes / tanks

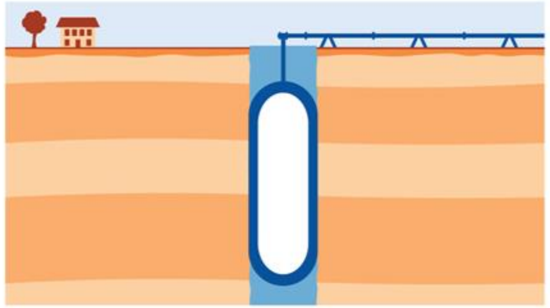
Delivers kW to MW over hours

Subsurface silos / pipes



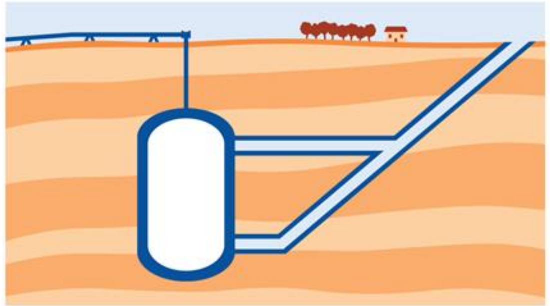
Delivers MW to GW

Lined shafts



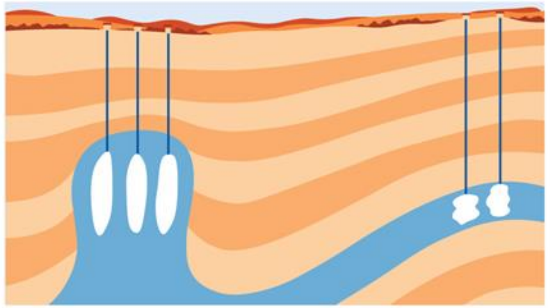
Delivers MW to GW over weeks

Lined rock caverns



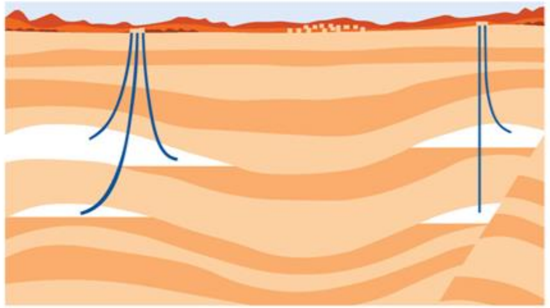
Delivers MW to GW over weeks

Salt caverns



Delivers GW over weeks to months

Porous rock reservoirs



Delivers TW over months

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Worldwide Underground hydrogen storage experience = Commercially and technically feasible

Aquifer storage of hydrogen (town gas)

- Ketzin, Germany (62% hydrogen town gas – now closed)
- Beynes, France (50% hydrogen town gas from 1956-1972)
- Lobodice, Czech Republic (50% hydrogen town gas from 1965, now used for natural gas storage)

Salt cavern storage of hydrogen

- Teeside, UK (active since 1959 storing 95% hydrogen)
- Kiel, Germany (62% hydrogen, now operating with natural gas)
- Spindletop, US (95% hydrogen storage)
- Clemens Dome, US (95% hydrogen storage)
- Moss Bluff, US (95% hydrogen storage)

Hydrogen storage for biomethane production

- Hychico, Argentina (10% hydrogen storage in a depleted gas reservoir)
- Underground Sun Storage, Austria (10% hydrogen storage in a depleted gas reservoir from 2015)

Hydrogen storage in lined rock caverns

- HYBRIT, Sweden for 100% decarbonised steel production

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Dedicated Pipeline Storage

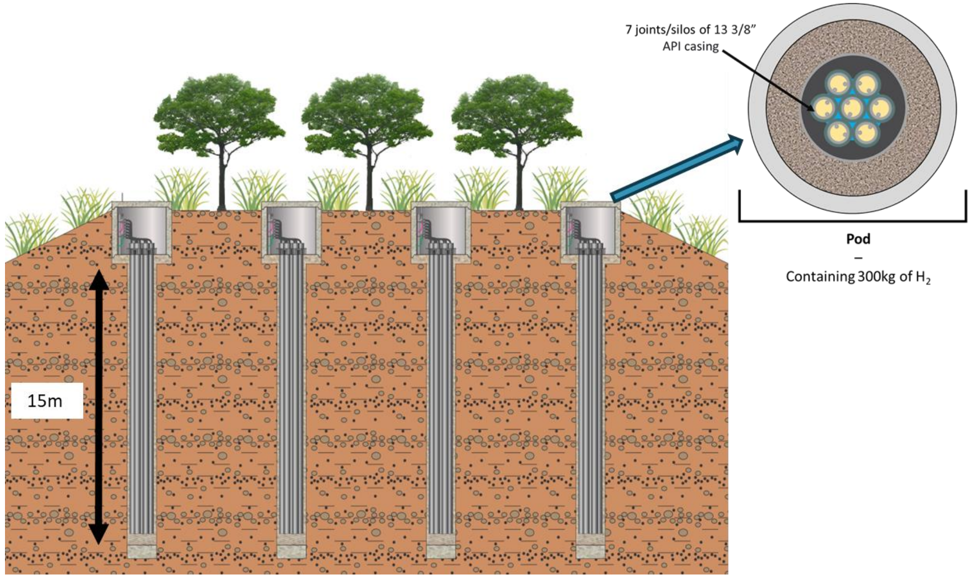
- Independent of Geology
  - 1 - 2m excavation required.
- **1 GWh facility requires ~4 acres land**.
- Natural gas storage in dedicate pipelines in commercial operation e.g. Urdorf (Switzerland).
- 4500 kilometres of hydrogen pipelines operational worldwide.
- High operational flexibility.
  - Delivers MW to GW at constant rates.
- Fast deployment (~2 years).

Saarstahl AG dedicated pipeline storage facility in Neunkirchen in Saarland, Germany Invisible gas storage facility for Saarstahl AG (steeltimesint.com)

Requirements for a 1 GWh Storage Facility	
	Pipeline 1 – best case
Pipe specification	24” Schedule 100
Inner diameter	532 (mm)
Operating pressure	139 (bar)
Length of pipe required	~13 (km)
Land required	~16,000 m2 (~4 Acres)

Silos

- Independent of geology
  - Placed into cemented boreholes ~15m deep.
- Technology:
  - Silos are comprised of 7 canisters rated to 50 MPa
  - Each pod can hold 300kg hydrogen
  - Sites can be scaled to meet demand:
  - **1 acre can house 136 pods = 1.35 GWh**
- Natural gas storage successfully operated in silos since 2016.
- Hydrogen storage facility planned to open in 2025 (Oklahoma).
- High operational flexibility
  - Delivers MW to GW at constant rates.
- Fast deployment (2-3 years).



BEDROCK Ventures

https://bedrockgs.com

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Safe underground hydrogen storage in earth subsurface reservoirs

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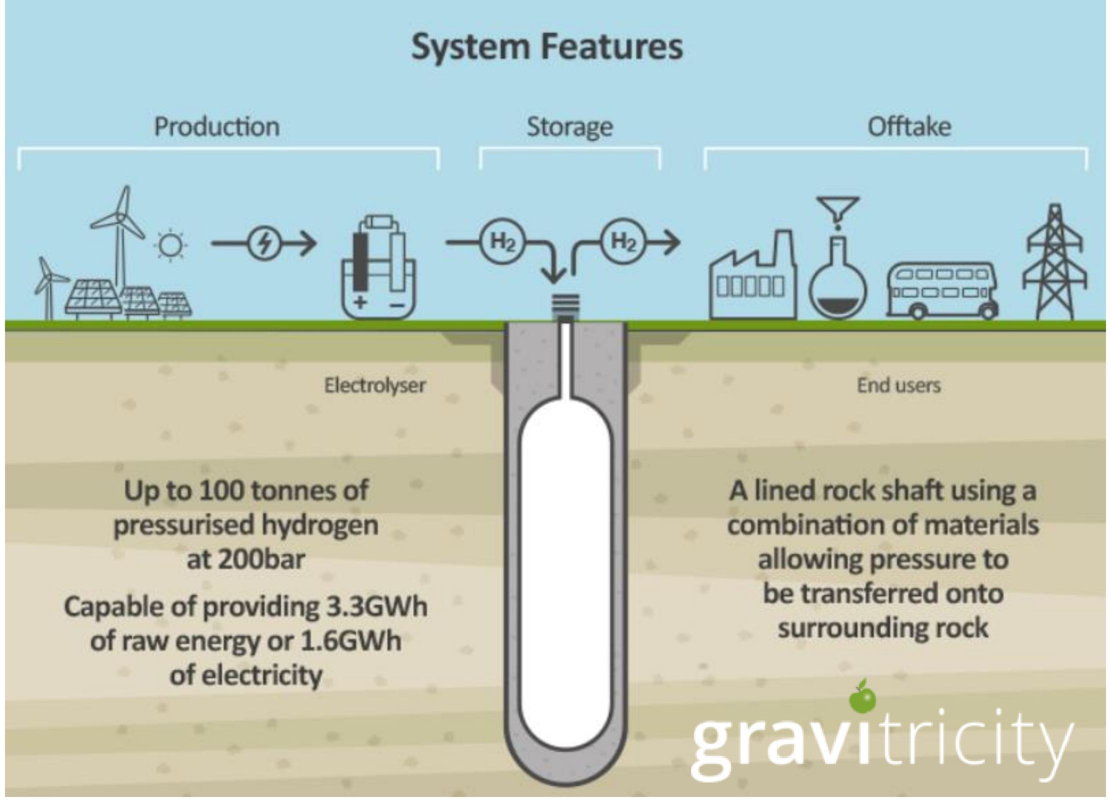
Lined Rock Shafts

- Geological requirements:
  - Strong rocks
  - Minimal faulting of surrounding rocks
- Technology:
  - 300m deep shaft ~2m in diameter.
  - Cement and steel lining for pressure dispersal and gas tightness.
  - Low cushion gas requirements
- No active deployment as yet, but pilot project being planned.
- **Storage capacity of 3.3 GWh**
- High operational flexibility
  - >18,000 cycles per 50-year life span.
- Fast deployment (3-4 years)



https://gravitricity.com/technology/

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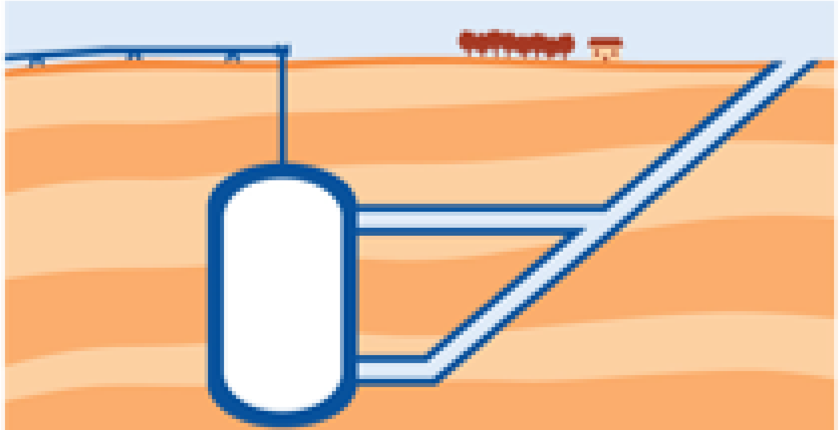
Lined Rock Caverns

- ➢ Geological requirements:
  - ➢ Strong rocks
  - ➢ Minimal rock layering and faulting of surrounding rocks
- Technology:
  - ➢ 100-200 m deep
  - ➢ Caverns typically 40 m in diameter, 60-100 meters in height
  - ➢ Multiple caverns can be hosted from the same surface facility
  - ➢ Cement and steel lining for pressure dispersal and gas tightness.
  - ➢ **Single cavern of ~40,000 m3 at 20 MPa pressure will hold around 15-20 GWh (500-800 tonnes) hydrogen**.
- ➢ Can operate at low pressures meaning low cushion gas requirements.
- ➢ High operational flexibility to provide future fast response and daily electricity grid balancing/resilience
- ➢ Over 200 LRC in gas storage operation globally
  - ➢ Swedish Hybrit project underway, with hydrogen gas testing ongoing.
- ➢ Reasonable high operational flexibility
- ➢ Moderate deployment time (5 years)



Steel liner = gas tightness
Concrete layer = stress distribution
Rock mass = confining pressure

HYBRIT's Lined Rock Cavern

https://www.hybritdevelopment.se/en/a-fossil-free-development/hydrogen-storage/

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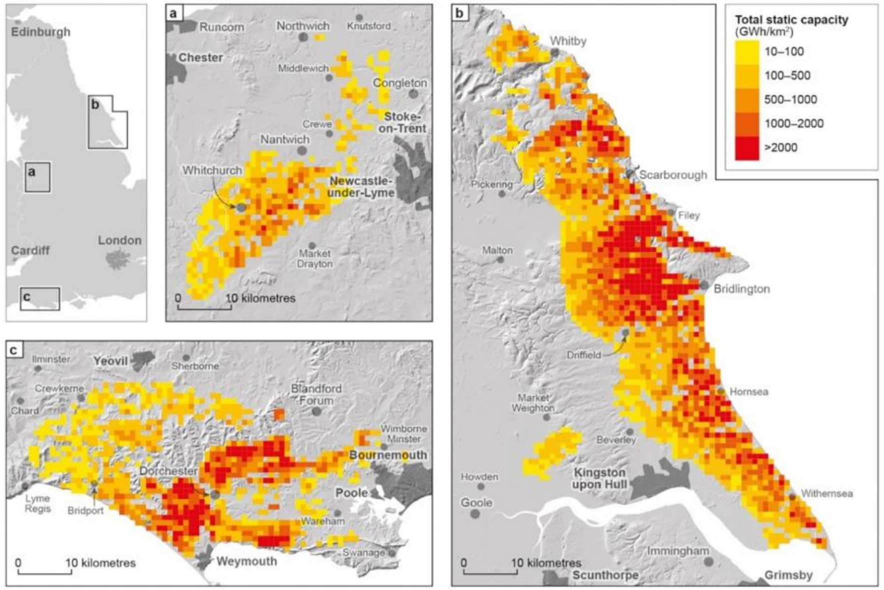
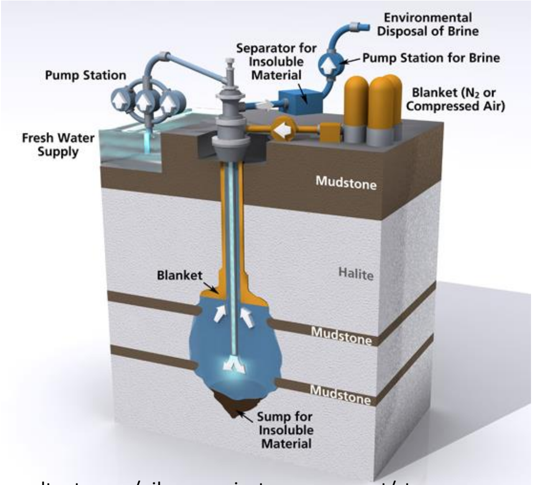
UK onshore salt for hydrogen storage

- Geological requirements:
  - Salt rocks with suitable depth and thickness.
  - Salt deposits in the UK are geographically constrained
- Technology:
  - Caverns voids solution minded from the salt formations
  - 500 – 2000 m deep
  - Caverns typically 20-50 m in diameter, can be 100’s meters in height
  - Multiple caverns (8-20) will be hosted from the same surface facility
  - Salt rocks provide gas tightness and healing
  - **Single cavern with a volume of 300,000 cubic meters could store approximately 50-170 GWh of energy, depending on depth (pressure)**
- 100’s of salt caverns in operation for natural gas storage.
  - Five salt caverns (3 in UK and 5 in US) have been storing hydrogen for decades.
  - BGS estimate theoretical capacity for hydrogen storage in salt caverns at 2150 TWh
- Moderate operational flexibility to provide both fast cycling and seasonal storage
- Relatively long deployment time for a new cavern (8-10 years)



https://www.sciencedirect.com/science/article/pii/S2352152X22011100#f0005



https://cbwresourceconsultants.com/oil-gas-project-management/storage-caverns/

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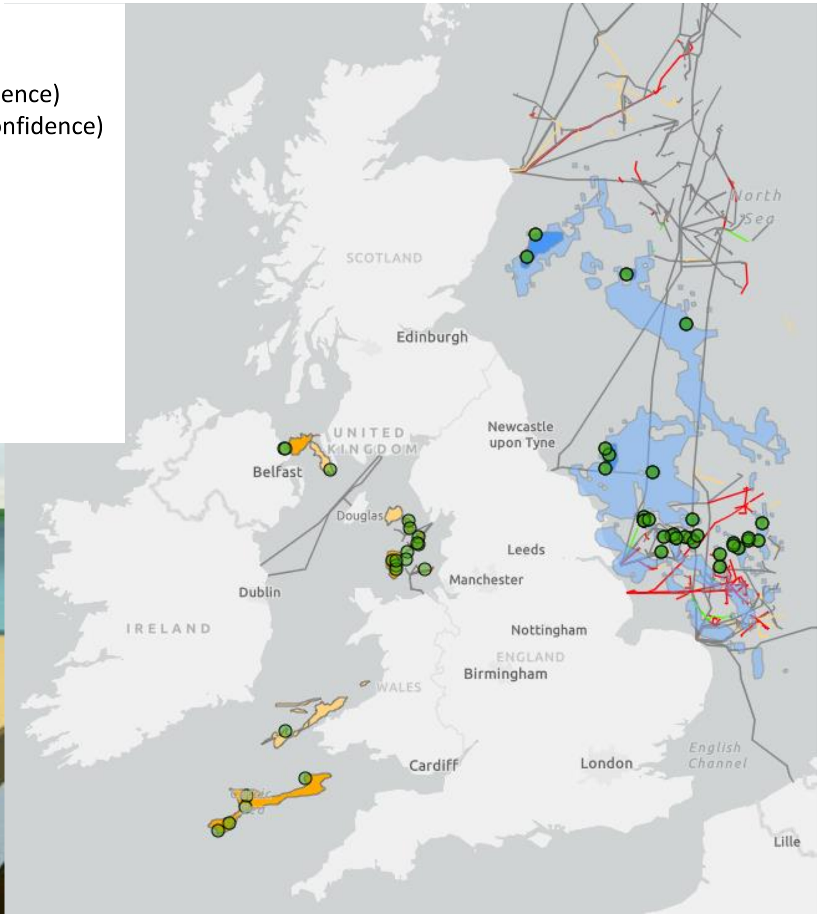
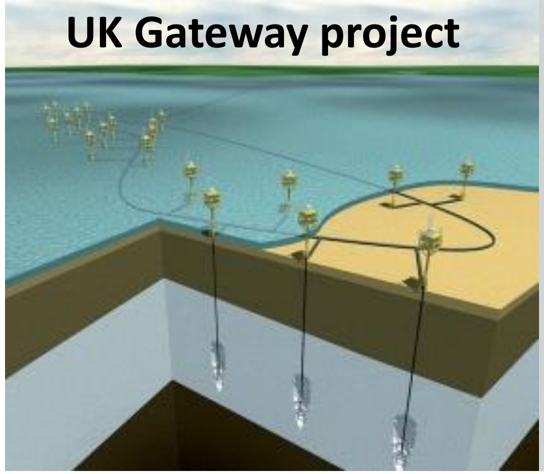
UK offshore salt for hydrogen storage

Hydrogen storage in offshore salt caverns:

- ➢Offshore may be necessary depending on public perception.
- ➢Higher costs than onshore.
- ➢https://doi.org/10.1144/SP528-2022-82

The theoretical capacity for hydrogen storage in UK OFFSHORE salt caverns in the Southern North Sea is 292 TWh





https://www.imeche.org/news/news-article/go-for-gas

https://www.lyellcollection.org/doi/abs/10.1144/SP528-2022-82

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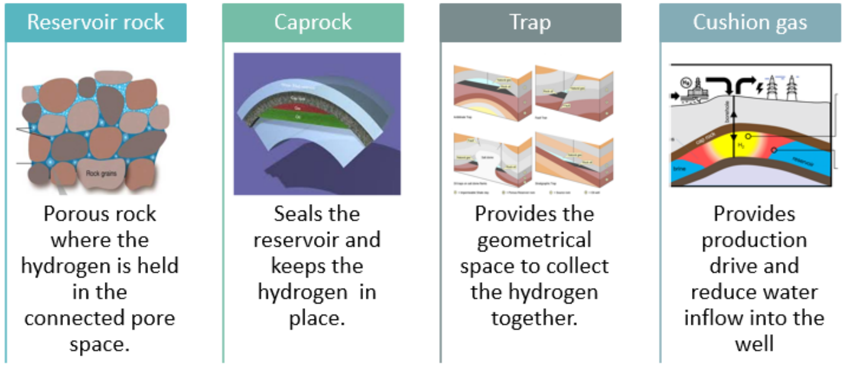
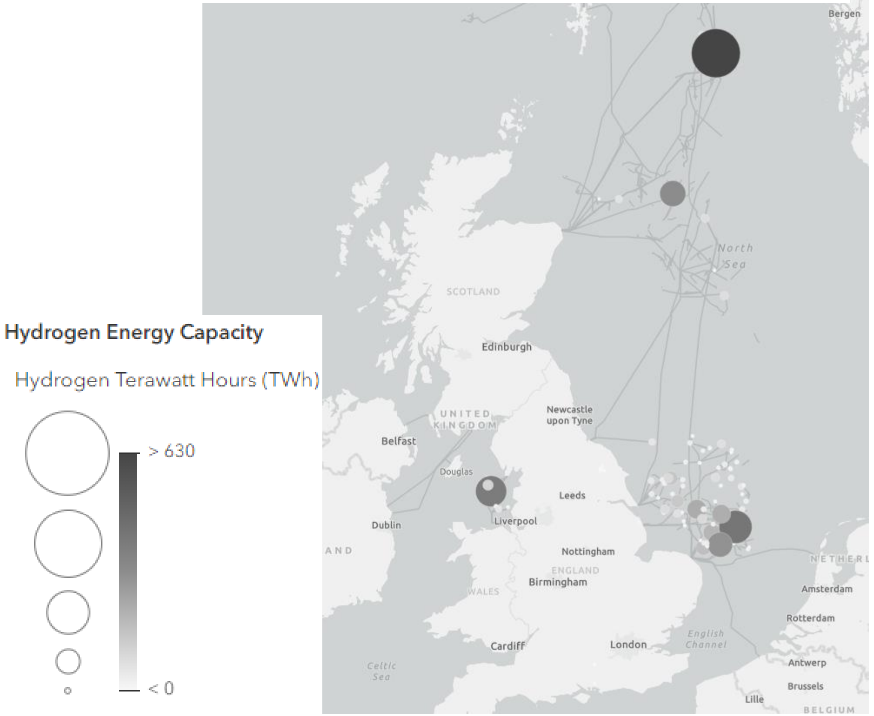
Porous Rock Storage: UK Depleted gas fields

- ➢ Geological requirements:
  - ➢ Porous and permeable reservoir rock
  - ➢ Extensive sealing caprock
  - ➢ Suitable trapping structure geometry
- Technology:
  - ➢ Proved ability to securely hold and deliver gas
  - ➢ 1000 – 2000 m deep
  - ➢ Can utilize existing infrastructure associated with gas operations
  - ➢ **Single field can hold 100's GWh to 10's TWh hydrogen storage capacity**
- ➢ 100's of depleted gas fields in operation for natural gas storage.
  - ➢ Porous rocks were used to store town (~60%) hydrogen) gas for decades, proving tightness and integrity of caprock and well cements with no safety issues reported.
  - ➢ Rag "Underground Sun Conversion" pilot project in Austria
  - ➢ Rough gas field has hydrogen suitability testing underway
- ➢ Operational flexibility to provide weekly to seasonal storage
- ➢ Relatively long deployment time to repurpose a gas field (6-15 years)





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Global hydrogen storage projects underway

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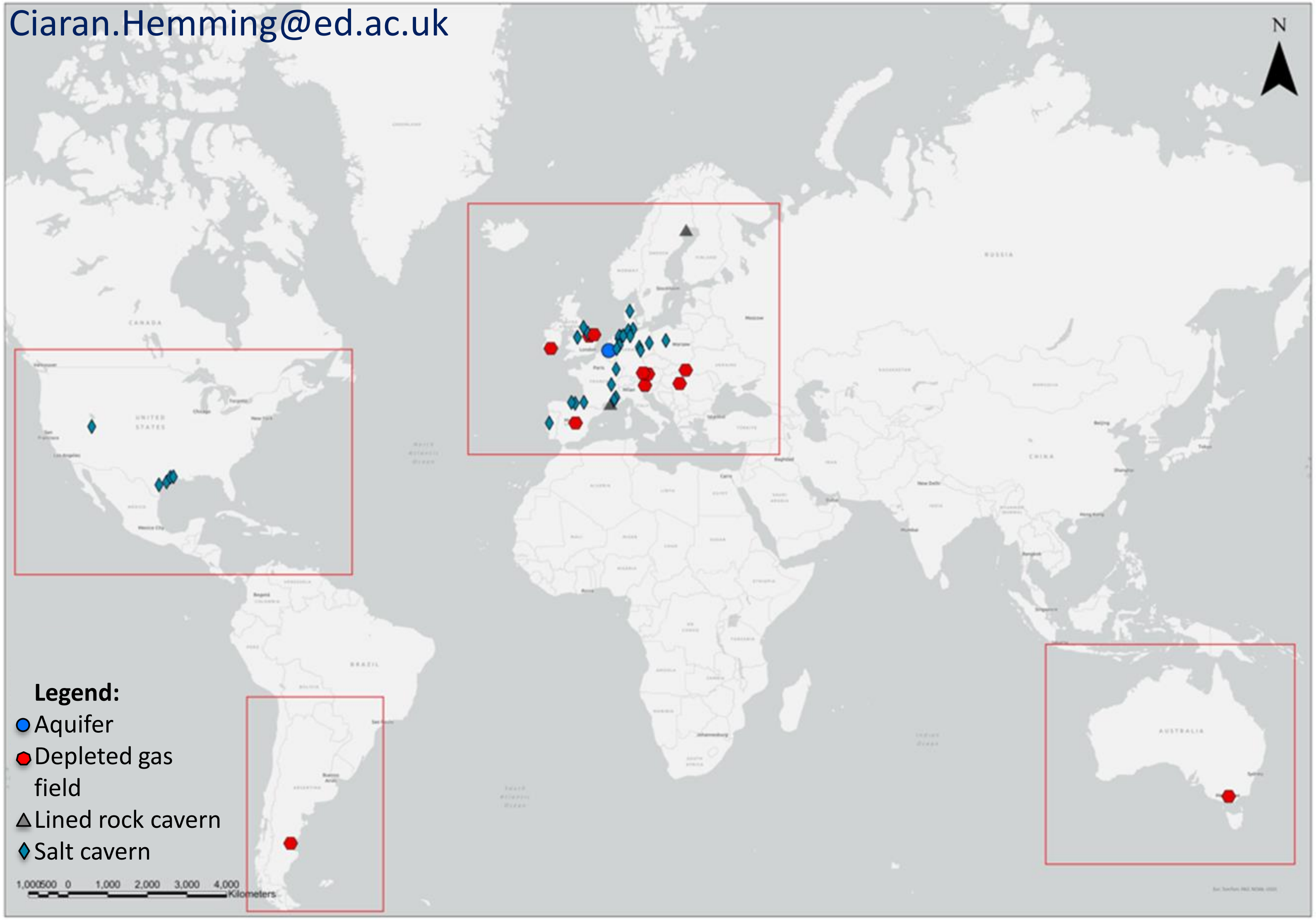

#	Name	Type	Country
1	HyChico	Depleted gas field	Argentina
3	Loenhout Hydrogen	Aquifer	Belgium
4	HyGreen Provence	Salt cavern	France
5	Green Hydrogen @Kinsale	Depleted gas field	Ireland
6	North Adriatic Hydrogen Valley	Depleted gas field	Italy
7	Undergy	Depleted gas field	Spain
8	Angus+	Depleted gas field	UK
9	U.S. Clemens Dome	Salt cavern	U.S.
10	Moss Bluff	Salt cavern	U.S.
11	Spindle Top	Salt cavern	U.S.
12	Advanced Clean Energy Storage	Salt cavern	U.S.
13	Entergy Salt cavern	Salt cavern	U.S.
14	CSIRO's Hydrogen Storage Demonstration Facility	Depleted gas field	Australia
15	Teesside	Salt cavern	UK
16	Aldbrough Hydrogen Pathfinder and Storage	Salt cavern	UK
17	HyNet NW Keuper Gas Storage	Salt cavern	UK
18	HySecure	Salt cavern	UK
19	Rough Gas Storage Facility	Depleted gas field	UK
21	Cerville (Emil'Hy)	Salt cavern	France
22	Kiel	Salt cavern	Germany
23	HyPSTER	Salt cavern	France
25	GeoH2	Salt cavern	France
26	HyGeo and HySow	Salt cavern	France
27	H2 Storage North 2	Salt cavern	Spain
28	H2 Storage North 1	Salt cavern	Spain
29	Carriço	Salt cavern	Portugal
30	Green Hydrogen Hub Denmark	Salt cavern	Denmark
31	HyStock	Salt cavern	Netherlands
32	Westküste 100	Salt cavern	Germany
33	SaltHy	Salt cavern	Germany
34	Astora H2 Jemgum	Salt cavern	Germany
35	Salt cavern Krummhörn	Salt cavern	Germany
36	H2CAST	Salt cavern	Germany
37	Get H2 Nukleus Gronau - Epe	Salt cavern	Germany
38	H2 Storage Xanten	Salt cavern	Germany
39	HyCAVmobil	Salt cavern	Germany
40	UGS Damasławek	Salt cavern	Poland
41	H2 Storage Staßfurt	Salt cavern	Germany
42	Bad Lauchstädt Energy Park	Salt cavern	Germany
43	Underground Sun Storage	Depleted gas field	Germany
44	UGS Veľké Kapušany (H2I)	Depleted gas field	Slovakia
45	HyStorage	Depleted gas field	Germany
46	HyBRIT	Lined rock cavern	Sweden
47	Aquamarine	Depleted gas field	Hungary
48	GEOGAZ H2	Lined rock cavern	France

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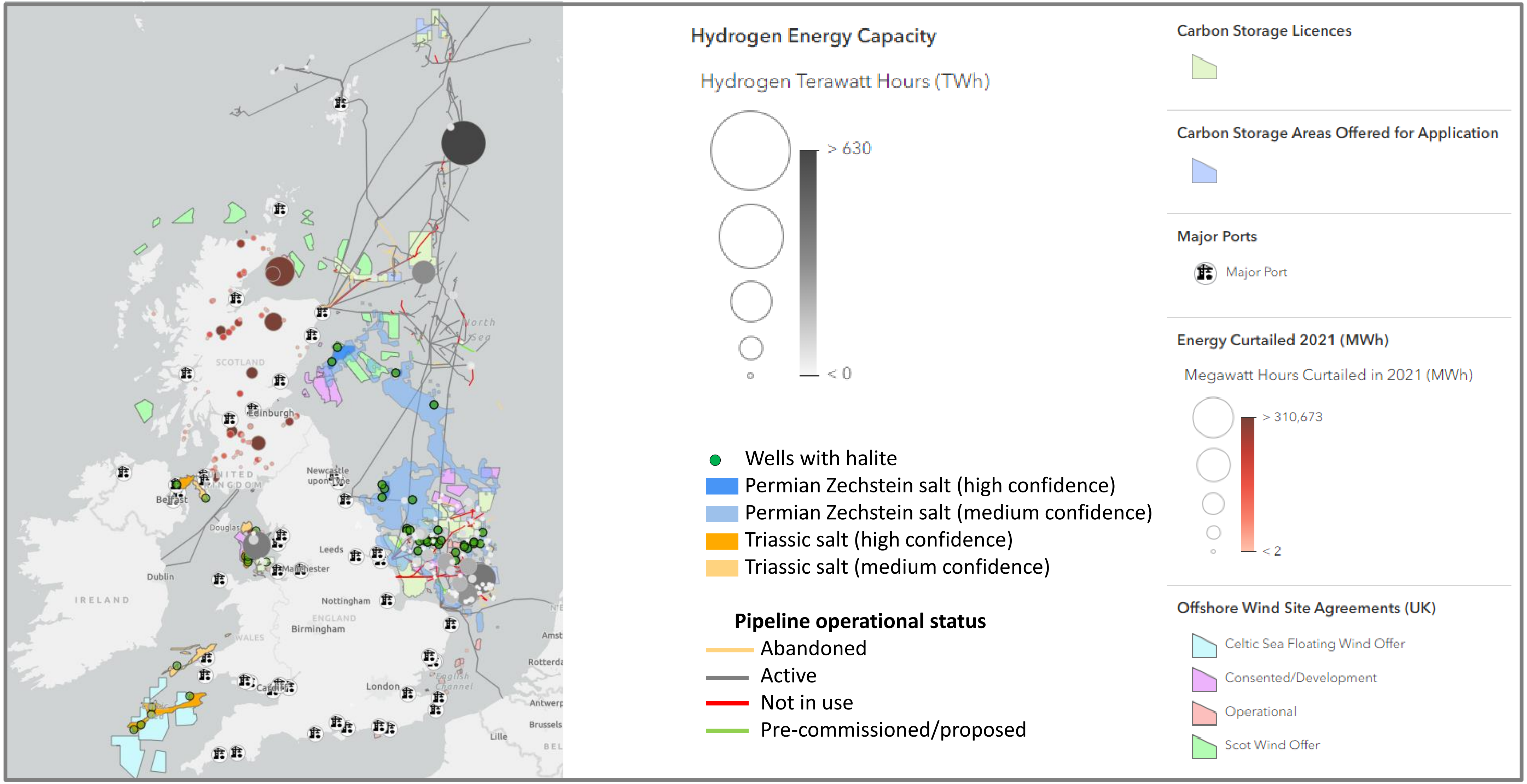
Storage: Energy System Integration



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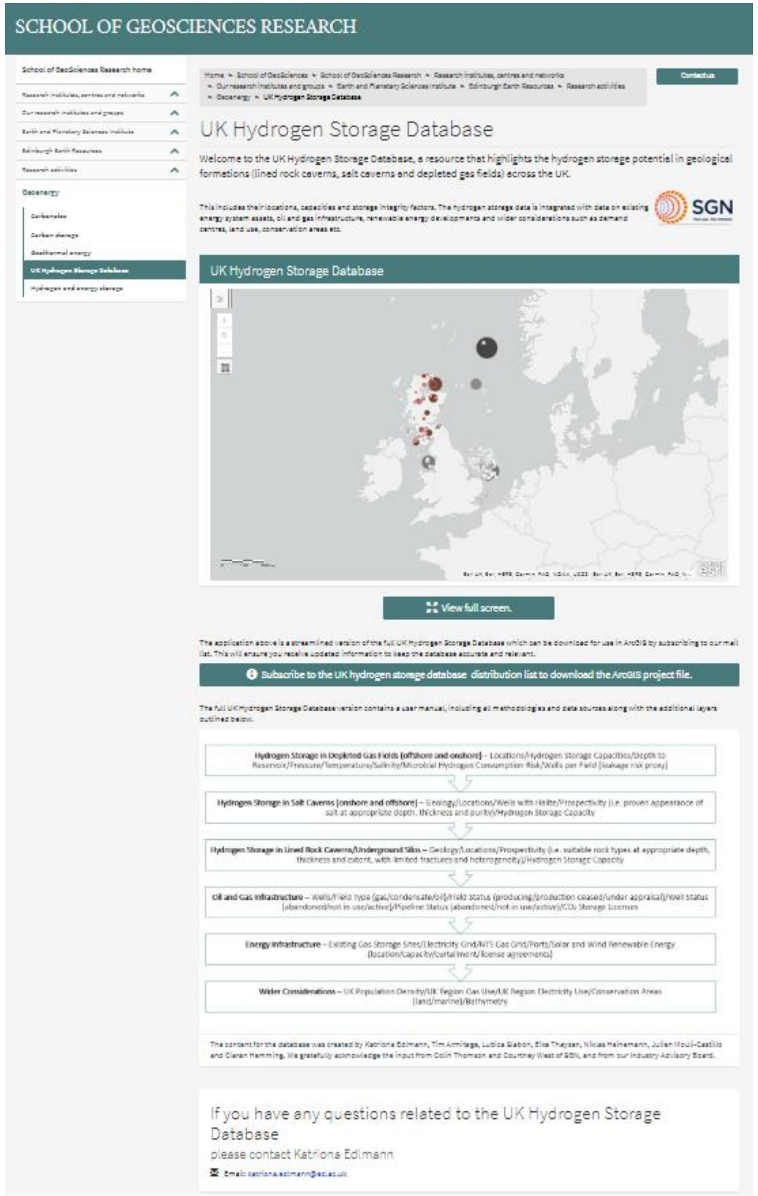
Hydrogen storage database

- GIS based map of geological storage locations and capacities integrated into the existing energy infrastructure
- Landing page@ www.edin.ac/uk-hydrogen-storage-database
- The database comprises:
  - Streamlined public facing online version
  - Full database shapefiles available for download on the website



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Funding acknowledgements:

- Ofgem Strategic Innovation Funding: **EMStor** and **B-Linepack+** projects
- IDRIC FF 4-6 **Assessing Regional Demand for Geological H2 Storage: Building a Strategic Case for Investment in the East Coast Cluster**.
- EPSRC HyStorPor "Hydrogen Storage in Porous Rocks. Grant Agreement EP/S027815/1.
- EU H2020 and Clean Hydrogen Partnership HyUsPRe "Hydrogen storage in underground reservoirs" project. Grant Agreement 101006632.
- EU Marie Curie Post Doctoral Network: SHINE "Safe underground Hydrogen storage IN porous subsurface rEservoirs" Grant Agreement 101073271 and UKRI EPSRC Grant EP/X026957/1
- Scottish Government Emerging Energy Technology Fund "StorageUpscale" project
- Net Zero Technology Centre and CGG "Geological controls on efficient hydrogen storage operations: Investigating depleted gas field reservoirs for future low carbon energy storage" project.
- NERC "Hydrogen Emissions: Constraining The Earth System Response" project. NERC Grant Agreement NE/X010236/1
- Net Zero Technology Centre and SGN funded "Hydrogen Storage in Porous Rock, Demonstrator Feasibility Study, Balgonie Fife".
- SGN funded "Balgonie hydrogen storage" project
- SGN funded "Hydrogen Storage Database" project

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