Geological storage of hydrogen for Net Zero

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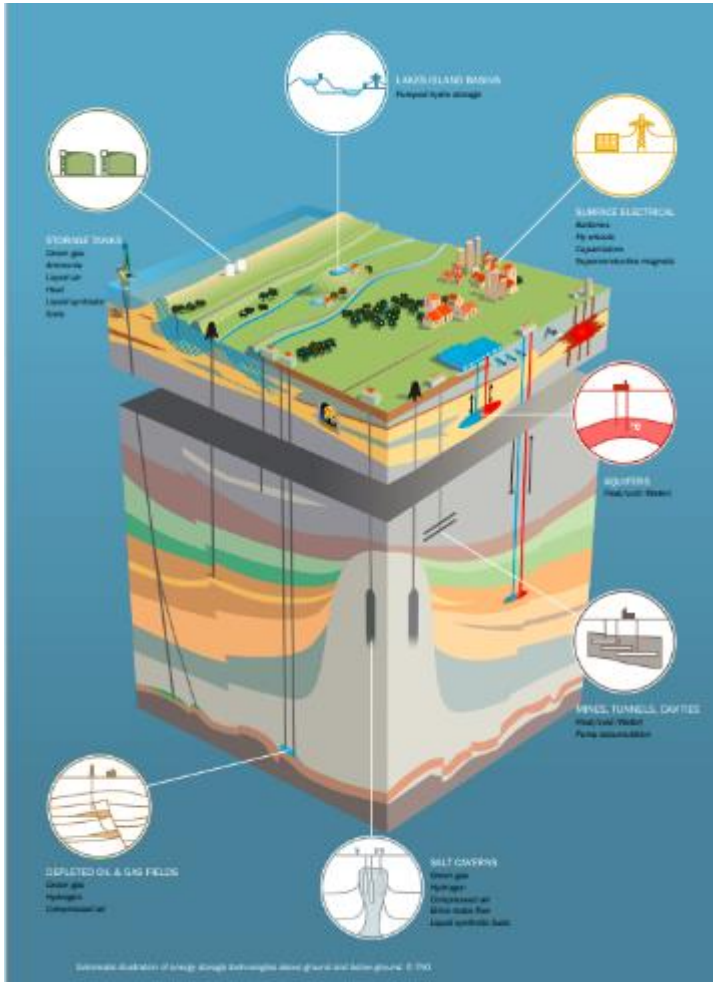

With input from the entire subsurface hydrogen team at Edinburgh Geosciences including Niklas Heinemann, Eike Thaysen, Saeid Abadi, Ciaran Hemming, Andrew Kilpatrick, Tim Armitage, Andrew Cavanagh, John Low, Lubica Slabon, Mark Wilkinson, Ian Butler, Stuart Haszeldine, David Stevenson, Ali Hassanpouryouzband, Hannah Bryant, Solmaz Abedi, Ismail Saricam, Behjat Kari, Marianna Skupinska …

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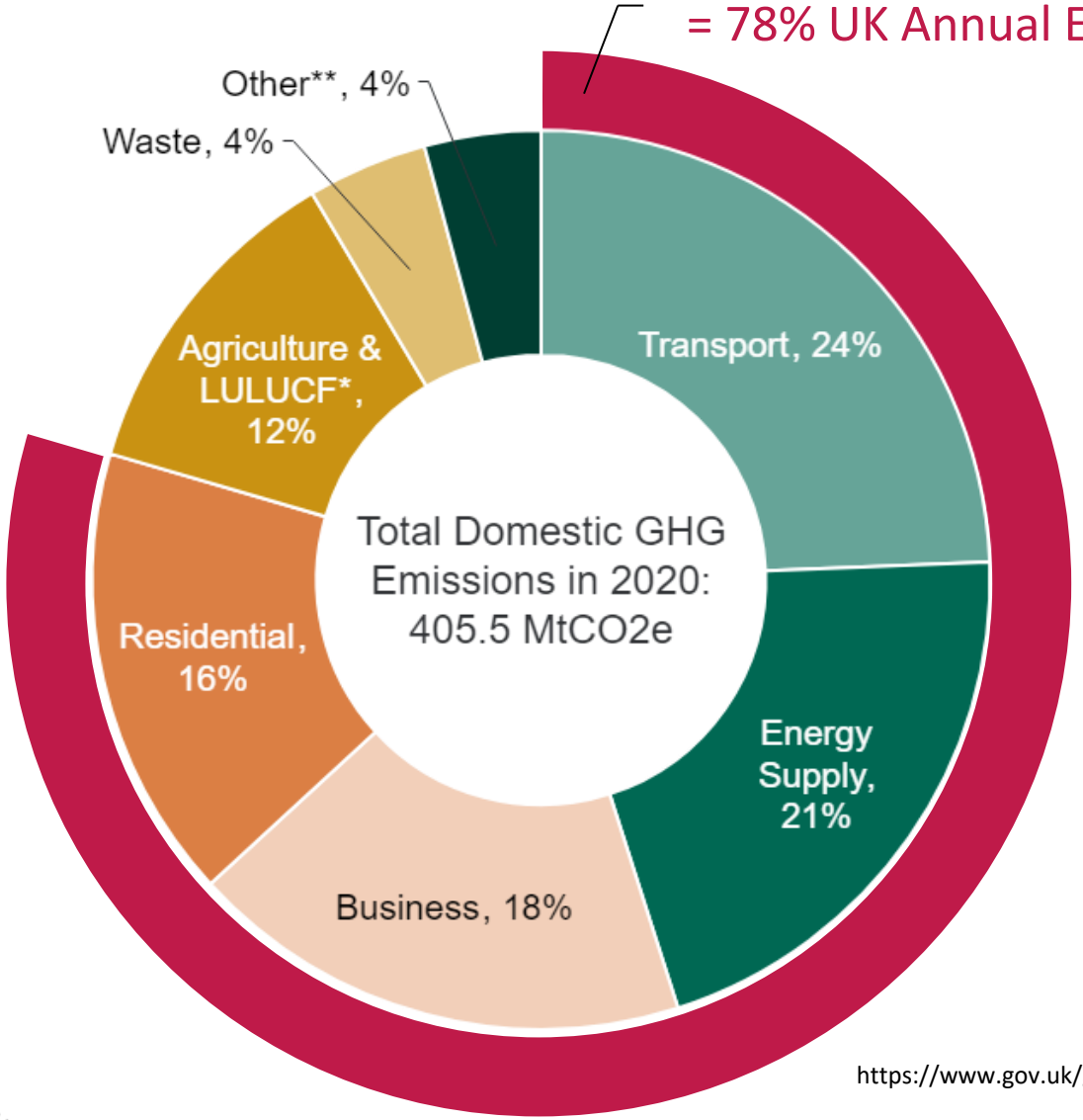
Net Zero Challenge: Decarbonising Energy

Energy from fossil fuels (2020)
= 78% UK Annual Emissions

Energy transition to achieve Net Zero:
2023: 80% fossil fuels/20% renewable electricity energy mix
2050: ~70% renewable electricity/~30% hydrogen energy mix



- ✓ Reduction of emissions from electricity.
  - ✓ Energy efficiencies.
  - ✓ Heat pumps.
  - ✓ Switching from coal to gas power generation.
  - ✓ Increased variable renewables.
- ✗ Limited progress reducing emissions in the harder to electrify/decarbonise sectors (80% still from fossil fuels).

https://www.gov.uk/government/statistics/transport-and-environment-statistics-2022/transport-and-environment-statistics-2022

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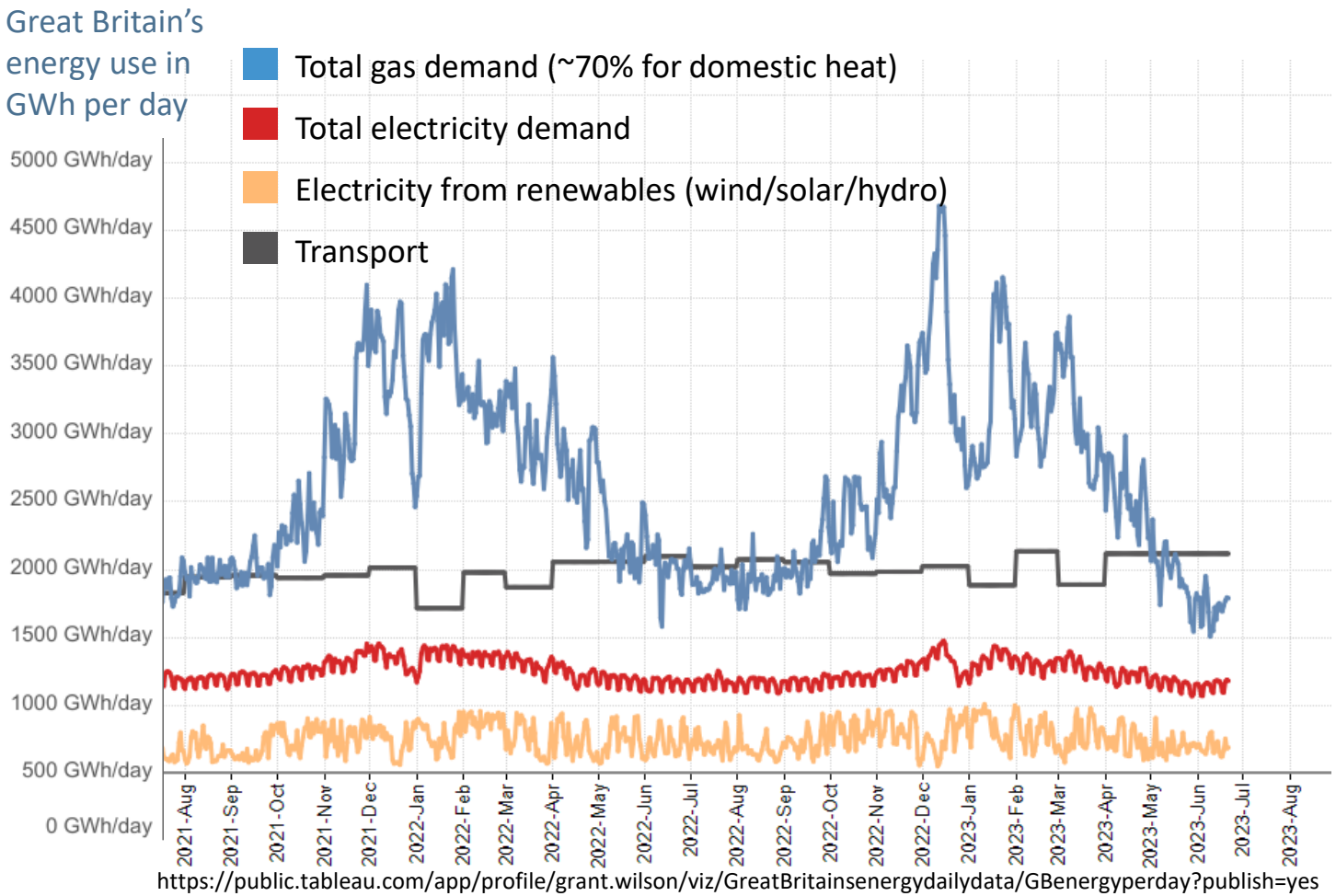
Decarbonising energy: Scales and patterns in GB energy use



https://public.tableau.com/app/profile/grant.wilson/viz/GreatBritainsenergydailydata/GBenergyperday?publish=yes

- ✓ Reduce overall energy demand.
- ✓ Energy demand increases by ~2000 GWh/day from summer to winter (delivered by gas) = hydrogen energy storage.
- ✓ Increase variable renewable electricity to meet existing electricity demand = hydrogen energy storage.
- ✓ Transport has a daily demand of ~1500 GWh almost entirely delivered from fossil fuels.

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Hydrogen for decarbonisation

Support the renewable energy system

Enable large scale renewable integration and power generation

- Distribute energy across sectors and regions

Provide grid scale energy storage

- Provide inter-seasonal renewable energy balancing
- Reduce curtailed energy wastage
- Act as a buffer to increase system resilience
- Provide security of supply and energy security

Plus, hydrogen supports improved air quality.

Support end users and "hard to abate" sectors

- Support decarbonisation of transport (haulage, shipping, aviation)
- Serve as a renewable feedstock for industry
- Increase decarbonisation of building heat
- Help decarbonise industrial energy use
- Decarbonise power generation
- Support the development of carbon capture and storage (CCS)

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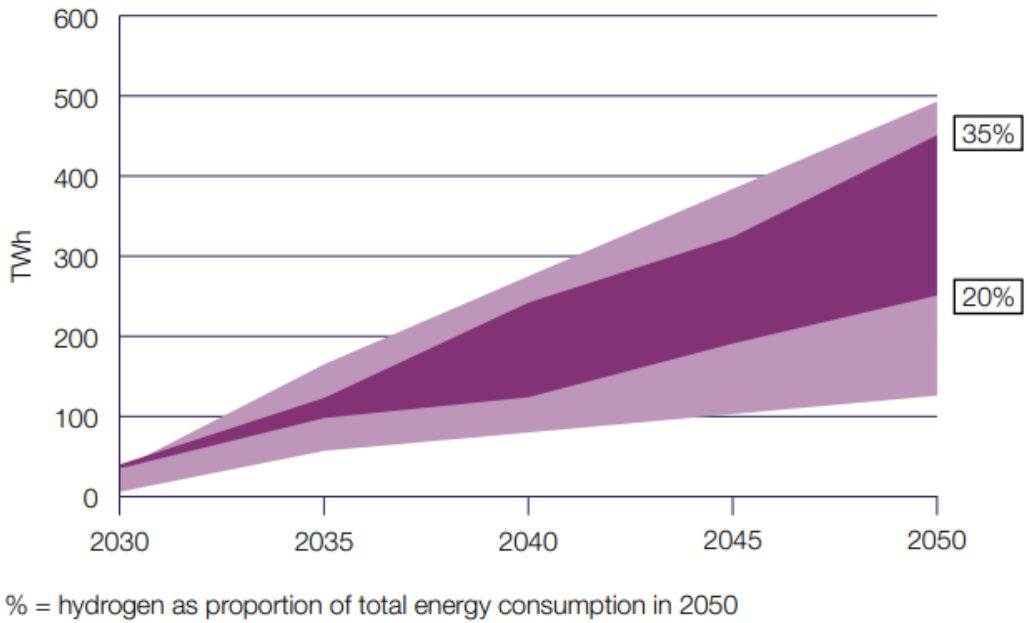
- Most UK and EU Net Zero scenarios that reach net zero by 2050, include a contribution from hydrogen.
- Scenario modelling for the UK Net-Zero strategy suggests that even in the High Electrification Scenario, 240 TWh/y of hydrogen would be required by 2050, rising to 500 TWh/y of hydrogen for the High Resource Scenario which includes hydrogen for heat.
- The National Grid Future Energy Scenarios suggest that even in the Consumer Transformation Scenario (high electrification), 113 TWh/y hydrogen would be required by 2050, rising to 591 TWh/y of hydrogen for the System Transformation Scenario which includes hydrogen for heat.

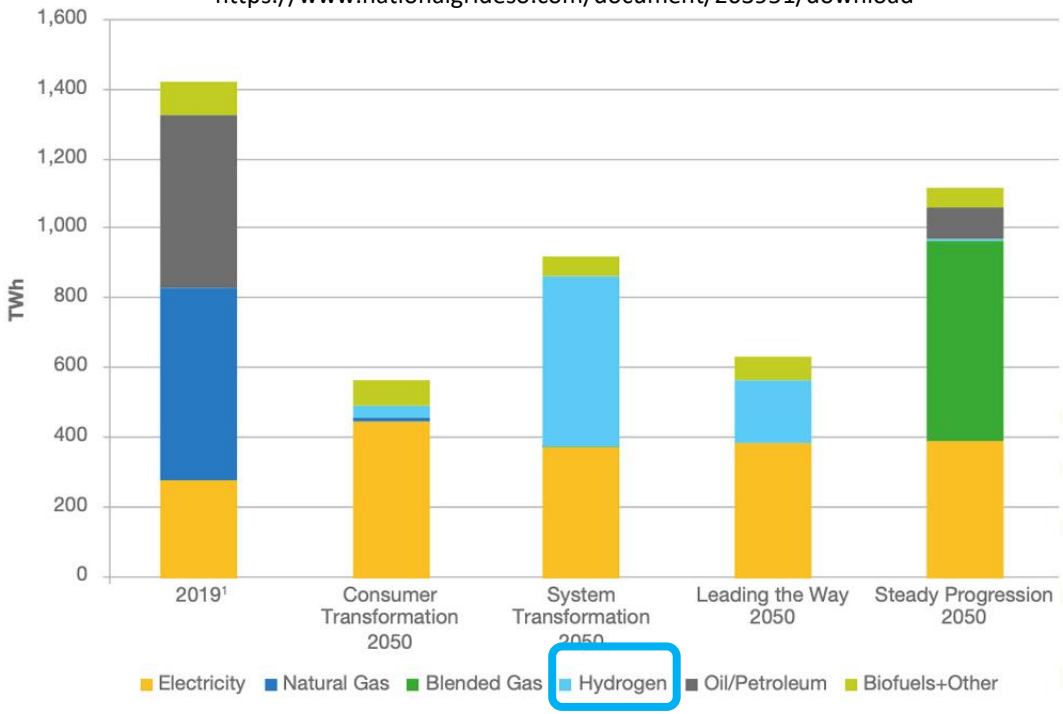
UK Net Zero scenarios (CCC and BEIS)



% = hydrogen as proportion of total energy consumption in 2050

National Grid Future Energy Scenarios

https://www.nationalgrideso.com/document/263951/download



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CCC Hydrogen in low carbon economy
(2018)

2020

Ten Point Plan
(Nov 2020)

Energy White Paper, UK
(Dec 2020)

CCC 6th Carbon Budget
(Dec 2020)

Scottish Hydrogen Assessment Report
(Dec 2020)

2021

Hydrogen Wales Consultation
(Jan 2021)

North Sea Transition Deal
(March 2021)

Net Zero Strategy UK
(Oct 2021)

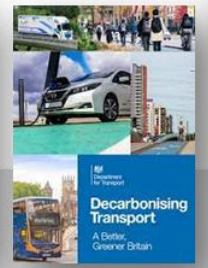
2022

Heat in buildings Strategy UK
(Oct 2021)

Heat in buildings Strategy Scotland
(Oct 2021)

Consultations: UK low carbon standards, Net Zero hydrogen fund, hydrogen business model

UK Hydrogen Strategy
(Aug 2021)



Decarbonising Transport
(July 2021)

Industrial Decarbonisation Strategy
(July 2021)

British Energy Security Strategy
(April 2022)

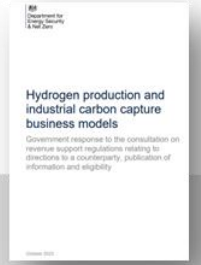
Hydrogen Sector Development Plan
(Dec 2022)

Hydrogen Action Plan Scotland
(Dec 2022)

2023

Powering Up Britain
(March 2023)

Hydrogen Transport and Storage Business Model minded to positions
(August 2023)



Hydrogen Production and carbon capture business model
(October 2023)

UK Low Carbon Standards
(Dec 2023)

HSBM/HTBM market engagement
(Dec 2023)

2024

Hydrogen Net Zero Investment Roadmap
(Feb 2024)

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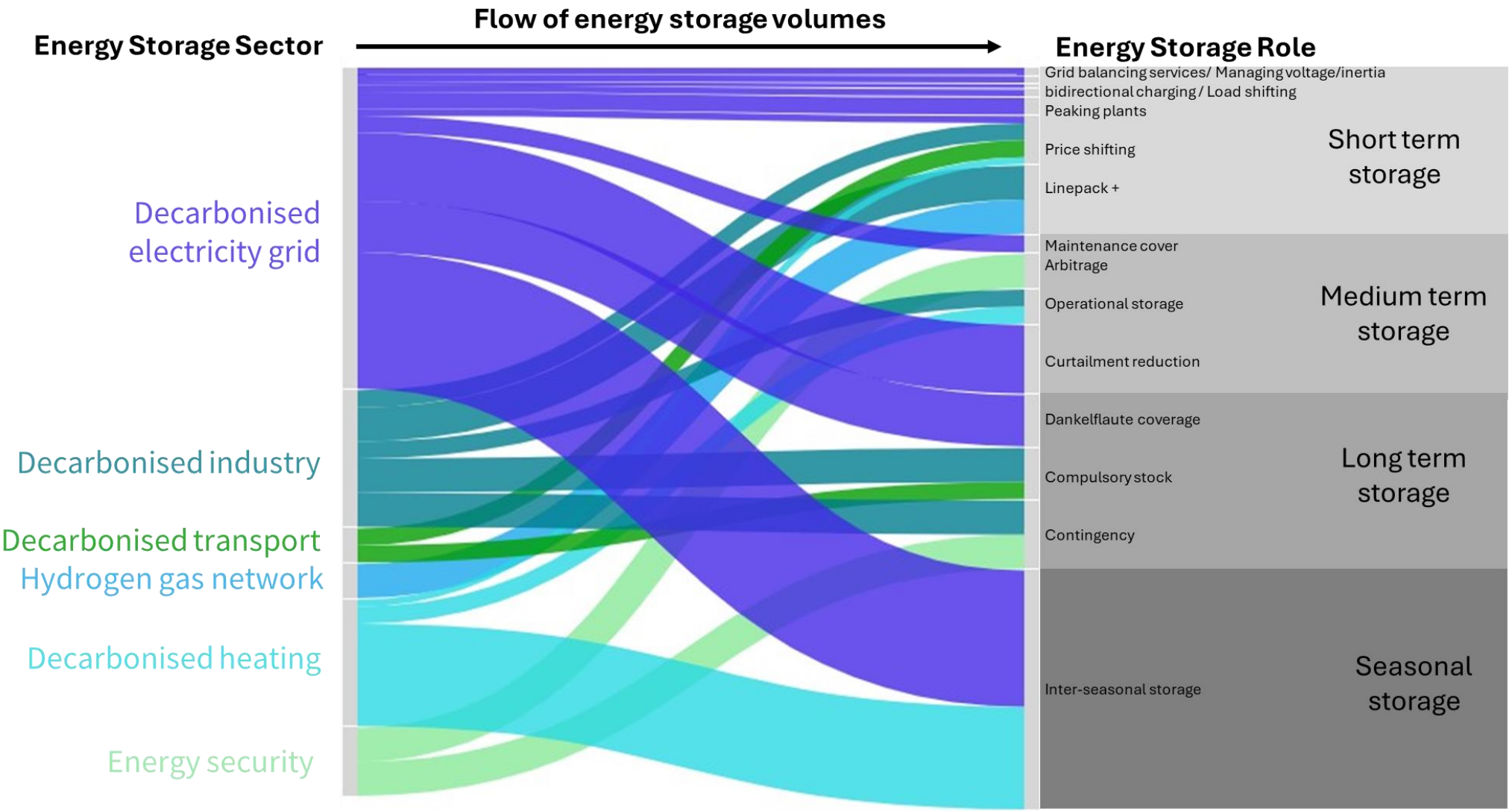
Energy storage



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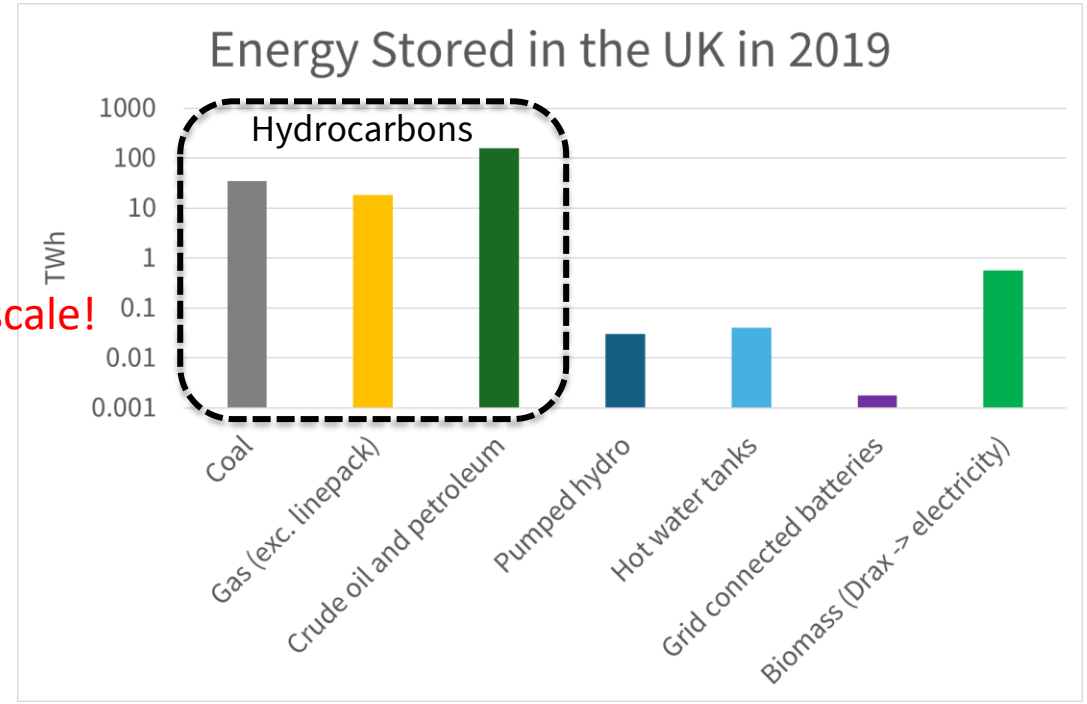
Anticipated scales of energy storage



Log scale!

Data from https://royalsociety.org/-/media/policy/projects/large-scale-electricity-storage/large-scale-electricity-storage-report.pdf

There are a wide range of UK decarbonised energy storage estimates for 2050:

- 11.2-17.4 TWh
  - Benefits of Long Duration Energy Storage report for BEIS (2022)
- 19-56 TWh
  - FES 2023: National Grid Future Energy Scenario.
- 100 TWh
  - Royal Society, Large Scale Electricity Storage (2024)

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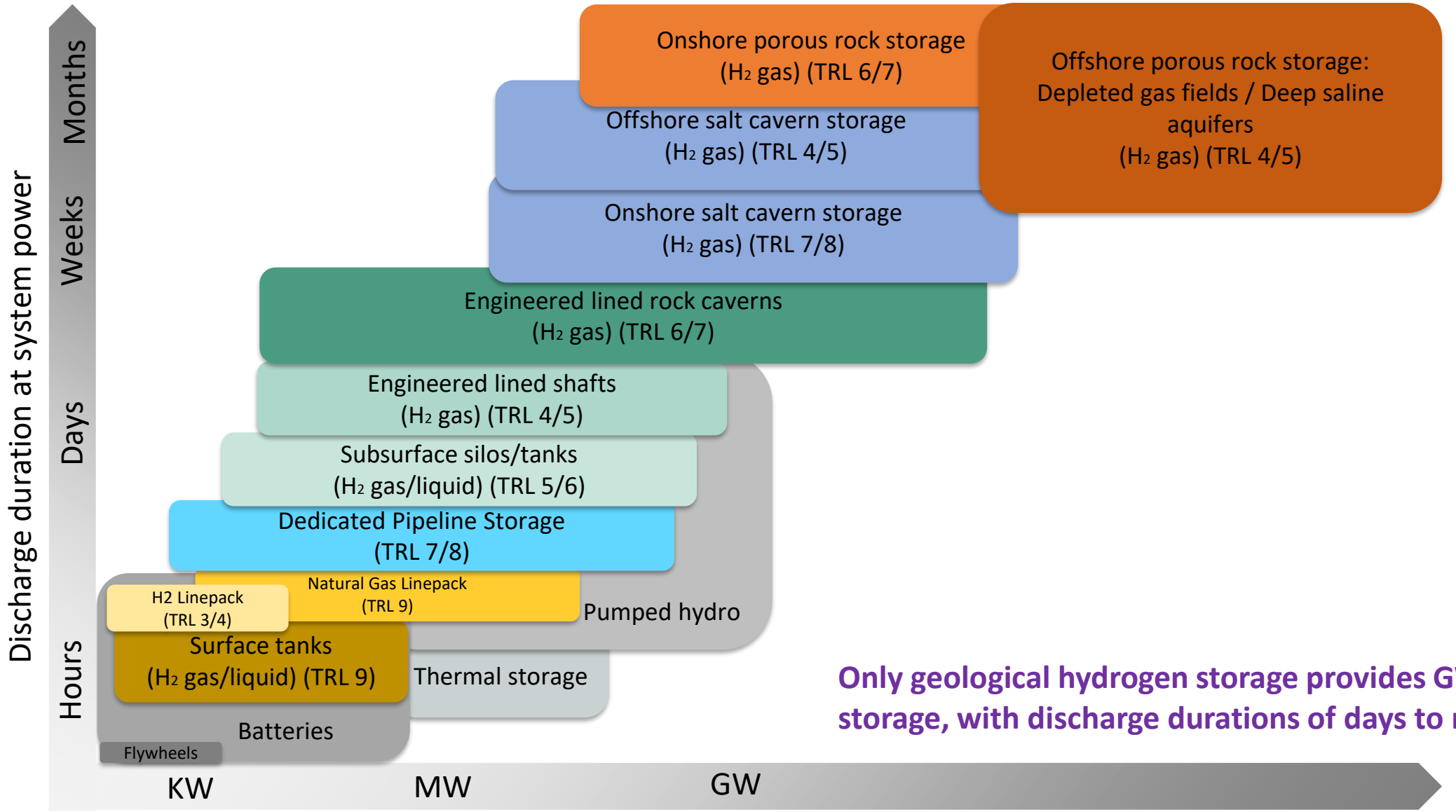
Energy storage options



Only geological hydrogen storage provides GW-TW scale storage, with discharge durations of days to months….

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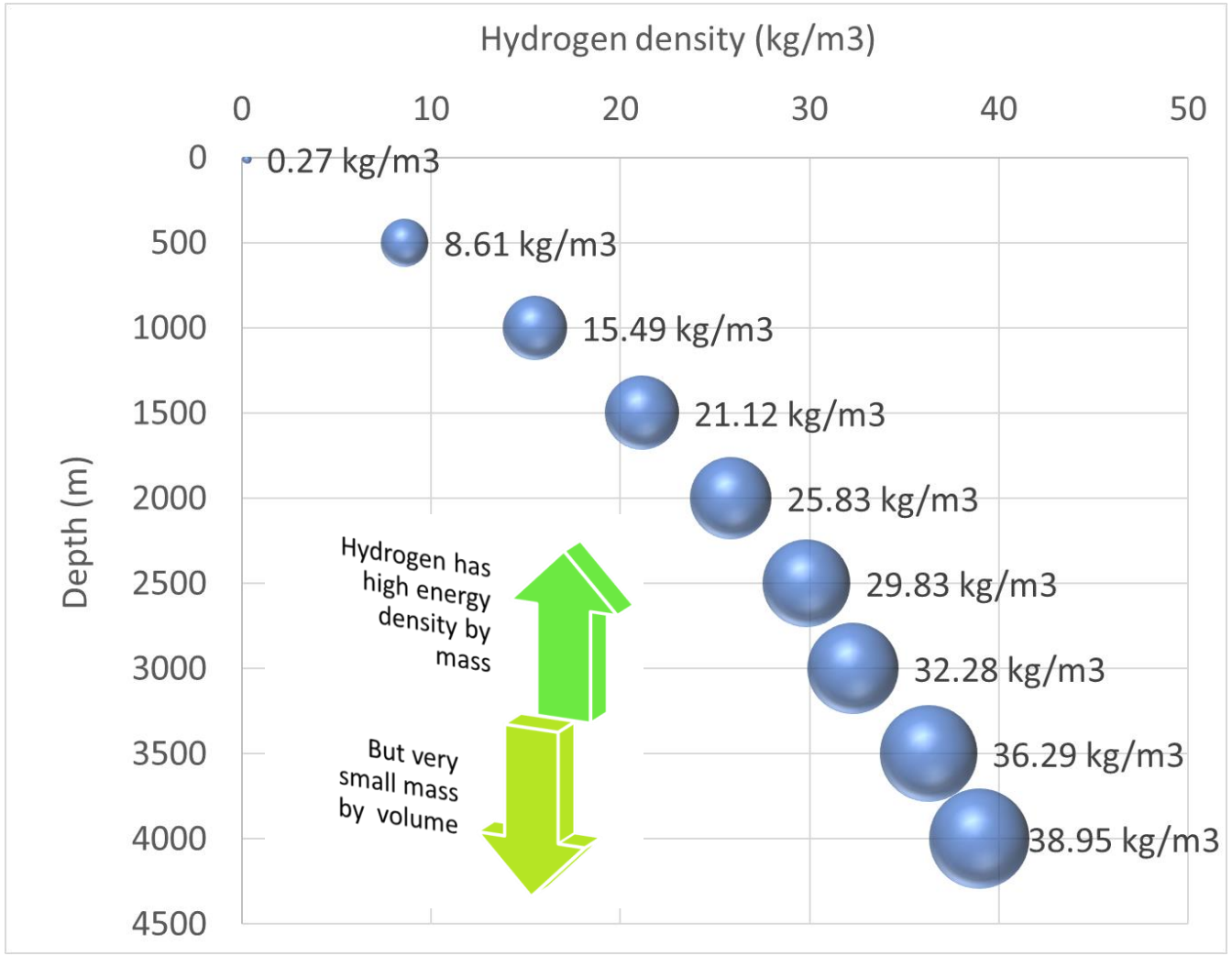
Why geological storage?

- 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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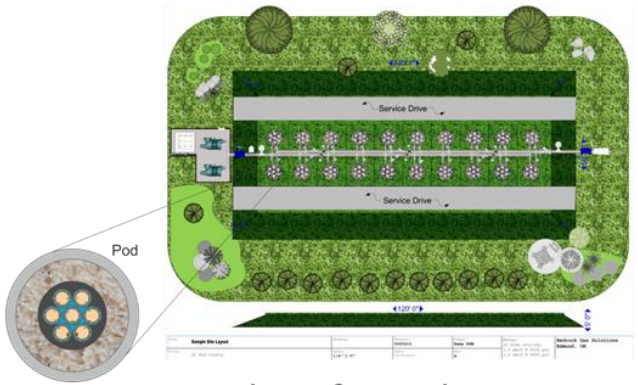
Geological hydrogen storage technologies…

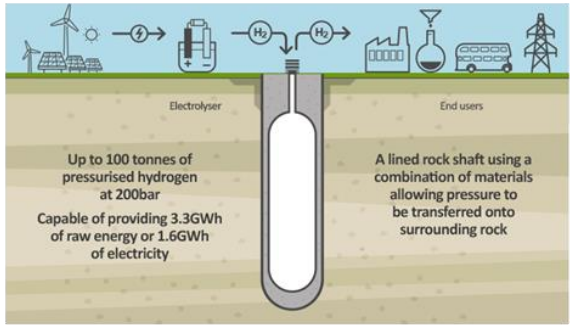
Dedicated pipeline storage/tanks

Delivers kW to MW over hours



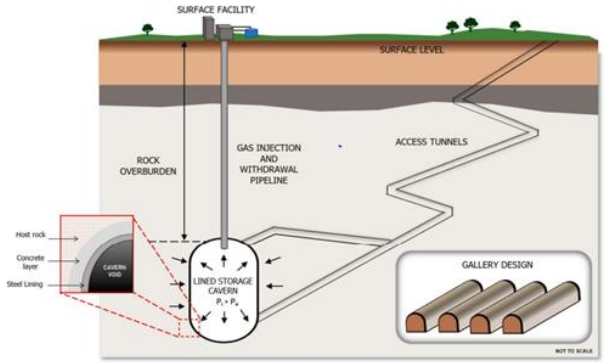
Subsurface silos

Delivers MW to GW



Lined shafts

Delivers MW to GW over weeks

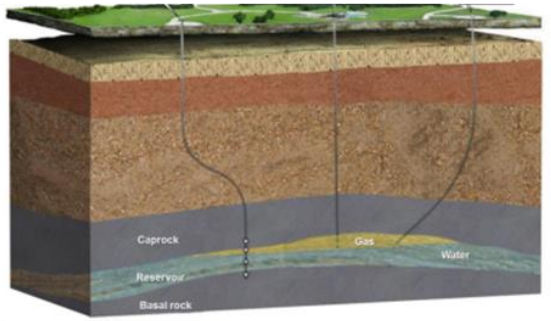


Lined rock caverns

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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Global hydrogen storage projects underway

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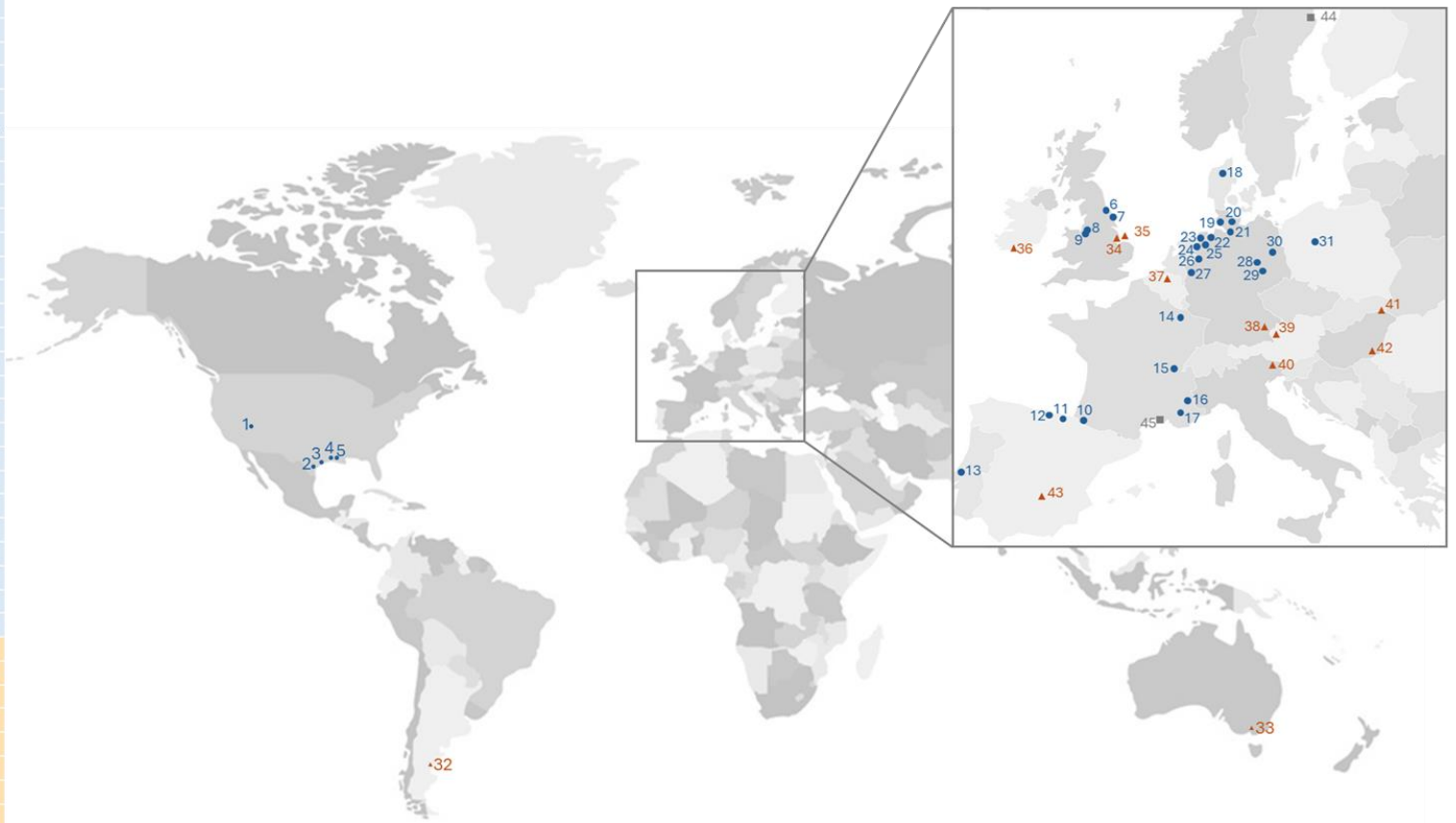
1	Advanced Clean Energy Storage (ACES)
2	Entergy Salt Cavern
3	US Clemens Dome
4	Moss Bluff
5	Spindle Top
6	Teesside
7	Aldborough
8	HyNet NW Keuper
9	HySecure
10	HyGeo and HySow
11	H_2 Storage North 1
12	H_2 Storage North 2
13	Carrico
14	Cerville (Emil'Hy)
15	HyPSTER
16	HyGreen Province
17	$GeoH_2$
18	Green Hydrogen Hub Denmark
19	WestKuste 100
20	Kiel
21	SaltHy
22	H2CAST
23	Krummhorn
24	HyStock
25	Astora H2 Jemgum
26	Get H2 Nukleus
27	H2 Storage Xanten
28	H2 Storage Stasfurt
29	Bad Lauchstadt
30	HyCAVmobil
31	UGS Damastawek
32	HyChico
33	CISRO Hydrogen Storage Demonstrator
34	Angus+
35	Rough
36	Green Hydrogen @Kinsale
37	Loenhout Hydrogen
38	HyStorage
39	Underground Sun Storage
40	North Adriatic Hydrogen Valley
41	UGS Velke Kapusany
42	Aquamarine
43	Undergy
44	HyBrit
45	GEO Gaz H2



Salt caverns

Depleted gas fields

Lined rock caverns

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Thank you

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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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