RESEARCH AND GUIDANCE FROM HSE

Knowledge gaps in the risk assessment of hydrogen and carbon dioxide pipelines

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Health and Safety Executive (HSE)

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Research - HSE funded to provide evidence which underpins its policy and regulatory activities
Guidance - freely available to help people comply with health and safety law

Overview

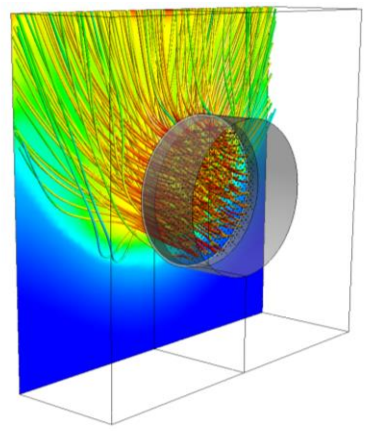
- Quick introduction to HSE
- Current and future UK support for Net Zero technologies
- Hydrogen
  - Properties, experience, knowledge gaps and future work
- CO_2
  - Properties, experience, knowledge gaps and future work
- Conclusions

Introduction to HSE

- HSE is the UK regulator for workplace health and safety
  - Includes onshore/offshore pipelines, chemical/oil/gas infrastructure, offshore platforms etc.
  - Activities: evidence gathering, policy development, consultation, regulation, incident investigation, enforcement
  - HSE acts as an enabling regulator, supporting the introduction of new technologies
  - 2,400 total staff
  - £230M (€260M) budget: 60% from Government, 40% from external income



- HSE Science and Research Centre, Buxton, UK
  - 400 staff, 550 acre test site
  - Scientific support to HSE and other Government departments
  - “Shared research” or joint-industry projects co-funded by HSE
  - Bespoke consultancy on a commercial basis

UK Government and Net Zero

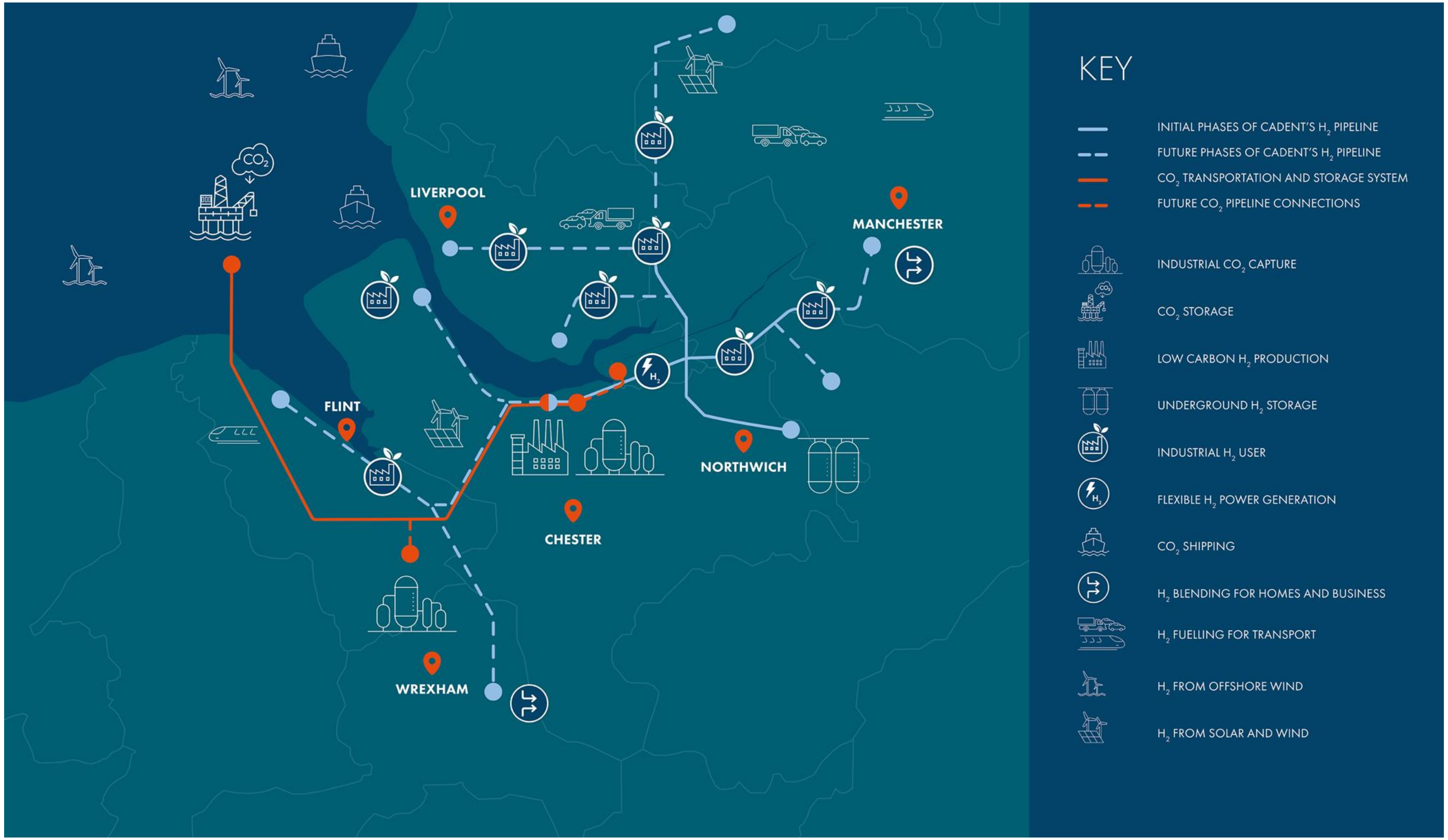
UK Government support for Net Zero

Map data: © 2022 Google

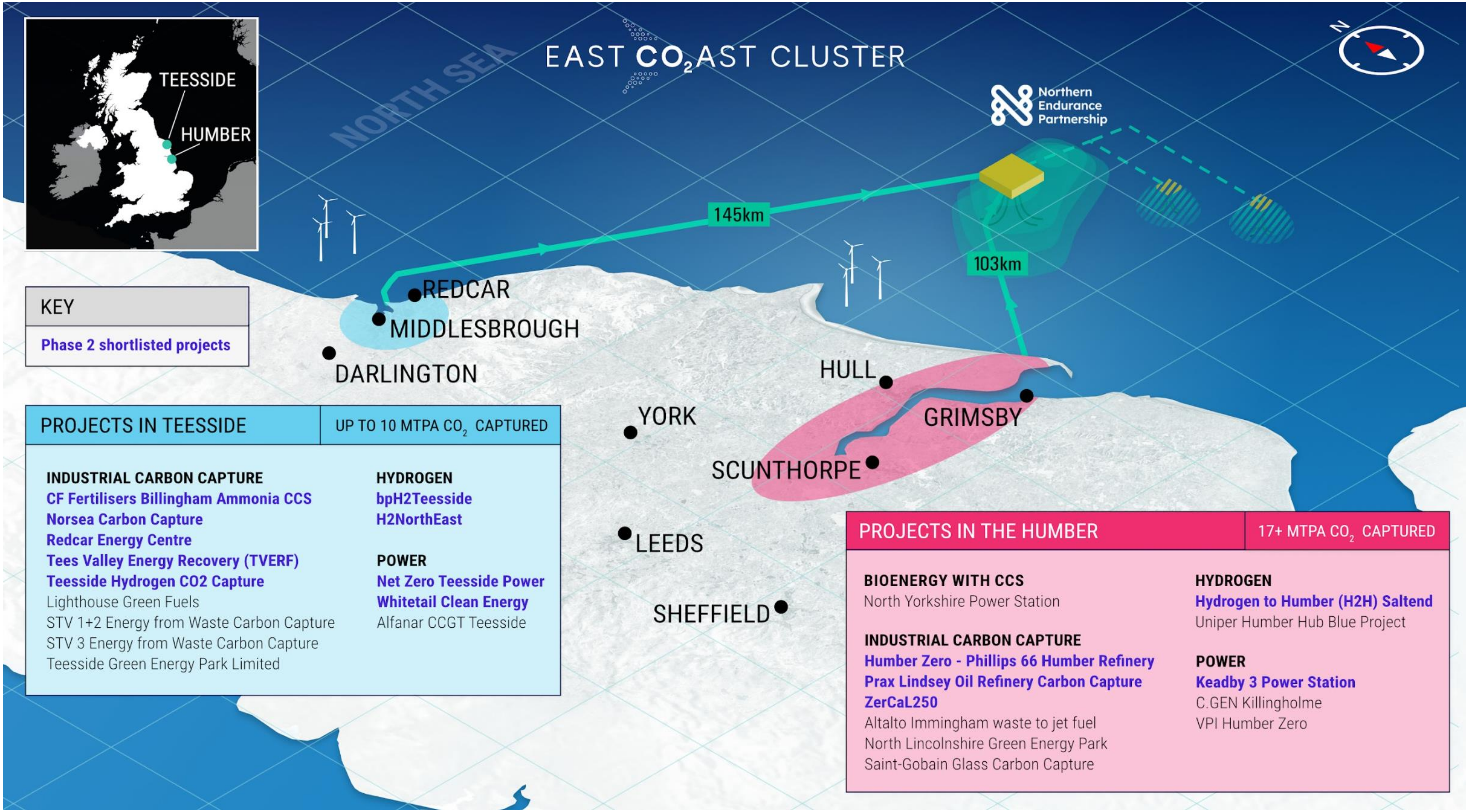
- Net Zero 2050
  - UK Government announced Ten Point plan[1] in November 2020
- Growth of low-carbon hydrogen and CCUS based around
  1. Regional hydrogen and CCUS industrial clusters
  2. Hydrogen for heating:
     - Government policy decision on hydrogen heating in 2026
     - 2023/4: Neighbourhood trial (300 properties, new PE distribution network, https://www.h100fife.co.uk/)
     - 2025/6: Village trial (1,000 – 2,000 properties, repurposed gas distribution network)
     - By 2030: Town pilot (start of roll-out)
  - Targets of 5 GW of low carbon hydrogen production and 10 Mt carbon capture by 2030
- Other Net Zero ambitions
  - Offshore wind, nuclear, zero-emission vehicles/planes/ships, greener buildings, protecting environment, green finance and innovation

[1] https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

HyNet North West



https://hynet.co.uk



https://eastcoastcluster.co.uk

Hydrogen

Properties of hydrogen and CO_2

	Methane, CH_4	Hydrogen, H_2	Carbon Dioxide, CO_2
Molecular Mass (g/mol)	16.043	2.016	44
Density (kg/m^3)	0.68	0.08	1.9
Density relative to air	0.55	0.07	1.5
Burning velocity (m/s)	0.37	3.2	N/A
Lower flammable limit (% v/v)	4.4	4.0	N/A
Upper flammable limit (% v/v)	17	77	N/A
Lower detonation limit (% v/v)	6.3	18	N/A
Upper detonation limit (% v/v)	13.5	59	N/A
Minimum ignition energy (mJ)	0.26	0.01	N/A

Hydrogen properties

- Molecular hydrogen can dissociate into atomic hydrogen on metal surfaces
  - Can enter the lattice structure leading to hydrogen embrittlement
  - Lead to reduction in mechanical properties e.g. ductility, toughness, fatigue resistance
  - Limits what steels can be repurposed
- Ignites more readily over a wider range of concentrations
  - Plus ignition is more likely to progress to detonation

Implications of hydrogen properties

- Potentially higher failure rates
- Higher ignition probabilities
- Possibility of explosions
  - Not currently considered for natural gas in Great Britain
- Possibly higher risk overall for some pipelines

Hydrogen experience and experiments

- Lack of operational experience
  - ~2,200 km of H_2 pipelines in the USA
  - ~1,600 km in Europe
  - Compares to ~22,000 km natural gas pipelines operating for over 40 years in Great Britain alone

- Limited large-scale experimental data
  - Two large-scale 60 bar H_2 pipeline experiments (Acton *et al*., 2010)
  - NaturalHy 20% blend, 70 bar (Lowesmith and Hankinson, 2013)

Hydrogen knowledge gaps

- Failure rates
  - Research conducted to investigate effect of hydrogen on steel but:
  - Still some uncertainty over material response to long-term exposure at typical pipeline pressures
  - Findings so far suggest:
    - Steel strength not significantly affected but effect on elongation to failure is significant
    - Fracture toughness reduced for most steel grades
    - Some studies indicate that theoretical net fatigue life in the presence of hydrogen is 10-100 times less than in natural gas. Greatest effect on crack growth rate
    - Effect of H_2 on resistance of steel to fast running fractures has not been evaluated
  - Ultimately leads to uncertainty in failure rates

Hydrogen knowledge gaps

- Fire and explosion
  - Vapour Cloud Explosions (VCEs) not currently considered in Great Britain for natural gas pipelines, since the risk is dominated by fires
  - Higher flame speed for hydrogen implies greater detonation potential
  - VCEs observed in 60 bar hydrogen jet release experiments with delayed ignition (Jallais *et al*., 2018)
  - Implication is that explosions may need to be modelled
  - Is delayed ignition a credible event for transmission pipeline releases?
  - What overpressures are generated in VCEs from pipeline releases?
  - Is the overall VCE risk significant when compared to effects from fires?

Hydrogen knowledge gaps

- Ignition probabilities
  - Lower MIE and wider flammable range mean that hydrogen is easier to ignite than natural gas
  - HSE previously reviewed ignition probabilities, but not specifically for hydrogen
  - No specific probabilities for hydrogen identified previously
    - Currently reviewing previous work to see if any suitable ignition probabilities have been identified in the interim
  - Always an area of uncertainty

Ongoing UK Hydrogen Studies

- Failure rates
  - HyDeploy – fracture toughness and fatigue testing
  - FutureGrid – testing in full-scale repurposed assets
- Fire and explosion
  - FutureGrid – testing of explosion potential
- Ignition probabilities
  - HSE reviewing available information
  - Indications from recent and proposed experiments?

CO_2

Properties of hydrogen and CO_2

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Molecular Mass (g/mol)	16.043	2.016	44
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CO_2 properties and issues

- Toxic rather than flammable
- Denser than air
  - CO_2 likely to slump to the ground and disperse close to the ground, collecting in low-lying areas, valleys etc.
- Impurities in the CO_2 can significantly affect steel corrosion rates
- Potential for long-running fractures in dense-phase CO_2 pipelines

Implications of CO_2 properties

- Terrain becomes important for dispersion
  - Risks can extend a significant distance from the pipeline
- Materials effects could increase failure rates
  - Corrosion rates
  - Third-party activity rates if corrosion has affected wall thickness
- Long-running fractures could lead to changes in hole size distributions
  - More likely to get larger holes/ruptures?

Demonstration of importance of terrain: Satartia

- Failure of Denbury Gulf Coast Pipelines 24-inch CO_2 pipeline near Satartia, Mississippi due to landslide
- Dense CO_2 cloud rolled downhill and engulfed Satartia village, a mile away
- Approximately 200 people evacuated and 45 required hospital treatment
- Communication issues: local emergency responders were not informed by pipeline operator of the rupture and release of CO_2
- Denbury's risk assessment did not identify that a release could affect the nearby village of Satartia

Figure 6: Topographical Map Showing the Delhi Pipeline (Green) and Denbury's Buffer Zone (Red) on Either Side of the Pipeline and the Proximity to Satartia (Blue Star Indicates the Rupture Site)

Image sources: Yazoo County Emergency Management Agency/Rory Doyle for HuffPost and PHMSA

- https://www.huffingtonpost.co.uk/entry/gassing-satartia-mississippi-co2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f
- https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf

CO_2 experience and experiments

- Lack of operational experience
  - ~6,000 km of CO_2 pipelines globally
  - Majority in the USA and Canada for Enhanced Oil Recovery (EOR)
  - Impurities in EOR CO_2 streams may differ from CCS impurities, so possible that EOR experience is of limited use
- Limited experimental data at large scale
  - DNV 8” dense phase pipeline experiment at Spadeadam
  - International projects
    - CO2PipeHaz
    - MATTRAN
    - COOLTRANS
    - COSHER
    - CO2PIPETRANS

CO_2 knowledge gaps

- Failure rates
  - Corrosion highly dependent on presence of free water
    - If water present, other impurities (NOx, SOx) can increase likelihood of corrosion
    - What to do in case of process upset (e.g. CO_2 composition outside specification)?
  - Fracture propagation
    - Brittle fractures due to rapid cooling of CO_2 on decompression that changes fracture behaviour of steel from ductile to brittle
    - Long-running ductile fractures for supercritical CO_2 due to net decompression speed of the fluid < fracture propagation speed along the pipe

CO_2 knowledge gaps

- Fracture arrest
  - Difficult to determine requirements, particularly if impurities are present
  - More work done on dense-phase than gaseous; therefore less certainty in fracture arrest requirements for gaseous CO_2
  - Existing methods to predict crack arrest in natural gas pipelines (Battelle Two Curve Method) are not conservative for dense-phase CO_2
- Fracture tests
  - Uncertainty around suitability of Charpy impact test and Drop-Weight Tear Test (DWTT) to determine fracture resistance

CO_2 knowledge gaps

- Fracture arrest
  - Recent publications on running ductile fractures:
    - Skarsvåg *et al*. (2023) “Towards an engineering tool for the prediction of running ductile fractures in CO_2 pipelines” Process Safety and Environmental Protection 171 (2023) 667–679. https://doi.org/10.1016/j.psep.2023.01.054
    - Cosham *et al*. (2022) “The decompressed stress level in dense phase carbon dioxide full-scale fracture propagation tests”. Proceedings of the 14th International Pipeline Conference IPC2022, 26-30 Sept 2022, Calgary, Canada
  - Revision of guidance in DNV-RP-F104 and ISO 27913?

CO_2 knowledge gaps

- Dry-ice formation
  - Dry-ice possible for both gaseous and dense-phase releases
  - Reported to have blocked pipeline valves in their open position
  - Could dry-ice block parts of the pipeline and/or valves?

- Terrain effects
  - CO_2 cloud denser than air so affected by gravity
  - CO_2 cloud will tend to follow local terrain, accumulating in dips and hollows

CO_2 knowledge gaps

- Terrain effects (continued)
  - Satartia CO_2 pipeline incident demonstrated that toxic hazard could extend large distances from a pipeline (~ 1 mile?)
  - Fast-running dispersion models (e.g., Phast) unable to simulate effects of sloping terrain
  - CFD models may (in principle) simulate terrain, but require long computer run times: impractical for assessing risks of long pipelines
  - For both CFD and fast dispersion models: lack of experimental data to validate models for dense-gas dispersion in sloping terrain. Can we trust the model predictions?

Potential future Joint-Industry Project on CO_2 dispersion

- Aims of collaborative JIP:
  - Conduct programme of large-scale CO_2 releases on sloping terrain, relevant to pipeline releases
  - Produce data to validate dispersion models and crater source models
  - Develop fast-running dispersion models suitable for pipeline risk assessment
- Test site: Porton Down (UK Defence, Science and Technology Laboratory)

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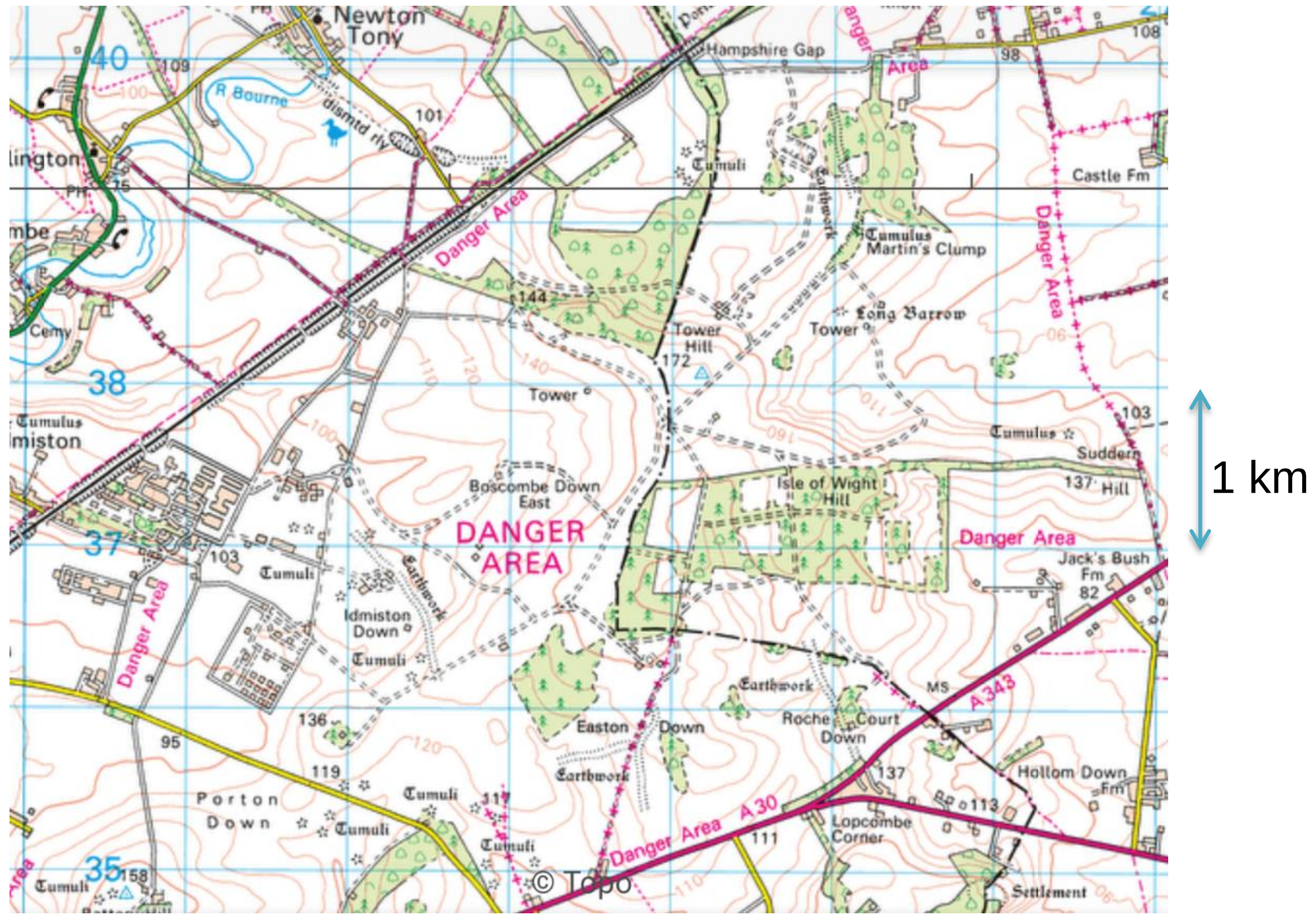

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Conclusions

Conclusions

- Knowledge gaps exist for both hydrogen and CO_2
  - Therefore: uncertainties in risk predictions for pipelines
- Limited operational experience to fill the gaps
- Issues are international: benefits in working collaboratively
- Some work underway to address the gaps
- We would be interested to hear about any work aimed at filling these gaps
- Conservative approaches necessary in the short term?
- Please contact us if you are interested in participating in the proposed JIP on dispersion of CO_2 in complex terrain

Thank you for listening

- Contact: zoe.chaplin@hse.gov.uk, simon.gant@hse.gov.uk
- The contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy

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