Bacton Energy Hub

Hydrogen Storage – SIG supplementary report

Lead Author - Progressive Energy

2022

Report for the North Sea Transition Authority

Prepared by Progressive Energy Ltd

Approved by

David Hanstock

David Hanstock
(Project Director)

Progressive Energy Ltd
Swan House,
Bonds Mill,
Stonehouse GL10 3RF
United Kingdom

Tel: +44 (0)1453 822444

Web: www.progressive-energy.com

Version Control Table

Version	Date	Author	Description
V0.1	13/5/22	John Aldersey-Williams	Working draft (internal)
V1.0	21/9/22	John Aldersey-Williams	Near-final version (circulated to BEH SIG leads)
V2.0	26/9/22	John Aldersey-Williams	Final version following BEH SIG leads’ review

Executive Summary

The North Sea Transition Authority ("NSTA"), (formerly the Oil & Gas Authority ("OGA")) has procured the formation of a number of Special Interest Groups ("SIGs") to explore opportunities for the Bacton Catchment Area ("BCA") in the context of Net Zero.

This document is a supplementary report from the Hydrogen Demand SIG. The report provides an additional workscope considering hydrogen storage in the BEH.

Its key findings are:

- Storage requirements for hydrogen in the core project case are very limited, at around 5 GWh. If suitable pipelines are available, this scale of storage requirement could be accommodated by linepack flexibility within the high-pressure gas network.
- Storage requirements for hydrogen in the build out scenario are very much larger, at around 5 TWh. Storage volumes of this magnitude could be accommodated in geological structures such as salt caverns, depleted gas fields or aquifers. Although Underground Gas Storage in salt caverns has been well proven as a solution for medium-scale gas storage, further storage options will be necessary to meet the emerging hydrogen demand and storage capability.
- The transition from core project to build out case will likely involve an intermediate stage in which some salt cavern storage is used, allowing for a hierarchy of hydrogen storage from surface tanks or linepack (very small volumes, very high flow rates), through salt caverns (medium volumes, medium flow rates) to geological structures (aquifer and depleted gas fields).
- The relative merits of hydrogen storage in depleted gas fields and aquifers are outlined.

CONTENTS

Figures

Tables

Glossary of Terms

Bcf	Billion standard cubic feet
Bcm	Billion cubic metres
boe	Barrel of oil equivalent
CCS	Carbon Capture and Storage
cuft	cubic feet
MER	Maximising Economic Recovery
Mcf	Thousand cubic feet
MMcf	Million cubic feet
MMcm	Million cubic metres
NGET	National Grid Electricity Transmission
NGGT	National Grid Gas Transmission
NSTA	North Sea Transition Authority (formerly OGA)
NTP	Normal Temperature and Pressure (298 K, 1 atm)
NTS	National Transmission System (for gas)
OGA	Oil & Gas Authority
SNS	Southern North Sea
Tcf	Trillion cubic feet (=1,000 Bcf)

UK	United Kingdom
UKCS	United Kingdom Continental Shelf

Note on units

Hydrogen
1 tonne of hydrogen = 39.4 MWh[1] = 11,200 Nm^3 = 395,000 cuft (at NTP)

1 TWh of hydrogen = 10 billion cuft (at NTP) = 285 MMcm (at NTP)

Oil equivalent
6 Mcf = 1 boe[2]

CO_2 from natural gas
Combustion of 364 kg of methane (the principal component of natural gas produces 1 tonne of CO_2[3].

The energy content of this quantity of methane, which has an energy content of 55.5 MJ/kg, is 20.2 GJ = 5.6 MWh[1].

Load factor and capacity factor
Wind farm output is generally described in terms of capacity factor, which is the average annual output divided by the nominal capacity and is determined by the wind turbine type, hub height, wind conditions and operational availability.

Power station output is generally described in terms of load factor, which is the average annual output divided by the nominal capacity. It is determined by the demand for power from that power station (driven in terms by overall grid demand and supply and that station's position in the merit order), as well as operational availability. The merit order defines the priority in which power stations on the grid are called on to generate to satisfy demand.

[1] Source:
https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

[2] Industry standard
[3] Derived from stoichiometry and molecular weights of 16g/mol CH_4, 44 g/mol CO_2

1.0 ACKNOWLEDGEMENTS

This report was compiled by Progressive Energy Limited on behalf of the Hydrogen Demand Special Interest group of the Bacton Energy Hub, with the assistance of the following core members of the SIG:

2.0 INTRODUCTION

In late 2020, the North Sea Transition Authority (at that time, the Oil & Gas Authority) commissioned Progressive Energy to consider the potential for the Bacton area to be developed as an Energy Hub and the potential role of hydrogen in the area, in the contexts of Maximising Economic Recovery and Net Zero.

2.1 Maximising Economic Recovery (MER) and Net Zero

The North Sea Transition Authority states that "it works with industry and government to maximise the economic recovery of UK oil and gas and support the UK government in its drive to reach net zero greenhouse gas emissions by 2050"[i].

2.2 The role of hydrogen

The transition to Net Zero will involve the replacement of fossil fuels with zero carbon alternatives. The main options for this are electricity generated from renewable sources (mainly offshore wind), and the replacement of natural gas with hydrogen. Across the energy sector, there is a lively debate as to the potential roles of these alternatives. This SIG takes the view that hydrogen should be positively advocated as a key part of the energy mix in Net Zero.

It is clear that zero carbon thermal power generation technologies will be required to fill the generation gap when wind output is low: hydrogen can be used for this. Recent investigations conducted at Keele University demonstrated the viability of blending up to 20% of hydrogen into the domestic natural gas network. These studies suggest that hydrogen may be able to make use of existing gas distribution infrastructure, and adoption or conversion of hydrogen boilers at all scales, from domestic to industrial, to replace natural gas use with hydrogen, may offer a relatively limited cost decarbonisation option, and avoiding the costs of upgrades to the electricity grid.

Therefore, the BEH Hydrogen Demand SIG participants strongly endorse the development of hydrogen as a replacement for natural gas, and as a strong participant in the Net Zero transition.

2.3 Scope of work

The Bacton Energy Hub includes assessments of hydrogen demand and production, based on a "core project" and a "build out case". The mismatch between hydrogen production (both blue and green) and demand will give rise to a need for hydrogen storage at different timescales.

This scope of work will:

- Assess storage demand for core project
    - Assumptions:

    - blue hydrogen only
    - demand mainly from domestic, assess blending limit
  - Quantify storage volume, flow rates, timing of requirement (daily, seasonal)
  - Review pipeline requirements
- Assess storage demand for build out
  - Assumptions:
    - different mixes of blue and green hydrogen
    - demand mainly from domestic, assess blending limit
  - Quantify storage volume, flow rates, timing of requirement (daily, seasonal)
  - Review pipeline requirements
- Identify scale of storage requirements
  - Convert to gas field volumes
  - Identify gas field candidates
  - Identify pipeline candidates
- Discuss gas field vs aquifer for hydrogen storage

3.0 CORE PROJECT – SUPPLY AND DEMAND

3.1 Approach

An imbalance between production and demand of hydrogen could be managed by using temporary storage. In this section, we have considered the Core Project, which comprises a single 350 MW blue hydrogen production facility, serving domestic markets with a blend of up to $20\%_{vol}$ in natural gas.

3.2 Assumptions and methodology

The Core Project's assumption on hydrogen production comprises a single 350 MW blue hydrogen plant. At a constant 100% load factor, such a plant could produce around 3.1 TWh/yr.

We have further assumed that this plant will operate at a constant load factor of 95%, with a two-week shutdown in summer each year, making for total annual output of 2.8 TWh.

We have developed an hourly Excel™ model which varies these demand totals across realistic annual profiles, and compares these with available supply to determine any storage requirement.

We have assumed demand variability as set out in Table 2-1.

Table 2-1: Demand variability assumptions

Demand sector	Variability	Source
Domestic / commercial	High degree of hourly and seasonal variability; blending may mitigate. In 2030 case, we have assumed 2019 demand pattern: increased electricity for heat will increase variability further	Derived from WWU Pathfinder model
Power generation	High degree of hourly and seasonal variability, driven by availability of wind and other renewable energy, grid demand and other factors	Derived from Progressive Excel™ hourly model
Industry	Assumed seasonally invariant, 80% day time (0800-2000), 20% night time (2000 – 0800)	Progressive assumption
Transport	Assumed constant	Based on assumptions on local storage

We note that the blend proportion for domestic demand can be up to 20%$_{vol}$, but could in principle be varied between 0%$_{vol}$ hydrogen and 20% $_{vol}$ hydrogen, to accommodate imbalances between supply and demand.

3.3 Demand

Input from the demand SIG suggests that the total annual demand in 2030 could amount to 1.6 TWh from power generation, 0.6 TWh from industry, 0.2 TWh from transport and 5.7 TWh from domestic demand, based on a 20%$_{vol}$ blend.

We have assumed that the domestic demand varies as defined by Wales & West Utilities' Pathfinder model. The Pathfinder model is a sophisticated hourly model used to assess electricity and gas demand over a year, and has been one of the foundations on which Progressive has developed its own UK electricity system model.

This initial assessment assumes that industrial demand varies simply between night and day, with 20% of demand increase in the periods between 8pm and 8 am, and 80% in the daytime period from 8am to 8pm.

Finally, demand for hydrogen for power is calculated using Progressive's own hourly UK electricity system model. This model applies the available nuclear, solar and wind power to the electrical demand in each hour and calculates the implied amount of dispatchable power required to meet that fraction of demand which was not satisfied by nuclear or renewable generation. The model does not consider interconnectors or distinguish biomass generation from conventional thermal power generation.

Figure 2-1 shows the variability for power (grey) and domestic (blue) hydrogen demand for a typical wind year. We have the capacity to model different wind years, to see how this impacts the demand for hydrogen storage.

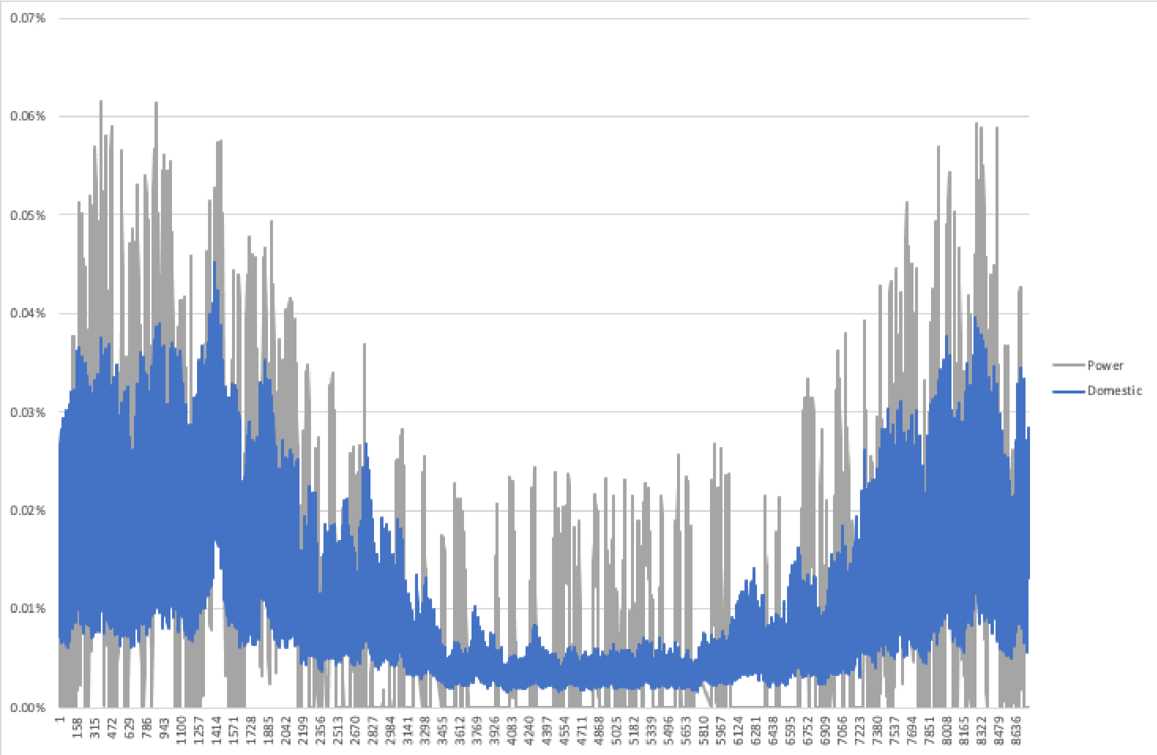

Figure 2-1: Variability of hydrogen demand: domestic and power

3.4 Supply

Supply is modelled as a single 350 MW blue hydrogen plant, whose variability is described in section 2.2 above.

3.5 Storage modelling and requirement

Our modelling calculates the hydrogen storage by comparing the available output in an hour with the demand in that hour, with the merit order being power and industry first. If supply is insufficient to meet power and industrial demand, it accesses any hydrogen in store. In hours where the combination of stored volumes and hourly supply do not meet demand, the model (implicitly) assumes that this demand is reduced to meet available supply or that alternative supplies are found.

Where production capacity exceeds demand from power and industry, the remaining balance is then assumed to be available for domestic blending. When the available hydrogen surplus is insufficient to achieve a $20\%_{vol}$ blend for domestic supply, the model assumes that the blend proportion is reduced as required to fully consume the available surplus.. In cases where available surplus of hydrogen exceeds the requirement for domestic blending, this excess hydrogen is put into storage.

On this basis, we find that the average amount of hydrogen storage required is around 5.7 GWh, and ranges from 10.5 GWh in a high wind year to 2.2 GWh in a low wind year.

Note that 1 GWh equates to around 250,000 m^3 of hydrogen at normal temperature and pressure (20°C at 1 atm), and that an average salt cavern can accommodate around 70 GWh. The core project case will not require geostorage in depleted gas fields or aquifers.

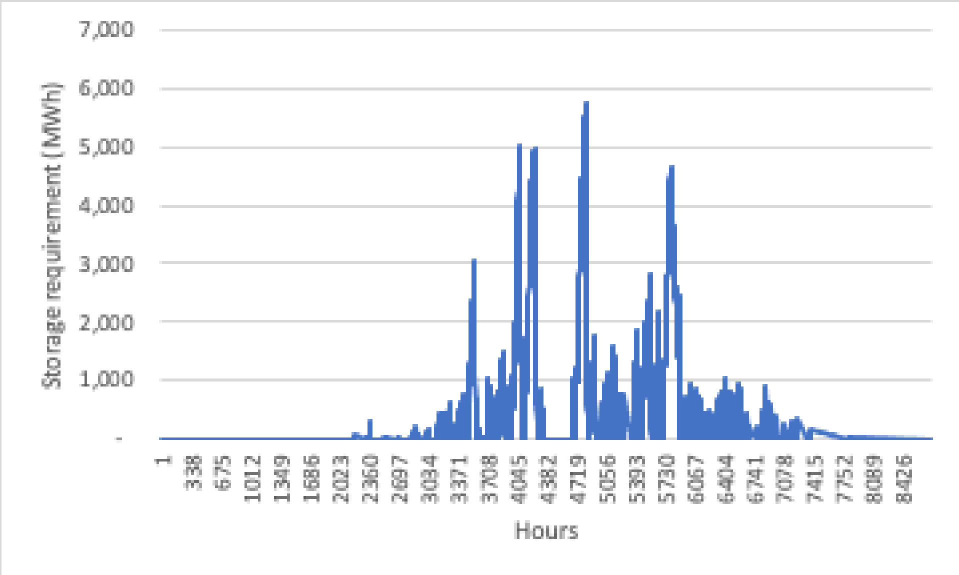

Figure 2-2: Hydrogen storage requirement (core project)

As a footnote, we conclude that in a lower wind year, the call on dispatchable power is higher and therefore there are fewer opportunities for excess hydrogen to be put into store. The opposite is true in high wind years, where the call on dispatchable power is lower, and there are more occasions on which excess hydrogen must be stored.

3.5.1 Flow rates

The maximum hourly flow rate in the modelling is 191 MWh/h (c. 54,000Nm^3/h, c. 45 MMSCF/d).

3.6 Pipeline requirements

We note that a hypothetical pipeline 100km in length, with internal diameter of 1,200mm has a volume of 113,000 m^3. When operated between 50 and 100 bar, the pipeline can offer storage volume of 565,000 m^3 – or around 2 GWh. Therefore, such pipeline network, if available, could provide adequate storage volume in the core project case. We note that considerable engineering work will be required to confirm that operating a pipeline in this manner will be safe and remain within fatigue limits.

4.0 BUILD OUT – SUPPLY AND DEMAND

4.1 Approach

A similar approach has been taken to modelling storage requirements in the build out scenario as for the core project. The build out scenario anticipates development of significant volumes of both blue and green hydrogen production capacity at Bacton.

4.2 Methodology

We have adopted the same methodology as in the core project, with a modification to recognise when build out demand exceeds potential hydrogen production from the blue and green production capacity build out scenarios.

As annual aggregate production in the buildout case is less than total demand, an unmodified storage model would assume that stored hydrogen could meet the supply shortfall. We have modified the model so that it only calculates the increasing demand for storage required to accommodate the periods in which blue and green hydrogen production exceeds energy demand .

4.2.1 Data sources

As with the core project case, we have used data on hourly variability from Pathfinder and from our own calculations to assess the hourly demand for hydrogen.

We have also assumed that the green hydrogen production achieves the same load factor, hour by hour, as the wind which provides the energy for hydrogen production. This is a simplified assumption, as the load factor achieved by electrolysis is a complex function. This factor can vary depending on the relative sizes of the supplying wind farms, the electrolysers, and the capacity factor achievable by the wind farms.

4.3 Demand

Total hydrogen demand assumed in this report comes from the Hydrogen Demand SIG's assessment: a total of 85.9 TWh, split between 61.8 TWh (domestic/commercial), 6.5 TWh (industry), 12.0 TWh (power) and 5.6 TWh (transport).

As with the core project, we have modelled hourly variability of this demand as set out in Table 2-1.

4.4 Supply

We have used estimates of hydrogen supply from the build out scenario's anticipated blue and green production volumes. The stated blue hydrogen capacity is 6.3 GW (which would require some 180 Bcf/year of feedstock). The stated green hydrogen capacity is 3.6

GW, for which we have assumed a load factor equal to that achieved by the aggregated wind fleet.

4.5 Storage modelling and requirement

Our assessment concludes that 5.5 TWh of storage is required to accommodate the excess of production during the low-demand summer periods.

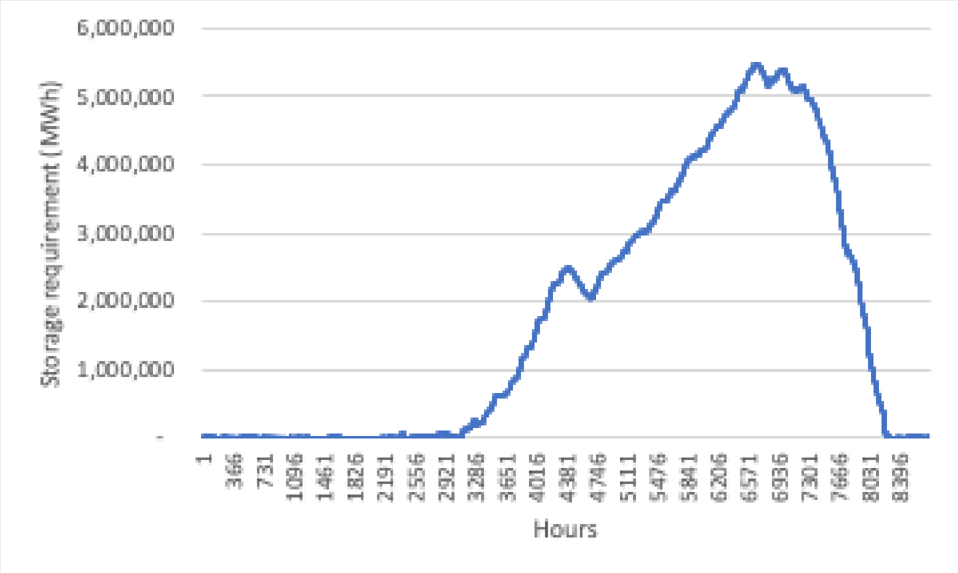

Figure 3-1: Hydrogen storage requirement (build out scenario)

We have previously assessed the typical capacity of an "average" salt cavern is in the region of 70 GWh. Therefore, it is immediately clear that storage of 5 TWh is more than could readily be accommodated in a single average salt cavern – it would require more than 70 such caverns.

4.5.1 Flow rates

The maximum hourly flow rate in the modelling is 7,400 MWh/h (c 2.1 MMNm^3/h, c. 1.8 Bcf/d). This flow rate would clearly require geological scale of storage and multiple wells.

4.5.1 Additional note

As noted above, this modelling assumes that storage is only required to accommodate periods when production exceeds demand. If additional supply was available, perhaps from import from the continent, additional storage capacity would allow grid fluctuations to be met during periods of high demand.

5.0 STORAGE REQUIREMENTS

5.1 Identify scale of storage requirements

Sections 2.5 and 3.5 identify the scale of storage requirements under the two scenarios. They are found to be around 5 GWh (core project) and 5 TWh (build out scenario).

5.2 Convert to gas field volumes

As noted in the “Note on units”, 1 tonne of hydrogen represents 39.4 MWh of thermal energy, and has a volume of 11,200 Nm^3 (395,000 scf). A typical gasfield with reserves of, say, 200 bcf, might therefore be capable of storing 20 TWh of hydrogen.

Mouli-Castelli et al (2021)[ii] undertook a review of the hydrogen storage potential of UKCS fields. That review identified a number of depleted gas fields with pipeline connections to Bacton with hydrogen storage potential, with capacities from 1.6 TWh (Brown) to Indefatigable (194 TWh).

Detailed assessment of storage candidates is required, to allow for candidate selection, based on:

- Integrity of store, decommissioned wells
- Distance from Bacton
- Availability and suitability of pipeline capacity
- Availability of reusable infrastructre
- Reservoir performance, numbers of wells required
- Impact of blending with residual methane
- Biogenic effects on stored hydrogen

5.3 Identify gas field candidates

Mouli-Castelli et al. (2021) undertook an overview of the storage potential of a number of gas fields on the UKCS. Figure 4-1 is taken from their work, and finds that the total storage potential across the UKCS is very significantly in excess of their estimate of the demand requirement. The red line on this graph shows their estimate of storage demand potential for the UK – around 78 TWh.

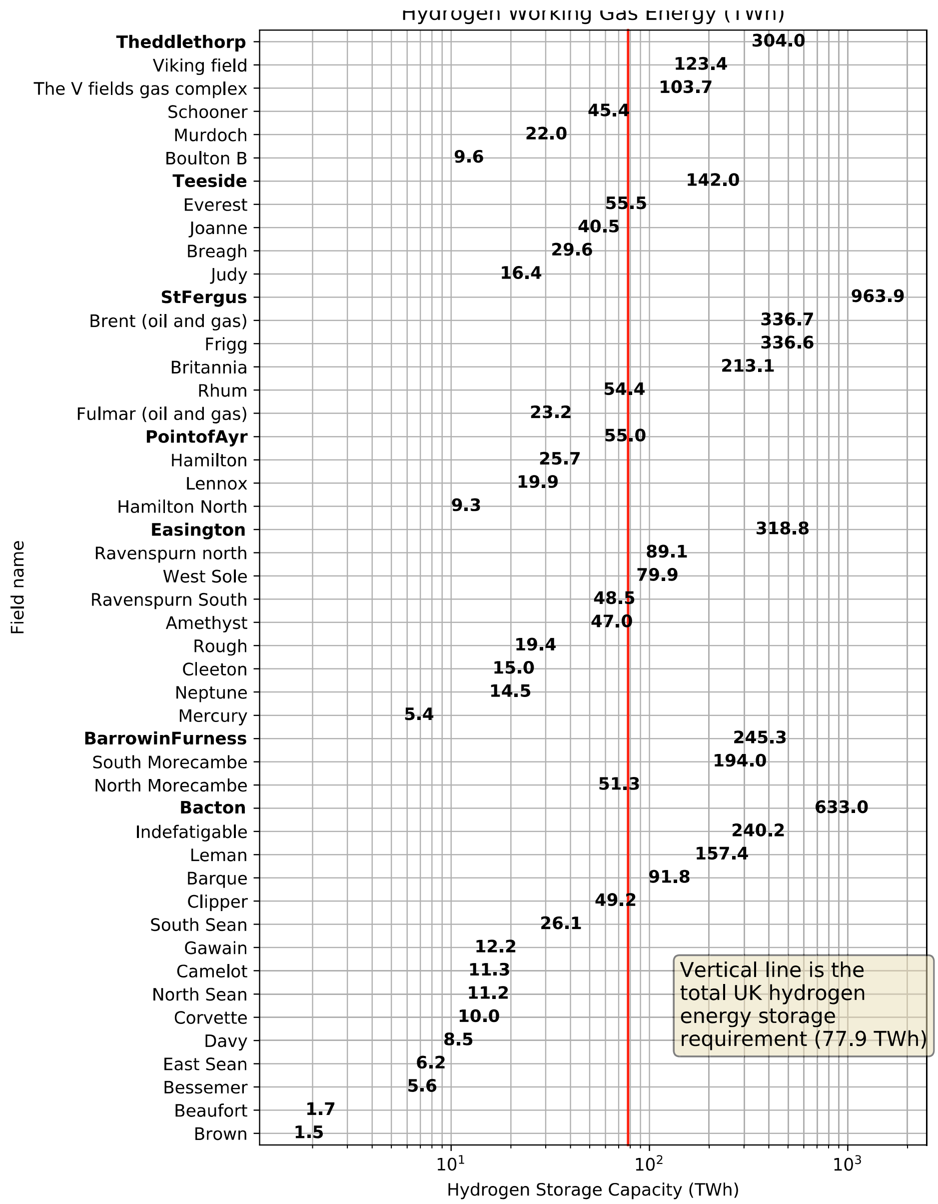

Figure 4-1: Hydrogen storage capacity in UKCS structures (Mouli-Castelli et al, (2021))

5.4 Identify pipeline candidates

There may be potential to reuse existing pipeline capacity into Bacton for hydrogen storage. The main pipelines into Bacton are:

- Shell terminal:
  - Leman
  - Clipper
  - SEAL
- Eni terminal
  - Hewett
  - LAPS
- Perenco
  - Leman
  - Indefatigable
  - Trent/Tyne

6.0 GAS FIELDS AND AQUIFERS FOR HYDROGEN STORAGE

6.1 Overview

Underground geological CO_2 storage is contemplated in both depleted gas fields and aquifer structures. The same broad categories of structure may be suitable for hydrogen storage. This section assesses the relative merits of these two classes of structure, and identifies further work which will be required to develop these assessments fully.

The storage of hydrogen has one critical difference relative to storage of CO_2 – stored hydrogen must be capable of being produced from the storage site in response to demand (when hydrogen production is insufficient).

6.2 Depleted gas fields

Depleted gas fields have been studied in some detail as potential sites for CO_2 storage. With well-defined structures, known reservoir performance and, in some cases, reusable infrastructure, they can represent attractive options for permanent geological storage of CO_2. HyNet plans to use the depleted gas fields of Liverpool Bay for CO_2 storage.

6.3 Aquifers

Aquifers –geological structures with a trapping geometry but which do not hold hydrocarbons – are also recognised as potential storage sites for CO_2. The East Coast Cluster plans to use the aquifer structure known as Endurance for CO_2 storage.

6.4 Comparison of depleted gas fields and aquifers

The key differences between hydrogen storage in depleted gas fields and aquifers is summarised in Table 5-1.

Table 5-1: Hydrogen storage in geological structures

	Depleted gas field	Aquifer	Comments
Structural definition	Excellent, structure well characterised by wells and seismic	Moderate, structure identified on seismic, potentially abandoned exploration wells	Aquifer will require good explanation of why it does not contain hydrocarbons – eg migration issues

Storage integrity – structure	Proven by retaining hydrocarbon gas for millions of years,	Not proven, only demonstrable through seismic interpretation and mapping, viable stratigraphy with reservoirs and seals	Regional geology can inform on aquifer structure, appraisal wells likely required
Storage integrity - wells	Likely to be penetrated by multiple production wells. Older exploration and appraisal wells may have lost abandonment records, or abandonment technology unsuitable	May be penetrated by limited number of exploration wells. Abandonment records may be lost, or abandonment technology unsuitable.	Current production wells may be reusable or decommissioned with hydrogen integrity in mind
Reservoir pressure	Likely to be very low, leading to cushion gas requirement	Likely to be undepleted, requiring little or no cushion gas	Aquifer storage may require removal of aquifer water to create space
Risk of overpressure	Limited, as reservoir likely to be very depleted	Potential for overpressuring as reservoir likely to be close to hydrostatic gradient at start of storage	Depressurisation of aquifer through water removal may lower aquifer pressure to below safety limit
Hydrogen contamination - chemical	Hydrogen likely to be contaminated with methane	Hydrogen likely to be wet	Case by case analysis required based on salinity, reservoir chemistry
Hydrogen contamination - biogenics	Hydrogen likely to be contaminated with methane, possibly biogenic species (incl H_2S)	Hydrogen likely to be wet, possibly biogenic species (incl H_2S)	Case by case analysis required based on salinity

6.5 Further work

As potential hydrogen storage structures are identified, the table above gives an indication of the further work which will be required to confirm their viability, risks and attractiveness.

7.0 REFERENCES

[i] Available at https://www.nstauthority.co.uk/about-us/

[ii] Mapping geological hydrogen storage capacity and regional heating demands: An applied UK case study, Mouli-Castelli, J et al, (2021), Applied Energy, 283, 116348