THE ROLE OF HYDROGEN AS AN ELECTRICITY SYSTEM ASSET

WP4 REPORT

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Introduction

WP4

SYNOPSIS

This report should be read in conjunction with the previous WP2/3 report, which outlines how hydrogen markets will develop under a range of scenarios. In this report, the hydrogen Value Chains (VCs) introduced in the previous report are explored in more detail.

The core aims are to:

- Provide a high level market sizing of the 10 VCs for the emerging hydrogen sector, including consideration of different timescales.
- Determine which of the VCs are relevant for inclusion within the four FES scenarios.
- Identification of the different ways the VC's could interact with the electricity system and assess how VC's will impact in different ways depending on their use cases.

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Glossary of terms

ATR

Autothermal Reforming

BECCS

Bioenergy with Carbon Capture & Storage

CCC

Committee for Climate Change

CCS

Carbon Capture & Storage

CCUS

Carbon Capture, Utilisation & Storage

CCGT

Combined Cycle Gas Turbine

GHR

Gas-heated Reformer

H2

Hydrogen

HGVs

Heavy Goods Vehicles

HRS

Hydrogen Refuelling Stations

LOHC

Liquid Organic Hydrogen Carrier

OCGT

Open Cycle Gas Turbine

PEM

Polymer Electrolyte membrane

SOE

Solid Oxide Electrolyser

SOEC

Solid Oxide Electrolyser Cell

SMR

Steam Methane Reformation

TRL

Technology Readiness Level

Contents

Summary of overall Project Scope & Approach 1/2

DELTA-EE

Overall project scope:

To increase understanding of the future development of hydrogen markets and how targeted investment can more effectively support the electricity system

Project scope

- Outline possible future low carbon hydrogen landscapes under a range of scenarios
- Define interactions between the hydrogen vector and the electricity system operations and markets
- Identify the potential roles of hydrogen take in supporting and optimising the electricity system
- Understand the opportunities for National Grid to best engage with the hydrogen sector across both the system and transmission parts of the business
- Assess how National Grid can best include the impacts of hydrogen in their forecasting and scenario planning including FES development and economic models

Outputs

- WP2/3: Final Report
- WP4: Final Report
- WP5: Final Report – including associated datasets, where applicable
- WP6: Final Summary Report
- WP8: Final Report – including associated datasets, where applicable

A six work-package approach

WP1 is mobilisation (complete)

Stage 1: Exploration
- **WP2:** Identification of H2 value chains and pathways
- **WP3:** Analysis of H2 value chains and pathways
- **WP4:** Analysis of interactions between H2, National Grid, and the broader electricity system

This Report is for WP4

Stage 2: Analysis
- **WP5:** Impact analysis
- **WP6:** Summary Report

WP7 is Project Management (ongoing)

Stage 3: Support Redispatch
- **WP8:** Input to Redispatch Power2X development and data requirements

Summary of overall Project Scope & Approach 2/2

Overall project approach:

An initial exploration stage followed by a more in-depth analysis stage. This will capture the breadth of potential hydrogen interactions, and provide in-depth analysis on a sub-set of impacts which are most pertinent to National Grid and FES 2022

Project approach

- **Stage 1** will involve an in-depth literature review, interviewing of industry experts and in-house modelling. This mixed methodology will be used to develop different use cases and value chains, which will then be long-listed and then short-listed.

- **Stage 2** will involve in-depth analysis of the impacts of the short-listed value chains from stage 1. During the second stage of work, several topics will be explored in more detail. This analysis will provide evidence to inform the FES scenario development for 2022, and inform the assumptions and datasets used within the BID3 modelling to further develop the Hydrogen modelling capability. The nature and type of analysis conducted during stage 2 will vary depending on the topics explored but we anticipate a range of quantitative analysis, including runs of the model developed in stage 1 and additional qualitative research, such as an interactive webinar with key stakeholders to inform the analysis.

- **Stage 3** will be to support National Grid (in collaboration with AFRY) on the Redispatch Power2X module development in WP8. We understand that the Redispatch module of BID3 will enable simulation of Hydrogen value chains. We will provide additional evidence to support the development of the Redispatch module. This will include data associated with balancing mechanism actions taken by hydrogen related technology including bid and offer spreads, as well as flexible demand. Final methodology and outputs for stage 3 are to be confirmed.

Introduction and Scope

Aims for WP4

Stage 1: Exploration: Strategic review of hydrogen pathways and scenarios

(WP2, 3 & 4)

Stage 1 will provide an overview of how the hydrogen sector is likely to evolve under a range of scenarios and provide the next level of detail for the FES analysis describing possible hydrogen transitions and system impacts. In WP4, this will include:

- Following on from the Value Chains (VC's) developed in WP3, in WP4 a high level market sizing exercise will be completed.
- A high level evaluation of all the possible hydrogen interactions across the electricity system will be considered.
- A comprehensive methodology will be developed to assess the different VC's potential to engage and/or impact with the different interactions identified.
- The analysis will identify the potential for hydrogen to provide flexibility, energy storage and power generation across the different FES scenarios.
- A more detailed analysis, using the market sizing information will confirm the MW capacity available. This information will form the foundation of the modelling exercise in WP5 (Stage 2).

Executive Summary

Key Findings

Market Sizing

Impacts to the electricity system will be substantial as **green hydrogen production increases**. This will begin with niche Value Chains producing small amounts of hydrogen up to 2035, followed by increasing diversity in the electrolyser use cases in the run up to 2050, leading to increased quantities.

A crucial dynamic will be between **electrolyser capacity, utilisation and storage**, which will be dependent on market forces and infrastructure development.

A national gas network is not essential for a flourishing hydrogen market, but as a minimum a regional network will be needed to reach the highest production levels. Similarly, salt cavern storage will be needed for the market to reach it's full potential.

Flex and Ancillary Services

Electrolysers: A small number of Value Chains have the potential to engage in flex and ancillary services. However, there is an indirect benefit to the grid from several VCs for example provision of nuclear power balancing (VC4) and reduced constraint management and renewables curtailment (VC5). Electrolysers will not begin engaging with flex until 2035 at the earliest.

Power generation: Natural gas for power generation will be phased out by 2035 and hydrogen will take over.* Hydrogen for power generation is costly so the Value Chains focus are specifically for peaking and mid-merit only. Therefore the VCs are suited to the provision of flex and ancillary services by definition and will operate in a similar way to peaking/mid-merit gas plants currently. Although the total amount of electricity generated from CCGTs/OCGTs will be significantly reduced.

*Source: https://www.gov.uk/government/news/plans-unveiled-to-decarbonise-uk-power-system-by-2035

Storage & Co-location

Storage has two main options, pressure vessels, usually for short-term, and salt caverns, best suited for long-term. The analysis considers four storage utilisation options:

- Daily – inter & intra day,
- Seasonal/quarterly,
- Both daily and seasonal,
- Strategic annual.

The ability of the different VCs to provide load-shifting and constraint management is also considered based on their storage specifications.

Distribution – three different gas network options are assessed: private gas networks, regional networks and nationwide network

Geography/co-location – the potential location of VCs dependent on their storage requirements is analysed and the feasibility of these locations considering VC production/end use.

WP4: Analysis of Interactions between H2, National Grid and the Electricity System

Analysis will consider a broad range of interactions with national grid – any element of the value chain which may, in a range of outcomes, have an effect on the operation (both short term operational and long term planning) of the electricity system

Final Short-list for analysis in WP4

Value Chains determined for inclusion based on hydrogen expert analysis and dialogue with National Grid.

No.	Value Chain	Detail
VC1	Centralised blue hydrogen production for industry provision and early hydrogen network injection	To account for initial blue hydrogen wave into industry. Likely to start as isolated blue plants for specific users, but as more users, plants and clusters come online network injection into a hydrogen network develops.
VC2	Peaking electricity generation using hydrogen for peaking power (high MWs)	Turbine, FC or engine to help mitigate national network issues, ancillary services and balancing mechanism.
VC3	Mid-merit electricity generation using hydrogen	Longer term electricity generation using hydrogen CCGTs to fill the gap between base load (renewables) and peaking plants (OCGTS, engines etc)
VC4	Centralised nuclear hydrogen for injection into hydrogen networks (smaller scale)	Covers the installation of electrolysers at existing or new nuclear built in the 2020s - i.e. large scale nuclear in isolated locations. Helps provide nuclear base loading and provides hydrogen.
VC5	Electrolysis for curtailment mitigation	Covers use case of electrolysis for avoiding curtailment of renewable assets (networked and non-networked); curtailment may occur due to electricity supply/demand imbalances and network constraints.
VC6	Centralised green hydrogen at onshoring point for transport near industrial clusters or ports	Covers HGV, trains and things like distribution centres (forklifts) that tend to be near industry clusters or ports that need high purity hydrogen and therefore can't easily use blue hydrogen.
VC7	Decentralised green hydrogen production for use in heavy road and rail transport	Distributed electrolysers that will be co-located with refuelling stations / transport hubs.
VC8	*Electrolysis for frequency ancillary services*	*This VC has been excluded since completion of WP3 as all VC's have been assessed for ability to provide ancillary services.*
VC9	Hydrogen production from bioenergy with carbon capture and storage (BECCS)	For use in industrial applications. Expensive production method, but may be required to offset emissions from Blue production.
VC10	Centralised green hydrogen production for industrial use in a cluster	Hydrogen storage will be a key aspect for this value chain to decouple potentially intermittent hydrogen production from industrial output.
VC11	Centralised marine electrolysis	Piped back from offshore wind (floating or fixed).

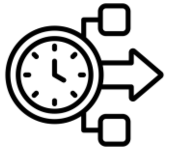
Categorisation of Short-listed Value Chains 1/2

Market sizing detail covered in the next two sections

Today-2035

No.	Value Chains - Short-list
VC1	Blue hydrogen production for industry provision and early hydrogen network injection
VC4	Nuclear hydrogen for injection into hydrogen networks (smaller scale)
VC6	Green hydrogen at onshoring point for transport near industrial clusters or ports
VC7	Green hydrogen production for use in heavy road and rail transport

Value Chains most likely to be ready in the **short-term** based on current technology and market readiness.



2035-2050

No.	Value Chains - Short-list
VC2	Peaking electricity generation using hydrogen for peaking power (high MWs)
VC3	Mid-merit electricity generation using hydrogen.
VC5	Electrolysis for curtailment mitigation
VC9	Hydrogen production from BECCS
VC10	Green hydrogen production for industrial use in a cluster
VC11	Marine electrolysis piped back from offshore wind

Value Chains most likely to be ready in the **long-term,** will require more time for markets to mature and develop.

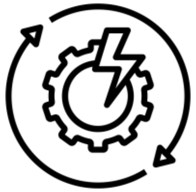
Categorisation of Short-listed Value Chains 2/2

The icons below will feature on the Market Sizing pages to show which value chains we think are of particular relevance to which FES

Consumer Transformation

Steady Progress

System Transformation



Leading the Way

Market Sizing: Value Chains

Headlines and summary of high level market sizing

Impacts on the electricity system will be significant

VCs involve Terawatt hours of H2 and Gigawatts of electrolysis capacity

Market sizing undertaken was used to bound the scale of impacts to the electricity system from hydrogen – many value chains present orders of magnitude change in capacities and demand.

Contextualising hydrogen demand and impact on the electricity system from VCs examined

Impacts to the electricity system will be substantial

Hydrogen production required for each value chain typically represents a significant change to the size of the hydrogen demand in the UK today.

Where this production is provided by electrolysis, the expected capacities (10s GWs) are substantial compared to current and future demand and will have wide ranging impacts on the electricity system.

Using Hydrogen demand from HGVs and trains (VC6) as an example of the scale of impacts

- VC 6 alone could require 20-80 TWh of hydrogen by 2035, this is a 100-400% increase in demand compared to UK hydrogen demand in 2020.
- This demand would require 6-24 GW of electrolysis capacity by 2035– roughly equivalent to the capacity of the UK coal generation fleet in 2020 (5 GW) at the low end, and close the UK gas generation fleet (35 GW) at the high end.

Major themes from market sizing

- Across all value chains involving green H2, there will be a **crucial dynamic** between electrolyser capacity (sizing), utilisation (load factor) and storage, which will vary significantly based on market and price drivers, and infrastructure development (e.g. networks). At this stage there is considerable uncertainty on how electrolysis will be designed in concert with storage for many, if not all, of the value chains.
- Many of the value chains, and especially those that are centralised, will likely require **geological scale storage** (i.e. over 2 GWh per year).
- A national or at least regional **hydrogen gas network** will support the viability of numerous value chains, especially the smaller scale and decentralised ones; a network makes these VCs much more viable, and much less geographically restricted, as daily small-scale storage can be avoided and hydrogen supply simplified.
- **The bulk of hydrogen demand will emerge post 2035.** Roughly one third of the value chains examined will emerge before 2035, and will consume between 35 – 145 TWh of hydrogen. The remaining value chains will appear post 2035 and will consume between 52 – 190 TWh of hydrogen.
- **Hydrogen fuelled power generation** will likely be present in similar capacities to natural gas power generation today – but will have far lower utilisation due to the high cost of hydrogen, meaning that far higher electricity prices are required to incentivise dispatchable power.

Market Sizing: Value Chains

These Value Chains will be ready in the short-term.

Between today and 2035

DELTA-EE

High level sizing of UK Market for each Value Chain (VC1)

Methodology and Assumptions

VC1: Centralised blue hydrogen production for industry provision and early hydrogen network injection

Includes first wave of blue hydrogen. Will likely begin as isolated plants for specific users, but will increase as more users, plants and clusters come online and the dedicated hydrogen network develops

Output: How much SMR capacity will be installed at industrial sites (clusters) for industrial use (including heat) in 2035, and how much hydrogen do they produce.

Methodology

1. Calculation: Industry demand
Inputs (assumption based):
- Industrial hydrogen demand (TWh) for 2030-35
- Demand in 2030 / 2035 (GWh and Tonnes/yr)
- Size of SMR plant
- 2035 market size for industry; industry demand (GWh); plants needed for tonnes/yr

2. Calculation: Demand for blending
Inputs (assumption based):
- Natural gas demand and CV today
- Calculation for blending demand by volume
- Number of blue plants required to satisfy blending demand

3. Calculation: Storage
Inputs (assumption based):
- 2035 storage requirement for a single plant if no network present (GWh)
- 2035 storage requirement for industry if no hydrogen network present – plant capacity (tonnes/yr)

Key Assumptions:

- Assumes options for both dedicated hydrogen for industrial use only and blending option.
- National natural gas network is open to 20% blends by 2035.
- No storage needed for blending.
- All industry satisfied by blue hydrogen in 2035.
- Blending is allowed and varies between 5% and 20% volume.

Sources used
- UK Hydrogen Strategy, 2021
- BEIS Hydrogen Production Costs, 2021
- Fuel Cells and Hydrogen Observatory, Hydrogen Demand, 2022

High level sizing of UK Market for each Value Chain (VC1)

Results: Capacity meeting industry demand in 2035

VC1: Centralised blue hydrogen production for industry provision and early hydrogen network injection

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	n/a	n/a
Hydrogen produced	13,000 GWh	52,000 GWh
Hydrogen consumed	n/a	n/a
Hydrogen storage need	1,250 GWh	2,250 GWh
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

Additional outputs

2035 market size for industry

Option	GWh/yr	Tonnes/ yr	No. of plants needed for different tonne capacities		
			100,000	150,000	200,000
Low	25,000	640,000	6	4	3
High	45,000	1,100,000	11	7	5

High level sizing of UK Market for each Value Chain (VC4)

Methodology and Assumptions

Output: How much hydrogen is likely to be generated by and how much electrolysis capacity will be installed at nuclear stations by 2035.

VC4: Centralised nuclear hydrogen for injection into hydrogen networks (pure or blended).

Covers the installation of electrolysers at existing or new nuclear built in the 2020s. Supports nuclear to run at baseload and provides hydrogen.

Methodology

1. **Calculation**: Capacity of electrolysers installed at nuclear power stations. (MW)

Inputs (assumption based):

- Installed capacity from nuclear stations in 2035. (MW)
- Uptake of electrolysers at nuclear stations. (%)
- Size of electrolysers relative to nuclear station capacity. (%)

2. **Calculation**: Hydrogen produced at nuclear stations. (GWh)

Inputs (assumption based):

- Low / medium scenario for electrolysis utilisation at nuclear stations. (%) This is influenced by other impacts on the network, e.g. installed base of intermittent renewables vs dispatchable power, storage capacities, demand response etc.
- Electrolyser efficiency (kWh per kg H2)

Key assumptions

- All capacity installed is Solid Oxide electrolysers (SOEs). SOEs can benefit from high temperature heat integration from nuclear plants and thus achieve high efficiencies.
- Electrolyser are sized at or close to nuclear plant capacity. This is due to the nuclear generation profile (high capacity factor) being much higher than renewable asset profiles.
- Installed capacity from nuclear stations in 2035: 4,000MW
- Electrolyser top end efficiency: 36.2 kWh per kg of H2 – assumes SOEs at full TRL and some heat integration.
- Electrolyser utilisation: 25% - 50%. Primary function of nuclear plants is to produce power, which is why a low/medium utilisation is used. Instead of ramping down, the power station can respond to price (or network) signals and produce hydrogen instead.

Sources used

- Energy and emissions projections: Net Zero Strategy baseline (partial interim update), December 2021
- Climate Change Committee 6th Carbon Budget, Electricity generation, 2020
- US DOE, Hydrogen Program Record 20003, September 2020
- World Nuclear Association, Nuclear Power in the UK, April 2022

High level sizing of UK Market for each Value Chain (VC4)

Results: Nuclear base loading and hydrogen provision

VC4: Centralised nuclear hydrogen for injection into hydrogen networks.

All pink hydrogen produced is injected into a national or regional dedicated hydrogen gas network, meaning no hydrogen is consumed or stored in this Value Chain.

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	900 MW	2,000 MW
Hydrogen produced	2,100 GWh	9,500 GWh
Hydrogen consumed	n/a	n/a
Hydrogen storage need	n/a	n/a
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

Additional outputs

Not applicable.

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High level sizing of UK Market for each Value Chain (VC6)

Methodology, Assumptions, References

Output: How much electrolysis capacity must be installed in a centralised location to meet hydrogen demand from rail and road transport.

VC6: Centralised green hydrogen at onshoring point for transport near industrial clusters or ports.

Covers HGV, trains and other distribution centres (forklifts) that tend to be near industrial clusters or ports that need high pure hydrogen and therefore can't easily use blue hydrogen.

Methodology

1. Calculation: Hydrogen demand for transport (GWh)

Inputs (assumption based):

- Size of hydrogen-powered HGV fleet in 2035 (# vehicles).
- Fuel cell efficiency (%).
- Number of hydrogen-powered trains in 2035 (# vehicles).
- Fuel cell efficiency (%).

2. Calculation: Installed electrolysis capacity at centralised production points for transport use. (GW)

Inputs (assumption based):

- Hydrogen demand for transport. (GWh)
- Total electrolyser capacity required at centralised green hydrogen production point for HGV and train demand. (GW)

Assumed inputs

- The efficiency of a hydrogen-powered HGV is estimated at 0.13 kg of hydrogen per mile. HGVs currently drive between 50,000-100-000 miles annually.
- Approximately 9% (1,300) km of the rail network will be used by hydrogen trains by 2035. Hydrogen-powered trains have an efficiency of 0.3 kg of hydrogen per kilometre.
- GB will count 100 HRS in 2035, each equipped with 2 MW electrolysers. These electrolysers are used at 40% load-factor, and their efficiency estimated at 50 kWh per kg of hydrogen. Most electrolysers are likely to be grid connected.

Sources used

- Climate Change Committee 6th Carbon Budget, Electricity generation, 2020
- Fraunhofer ISI, Fuel cell trucks, October 2020
- Fraunhofer ISI, Sustainability and Innovation Working Paper, September 2020
- UK Government, Domestic road freight transport, 2021
- Office of rail and Road, Rail Emissions, 2021
- Fuel Cells and hydrogen, FCH trains, 2017

High level sizing of UK Market for each Value Chain (VC6)

Results: Centralised electrolyser meeting demand from transport

VC6: Centralised green hydrogen at onshoring point for transport near industrial clusters or ports.

Goal of VC6 is to produce enough hydrogen in a centralised location to power most of the hydrogen-powered road and rail HGVs in GB.

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	6 GW	24 GW
Hydrogen produced	19,000 GWh	84,000 GWh
Hydrogen consumed	19,000 GWh	84,000 GWh
Hydrogen storage need	n/a	n/a
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

Additional outputs

Not applicable.

High level sizing of UK Market for each Value Chain (VC7)

Methodology and Assumptions

Output: How much electrolysis capacity must be installed in decentralised locations to meet hydrogen demand from rail and road transport.

VC7: Decentralised green hydrogen production for use in heavy road and rail transport.

Distributed electrolysers that will be co-located with refuelling stations / transport hubs.

Methodology

1. Calculation: Hydrogen demand for transport (GWh)
Inputs (assumption based):
- Size of hydrogen-powered HGV fleet, and fuel cell efficiency (%).
- Number of hydrogen-powered trains in 2035 and fuel cell efficiency (%).

2. Calculation: Installed electrolysis capacity at decentralised hydrogen refuelling stations. (GW)
Inputs (assumption based):
- Hydrogen demand for transport. (GWh)
- Total electrolyser capacity required at decentralised green hydrogen production point for HGV and train demand. (GW)

Note: VC7 doesn't include lower and upper bounds as per the CCC's 6th Carbon Budget

Assumed inputs

- The efficiency of a hydrogen-powered HGV is estimated at 0.13 kg of hydrogen per mile. HGVs currently drive between 50,000-100-000 miles annually.
- Approximately 9% (1,300) km of the rail network will be used by hydrogen trains by 2035. Hydrogen-powered trains have an efficiency of 0.3 kg of hydrogen per kilometre.

Sources used
- Climate Change Committee 6th Carbon Budget, Electricity generation, 2020
- Fraunhofer ISI, Fuel cell trucks, October 2020
- Fraunhofer ISI, Sustainability and Innovation Working Paper, September 2020
- UK Government, Domestic road freight transport, 2021
- Office of rail and Road, Rail Emissions, 2021
- Fuel Cells and hydrogen, FCH trains, 2017

High level sizing of UK Market for each Value Chain (VC7)

Results: Local HRS meeting demand from transport

VC7: Decentralised green hydrogen production for use in heavy road and rail transport

Goal of VC7 is to produce enough hydrogen in decentralised locations to provide hydrogen to hydrogen-powered road and rail HGVs locally.

Market sizing*

	Lower bound	Upper bound
Electrolyser capacity	200 MW	200 MW
Hydrogen produced	550 GWh	550 GWh
Hydrogen consumed	550 GWh	550 GWh
Hydrogen storage need	n/a	n/a
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

* Lower and upper bounds are the same for VC7

Additional outputs

Not applicable.

Market Sizing: Value Chains

These Value Chains will be ready in the long-term.
Between 2035 and 2050

High level sizing of UK Market for each Value Chain (VC2&3)

Methodology and Assumptions (VC 2&3)

Output: How much electricity supply and hydrogen demand there will be from hydrogen peakers and mid-merit by 2050

VC2: Peaking electricity generation for peaking power (high MWs)

VC3: Mid-merit electricity generation using green hydrogen

Methodology

1. Calculation: Current electricity demand from natural gas

Inputs (assumptions based):

- 2020 electricity plant capacity (MWs)
- 2020 electricity generated (GWh)
- 2020 lead factors (%)

2. Calculation: 2050 electricity supply and hydrogen demand from peakers and mid-merit

Inputs (assumption based):

- CCC Scenarios (6th carbon budget at 2050)
- 90:10 split in GW mid-merit to peakers in 2020; 50:50 split in GW mid-merit to peakers
- 2050 load factor (%)
- Energy generated per year (GWh)
- Hydrogen used per year (GWh)

3. Calculation: Electrolysis required to feed hydrogen electricity generation

Inputs (assumption based):

- GW of electrolysis needed in 2050 at 50%and 98% electrolyser utilisation

4. Calculation: Electricity generation plant required and the electrolysis and storage required to feed them

Inputs (assumption based):

- Peakers and mid-merit generators required (GWh H2)
- Storage requirements for each plant (GWh)
- Electrolysis requirements for each plant (MW)

Key Assumptions:

- CCGTs are mostly mid merit, OCGTs and other thermal are peakers.
- Electricity demand does not account for hydrogen production as this is assumed will come from curtailed electricity.
- No. peakers required at 850MW and 5% load
- No. mid-merit required at 75MW and 0.5% load
- Storage per peaker (GWh): pressure vessel storage, high and low at 1% & 10% of yearly energy use.
- Storage per mid-merit (GWh): geological storage, high and low at 1% & 10% of yearly energy use.

Sources used

- BEIS, DUKES, 2021: dataset
- Climate Change Committee 6th Carbon Budget, Electricity generation, 2020
- BEIS Hydrogen Production Costs, 2021

High level sizing of UK Market for each Value Chain (VC2)

Results: Peaking electricity generation supporting ancillary services & balancing market

VC2: Peaking electricity generation for peaking power (high MWs)

Mostly OCGT

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	220 MW	870 MW
Hydrogen produced	1,564 GWh	3,129 GWh
Hydrogen consumed	n/a	n/a
Hydrogen storage need	16 GWh	31 GWh
Power generation capacity	12,500 MW	25,000 MW
Power generated from hydrogen	n/a	n/a

Additional outputs

MWe	Hours of operation / yr	Days of operation / yr	GWh H2 / yr
75	44	1.8	9.4

Electrolysis Requirements

Tonnes / yr	MW Electrolysis required	MW @50% utilisation
240	1.5	2.9

Storage Requirements

storage (GWh) @1%	storage (GWh) @10%	Storage hrs @1%	Storage hrs @10%
0.09	0.94	0.44	4.4

High level sizing of UK Market for each Value Chain (VC3)

Results: Mid-merit generation supporting ancillary services & balancing market

VC3: Mid-merit electricity generation using green hydrogen

Mostly CCGT

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	1,600 MW	6,100 MW
Hydrogen produced	10,950 GWh	21,900 GWh
Hydrogen consumed	n/a	n/a
Hydrogen storage need	110 GWh	220 GWh
Power generation capacity	12,500 MW	25,000 MW
Power generated from hydrogen	n/a	n/a

Additional outputs

MWe	Hours of operation / yr	Days of operation / yr	GWh H2 / yr
850	440	18	750

Electrolysis Requirements

storage (GWh) @1%	storage (GWh) @10%	Storage hrs @1%	Storage hrs @10%
7.5	74	4.4	44

Storage Requirements

Tonnes / yr	MW Electrolysis required	MW @50% utilisation
19,000	120	230

High level sizing of UK Market for each Value Chain (VC5)

Methodology and Assumptions

Output: How much electrolysis capacity will be installed at renewable sites for curtailment mitigation in 2035, and how much hydrogen do they produce.

VC5: Centralised green hydrogen for curtailment mitigation.

Covers use case of electrolysis for avoiding curtailment of renewable assets (networked and non-networked); curtailment may occur due to electricity supply/demand imbalances and network constraints.

Methodology

1. Calculation: Capacity of electrolysers installed at renewable generation plants. (MW)

Inputs (assumption based):

- Installed capacity of offshore wind, onshore wind and solar (utility scale) generation plants in 2035. (MW)
- Uptake of electrolysers at offshore wind, onshore wind and solar (utility scale) generation plants. (%)
- Size of electrolysers relative to renewable station capacity. (%)

2. Calculation: Hydrogen produced at renewable generation sites. (GWh)

Inputs (assumption based):

- Utilisation for electrolysis at renewable generation sites. (%)
- Electrolyser efficiency (kWh / kg H2)

3. Calculation: Hydrogen storage estimated at different renewable / electrolyser asset sizes.

Input (assumption based):

- Storage requirement (% of H2 produced)

Key assumptions

- Expect to see higher uptake of electrolysis for curtailment mitigation at offshore wind sites, compared with onshore wind and solar. Assume that due to the higher capacity factors of offshore wind, the likelihood of curtailment will be higher, which leads to more electrolysers being installed.
- Expect to see size of electrolysers at offshore wind sites to be larger, compared with onshore wind and solar. Assume that due to the higher capacity factors of offshore wind, the scale of curtailment will be higher, which leads to larger electrolysers being installed.
- Installed capacity from renewable stations in 2035: Offshore – 30,000MW, Onshore – 19,000MW, Solar – 25,000MW
- Size of electrolysers relative to renewable station capacity: Offshore – 20-30%, Onshore – 10-20%, Solar – 5-10%
- Electrolyser efficiency: 50 kWh per kg of H2
- Electrolyser utilisation: 25%

Sources used

- Pathways for the GB Electricity Sector to 2030, Investment in large-scale generation capacity, PP. 84-97
- Aurora, Reaching the UK Government's target of 40GW of offshore wind by 2030 will require almost £50BN in investment, 2020
- BEIS, Modelling 2050: Electricity system analysis, 2020
- Energy Numbers, UK offshore wind capacity factors, 2022
- BEIS, DUKES: renewable sources of energy chapter 6, 2021
- BEIS, Hydrogen productions Costs 2021

High level sizing of UK Market for each Value Chain (VC5)

Results: Curtailment of renewable assets avoided

VC5: Centralised green hydrogen for curtailment mitigation.

Goal of VC5 is to reduce curtailment so no hydrogen is consumed or stored. Hydrogen produced could have multiple storage/distribution/ end uses, partly dependent on FES.

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	800 MW	6,000 MW
Hydrogen produced	1,300 GWh	11,000 GWh
Hydrogen consumed	n/a	n/a
Hydrogen storage need	n/a	n/a
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

Additional outputs: Storage requirements at different renewable sites

Storage requirements	Geological storage (GWh) @1% H2 stored	Geological storage (GWh) @10% H2 stored
1.5GW renewable sites with 300MW electrolyser	5.2	52
1GW renewable sites with 200MW electrolyser	3.5	35
500MW renewable sites with 100MW electrolyser	1.7	17
100MW renewable sites with 20MW electrolyser	0.4*	4*

* Will likely not require geological storage

High level sizing of UK Market for each Value Chain (VC9)

Methodology and Assumptions

Output: How much hydrogen can be produced in 2050 using bioenergy when supplying for a steady demand of hydrogen.

VC9: Hydrogen production from bioenergy with carbon capture and storage (BECCS), for use in industrial applications

Hydrogen production from bioenergy for steady demand, like industry or heat.

Methodology

1. Calculation: Hydrogen production from bioenergy plant (GWh/year)
Inputs (assumption based):
- Plant size (MW)
- Plant efficiency (%)
- Plan utilisation (%)
- Split of waste-using plants (50%) and bulk biomass plants (50%)

2. Calculation: Number of plants needed to meet hydrogen demand
Inputs (assumption based):
- Hydrogen supply from five different biomass processes out to 2050 (TWh/year)
- Bioenergy demand (TWh)

3. Calculation: Storage capacity required (GWh)
Input (assumption based):
- Plant annual hydrogen production

Assumed inputs

- Plant efficiency and size are given by BEIS in their hydrogen production costs 2021. In 2050, a 59 MW biomass plant has an efficiency of 67%, while a 473 MW plant has an efficiency of 70%. Efficiency is affected by whether syngas produced in the biomass gasification process is used to generate electricity, or whether electricity imported from the grid is used.
- Biomass demand has been forecast to 2050 in five scenarios by the Committee for Climate Change(CCC), and four by National Grid. The CCC has separated demand into 10 sectors, including electricity supply, residential buildings, surface transport and aviation.
- Biomass supply was forecast by the CCC and by National Grid. The CCC separated supply into 10 sectors, including forest residues and energy crops.
- Using the CCC's Balanced Pathway scenario, in 2050 16 Mt of CO2 would be captured for hydrogen production, and 13 Mt for electricity supply.

Sources used

- ECOFYS, Bioenergy heat pathways to 2050, Rapid evidence assessment summary report, 2018
- IEA Bioenergy, Hydrogen from biomass gasification, 2018
- kew projects, kew H2: zero-carbon bulk supply, 2019
- BEIS, Hydrogen productions Costs 2021
- Climate Change Committee 6th Carbon Budget, Surface Transport, 2020

High level sizing of UK Market for each Value Chain (VC9)

Results: Geological storage required for biomass hydrogen

VC9: Hydrogen production from bioenergy with carbon capture and storage (BECCS), for use in industrial applications

Goal of VC9 is to determine the production capacity of BECCS when providing hydrogen to a steady demand.

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	n/a	n/a
Hydrogen produced	320 GWh	2,600 GWh
Hydrogen consumed	n/a	n/a
Hydrogen storage need	29 GWh	240 GWh
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

Additional outputs

Hydrogen supply in 2050 depends on CCC scenarios

- In Widespread Innovation, Biomass + CCS produces 21 TWh of hydrogen per year.
- In Tailwinds, Biomass + CCS produces 63 TWh of hydrogen per year.
- The CCC has three other scenarios where bioenergy and hydrogen play a minor role.

Storage required depends on the plant capacity

- A 59 MW biomass hydrogen plant requires 29 GWh of hydrogen storage, while a 473 MW plant requires 240 GWh of hydrogen storage.
- Hydrogen storage would need to be geological, in salt caverns or depleted oil fields.

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High level sizing of UK Market for each Value Chain (VC10)

Methodology and Assumptions

VC10: Centralised green hydrogen production for industrial use in a cluster

This value chain requires geological storage located close enough to the industrial cluster to be viable.

Output: What is the electrolyser capacity needed to meet demand from an industrial cluster previously met by blue hydrogen production plants.

Methodology

1. Calculation: Total electrolysis needed to match blue hydrogen production in 2050 (GW)
Inputs (assumption based):

- Electrolyser utilisation
- Electrolyser efficiency (%)
- Plan utilisation (%)
- Industrial hydrogen demand (TWh)

2. Calculation: Total storage needed for electrolysers to match blue hydrogen production in 2050 (GWh)
Inputs (assumption based):

- Industrial hydrogen demand (TWh)
- Electrolyser utilisation (%)

Assumed inputs

- Electrolysers in this value chain must balance blue hydrogen production. We used production capacity, utilisation and efficiency rates of blue hydrogen production plants (SMR, ATR, ATR GHR, and other EU blue hydrogen production plants) to estimate the blue hydrogen production in 2050, and set it as the goal for this value chain. Using different utilisation and efficiency rates from electrolysers in 2050, as forecast in BEIS Hydrogen Production Costs, we estimated minimum and maximum electrolyser capacity.
- In its Hydrogen Strategy, BEIS forecast the total industry demand for hydrogen between 25-105 TWh in 2050.
- Hydrogen storage is key in this value chain to decouple potentially intermittent production from industrial output. We estimated total storage needed using the total industry demand for hydrogen in 2050, as forecast by BEIS, and electrolyser utilisation rates. This storage volume enables electrolysers to meet the demand from the industrial cluster.

Sources used

- BEIS, Hydrogen productions Costs 2021
- Eurofer, Map of EU steel production sites
- European Parliament, The potential of hydrogen for decarbonising steel production, 2020

High level sizing of UK Market for each Value Chain (VC10)

Results: Storage required for green hydrogen to match blue

VC10: Centralised green hydrogen production for industrial use in a cluster

Goal of VC10 is to use electrolysis to match the production from blue hydrogen plants, and meet the demand from industrial clusters.

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	3 GW	32 GW
Hydrogen produced	25,000 GWh	105,000 GWh
Hydrogen consumed	25,000 GWh	110,000 GWh
Hydrogen storage need	500 GWh	54,000 GWh*
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

Additional outputs

Not applicable.

*This assumes constant industrial output. In this case, industrial demand would be high and met solely by green hydrogen. Increases in electrolyser efficiency would be minimal and electrolysers would operate at an average utilisation of 0.5 annually (worst case scenario).

High level sizing of UK Market for each Value Chain (VC11)

Methodology and Assumptions

VC11: Centralised marine electrolysis piped back from offshore wind (floating or fixed)

Electrolysers serving many turbines on a central offshore platform to move wind power back to shore - entry to network or large scale storage.

Output: How much hydrogen can be produced offshore using wind power and marine electrolysis, to then be piped back to shore.

Methodology

1. Calculation: Total renewable electrolysis capacity using offshore wind in 2050 (GW)

Inputs (assumption based):

- Offshore wind capacity in 2050 (GW)
- Share of offshore wind used for hydrogen production (%)
- Number of offshore wind turbines (fixed and floating) dedicated to hydrogen

2. Calculation: Storage needed in 2050 (GWh)

Inputs (assumption based):

- Annual hydrogen production using offshore wind (GWh)
- Size of storage required (%)

Assumed inputs

- We used the CCC's 6th Carbon Budget's offshore wind power estimates in our market sizing. Offshore wind is set to produce between 65-140 GW (with 245 GW being the theoretical maximum capacity for UK offshore wind*) of power, most of it coming from fixed turbines.
- Approximately 10-20% of the power generated by floating turbines and 1-5% by fixed turbines would be used for marine electrolysis. This leads to 0.6-12 GW of floating marine electrolysis and 0.2-1.2 GW of fixed marine electrolysis.
- We used the Dolphyn Project's marine electrolysis plant utilisation rate (0.5) and efficiency (80%) to determine the annual total hydrogen production from marine electrolysis.
- To meet demand, we estimated storage had to be at least 10% of total hydrogen production, that is between 280-4,600 GWh.

Sources used

- Committee on Climate Change 6th Carbon Budget, Surface Transport, 2020
- BEIS, Dolphyn Hydrogen, Phase 1 final report, 2019
- RECHARGE, inside the all-Siemens push for the hydrogen wind turbine, 2021
- ORE Catapult, Floating Offshore Wind: Cost reduction pathways to subsidy free, 2021
- Interreg North Sea Region, Future Energy Industry Trends

High level sizing of UK Market for each Value Chain (VC11)

Results: Storage required for viable marine electrolysis

VC11: Centralised marine electrolysis piped back from offshore wind (floating or fixed)

Goal of VC11 is to use offshore wind power to produce hydrogen using marine electrolysis, and bring hydrogen back to shore in pipes, rather than electricity. This eventually saves on costs, as piping hydrogen over long distances is cheaper than transporting electricity.

Market sizing

	Lower bound	Upper bound
Electrolyser capacity	1 GW	13 GW
Hydrogen produced	2,800 GWh	46,000 GWh
Hydrogen consumed	n/a	n/a
Hydrogen storage need	280 GWh	4,600 GWh
Power generation capacity	n/a	n/a
Power generated from hydrogen	n/a	n/a

Additional outputs

Not applicable.

Expert Workshop: Results and Analysis

Analysis of the themes drawn out during the expert workshop on Value Chains, organised after conducting interviews.

Workshop analysis (1/5)

Hydrogen pipeline network

Echoing the findings in our interviews, the debate is more on the scale of the hydrogen pipeline network rather than on its presence/existence.

It is economically viable to transport hydrogen in tube trailers for distances under 50 miles. For longer distances, a hydrogen pipeline network is more suitable.

The development of a large-scale hydrogen pipeline network will depend on the value of the electricity produced using hydrogen.

- If the electricity generated from hydrogen is necessary to meet power demand, it'll warrant the development of a **large-scale pipeline network** for hydrogen.
- If power demand can be met by other sources, a **large-scale pipeline network** for hydrogen won't be required and investments will go into other areas.

In scenarios where a nationwide hydrogen network is not required, a smaller scale pipeline may emerge as an alternative.

- To use hydrogen for curtailment mitigation (VC5), a **small-scale hydrogen network** would be required to connect electrolysers.
- To use hydrogen in small-scale peaking plants, a more **localised hydrogen network** would be required to distribute hydrogen to each peaking plant (VC2+3).
- Transporting hydrogen to local HRS (VC7) would require a **localised hydrogen network**.
- As the electricity grid decarbonises, nuclear power will face more competition from renewables (VC4). To avoid curtailing nuclear power, which would be expensive, nuclear plants can continue to provide baseload power, with any surplus being used to produce hydrogen that is sent onto a **small-scale pipeline network**.

Workshop analysis (2/5)

Asset location and using renewables to produce electricity or hydrogen

Half of the experts agreed transporting energy as hydrogen would be more economic than as electricity. Other experts didn't express any opposition.

The location of assets has a direct impact on the system efficiency and responsiveness. Electrolysers need to be located strategically to ensure system frequency is maintained at 50Hz.

- **Distributed hydrogen power generation** would require a hydrogen pipe network, and lead to a well-balanced electricity grid.
- With no hydrogen network connecting electrolysers, a pipeline would still be required to store hydrogen produced by intermittent renewables, for it to then be used for power generation when needed (P2G2P).
- Echoing our interview findings, where hydrogen is produced for transport applications, **production and distribution should be co-located** (VC7). Implied, is the need for a hydrogen pipe network.
- With green electricity costs reducing by 2050, half the experts thought there would be more value in using **renewable electricity to produce hydrogen** than exporting to the grid. None of the other experts expressed any opposition to this statement. This is due to the market for hydrogen expanding more than the market for green electricity, as hydrogen can be used for power generation alongside other end uses (e.g. shipping, aviation or industry).
- Instead of sending electricity to more remote areas using the transmission network, half of the attendees agreed hydrogen would be a more effective way to carry energy, even when considering the efficiency losses associated with P2G2P.
- On very constrained electricity grids such as between North and South, **transporting energy as hydrogen** gas is much more efficient.

Workshop analysis (3/5)

Technologies to consider

SOEC, PEM and thermochemical processes are still in development to reach commercial or industrial scale, but promise major efficiency benefits out to 2050.

In the short-term, the heat source for SOEC electrolysers is a challenge, as it usually comes from fossil fuels. However, out to 2050, fossil fuels will have been replaced by other processes.

A number of hydrogen-related technologies are to be taken into account when thinking of the hydrogen market in 2050.

- **SOEC electrolysers** would be most appropriate for use in an **industrial cluster**, as they achieve better results by off-taking heat.
- **PEM electrolysers** would be better suited for providing **demand-side flexibility**.
- Digital services will be required to support the management of a decentralised production and distribution (VC7).
- Thermochemical processes and other non-electrolytic technologies can achieve very good efficiencies.

Nuclear could play a distinct role from renewables.

- Nuclear power stations would produce hydrogen at steady output which would match demand from a nearby industry or cluster. As a result, there would be no need for hydrogen storage.
- As the electricity grid decarbonises, nuclear electricity will increasingly face competition from renewables and be less price competitive. Nuclear power stations additionally offer heat-offtake that can be used for hydrogen production.

Workshop analysis (4/5)

Competitors to hydrogen and the role of storage

Batteries could compete with hydrogen on storage. But hydrogen power generation will have little competition.

Hydrogen is unique in the energy supply chain as it can provide inter-seasonal storage and power generation. We envisage low competition from other technologies.

- **Batteries** would be the main competitor to hydrogen on energy storage. Although battery technology has improved over time, long-term inter-seasonal storage would still favour hydrogen (as confirmed in our interviews).
- Hydrogen power generation will have little competition:
  - Unabated fossil power generation won't be an option due to the need to decarbonise by 2035.
  - Hydrogen power generation will focus on plugging the gap that nuclear and renewables can't meet (peaking and mid-merit).

Storage solutions are key to limit the intermittency of renewables and maintain steady supply despite low volumes of wind or sun.

- **Large hydrogen stores** are required for hydrogen to respond to a clear demand.
- When hydrogen is meeting a large, steady demand such as an industrial cluster, storage is not always necessary. For example, in the case of nuclear production of hydrogen, production can match demand (VC4), while the potential surplus can be sent onto the hydrogen pipeline network. The hydrogen gas network will still need to be kept at suitable pressure, and depending on surplus volume, storage may still be required.

Workshop analysis (5/5)

Hydrogen purity

In the end, purity is purely an economic question: the technology is readily available, but how does it fit into an attractive business model/proposition?

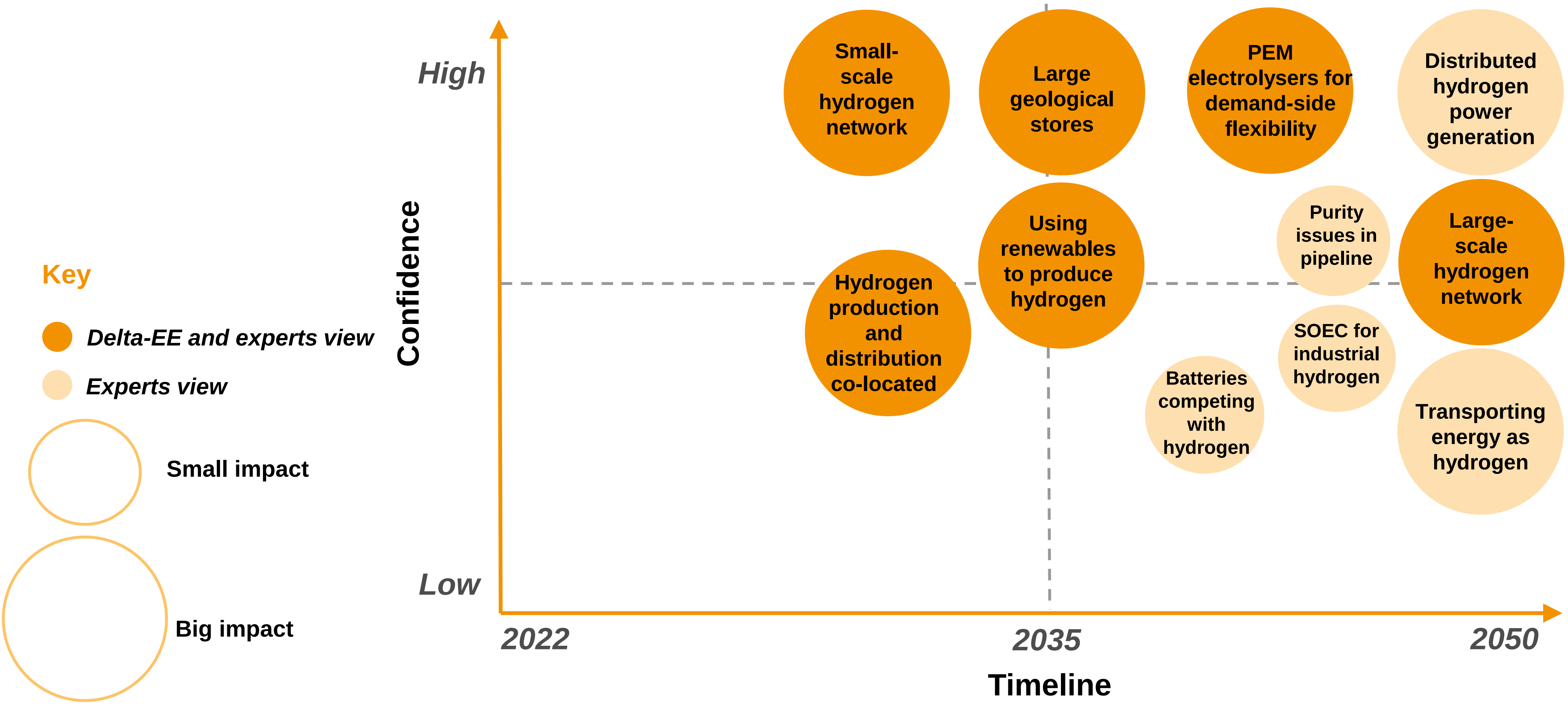
Purity depends on the distribution methods.

- If the production unit is 10-100 metres away from dispensing unit, purification can be engineered to the process to deliver required purity levels.
- If the production unit feeds directly into a nationwide pipeline network, it'll need to be **purified** at every outlet where it'll be used by fuel cells. This is technically feasible but perhaps not always economically viable.

- Depends on storage:
  - As green hydrogen travels through large infrastructure (pipeline, geological storage), it is more likely to be blended with hydrogen from other sources (blue, grey, pink) which will reduce overall purity.
    - If stored geologically, hydrogen will need to be purified for some applications e.g. transport.
    - If stored in LOHCs, tube trailers or metal hybrids, purification can be avoided.
- Depends on end-use:
  - In an industrial cluster, there might be a 10:1 usage ratio between industry and transport. Industry and transport may require different purity levels.
  - Long term transport demand is likely to be less than industrial, but it's higher value could lead to significant initial demand.

Key themes drawn out from expert workshop

Confidence is high across key themes, as experts tended to agree rather than disagree on value chains and developments out to 2050.



Identifying interactions within the electricity system (1/3)

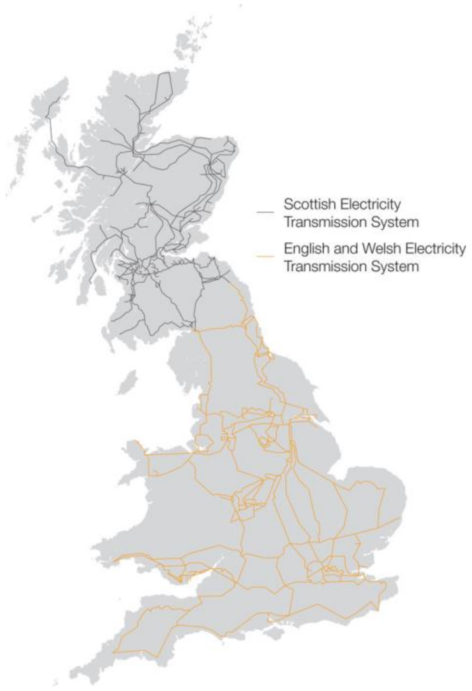
National Grid’s three roles

Electricity System Operator (ESO)

The ESO manages supply and demand of electricity on an hourly/daily basis to maximise efficiency and avoid supply interruptions. It is also responsible for the security of the power system.

Electricity Transmission Operator

The electricity TO is responsible for the infrastructure needed to transport electricity. These include high-voltage pylons and lines, underground cables, substations, and interconnectors.



Gas Transmission Operator

The gas TO is responsible for the infrastructure needed to transport gas. These include gas pipelines and compressor stations.

Identifying interactions within the electricity system (2/3)

Hydrogen use cases

Electrolysis is the only hydrogen production method that requires electricity. Alternatively, hydrogen can be produced using biomass or natural gas with CCUS.

Hydrogen for heat

Hydrogen can be used to replace natural gas in heating domestic and commercial buildings. Iron mains need to be replaced to enable 100% hydrogen transportation, and boilers must be updated to run on pure hydrogen.

System Transformation
Leading the Way

Hydrogen storage

Hydrogen can be stored in liquefied or gaseous form in storage tanks or underground salt caverns. The storage solution depends on the duration of storage needed. Stored hydrogen can then be used to meet either hydrogen, heating or power demand.

System Transformation
Consumer Transformation
Leading the Way

Power generation

Hydrogen can be used to generate electricity using a gas (hydrogen) turbine, or a fuel-cell. The generation method used depends on the scale of power needed.

Consumer Transformation

Identifying interactions within the electricity system (3/3)

National Grid – 3 different roles

Hydrogen generation will use excess renewable electricity. Hydrogen can be stored to meet energy demand at later time of a day or year. This includes power generation using hydrogen in CCGTs/OCGTs, gas engines or fuel cells.

Use of Hydrogen	Electricity System Operator	Electricity Transmission Operator	Gas Transmission Operator
Hydrogen for heat	No interaction. Only benefit is that in a scenario with high uptake of hydrogen for heat, the electric load related to heating is lower than in a full electrification scenario.	No interaction.	Assuming the existing gas network is converted to transport hydrogen, National Grid GTO will transport large quantities of hydrogen throughout the country. If a new hydrogen network is to be built, National grid GTO needs to invest in deployment and installation.
Hydrogen storage	At times of excess renewable supply, ESO can store clean hydrogen to provide flexibility to the grid later. Depending on the solution chosen, hydrogen storage can be used for inter-seasonal storage to prevent power shortages at times of low renewable generation.	Transmission works may be required to connect hydrogen peaker and mid-merit power plants to the grid in the case of new build (rather than refurbished plants).	The gas distribution/transmission must develop the appropriate infrastructure to transport and store hydrogen between production, storage and end use facilities, including power generation sites.
Power generation	Stored hydrogen can used by H2 gas power plants during demand peaks. It is important to create a market connection between the storage system and generation to meet ESO demands and to function as an efficient and responsive system.	Transmission system needs to connect power generators whose location may be determined by other factors such as storage, and therefore the H2 infrastructure drives the transmission requirements.	Interaction dependent on future of gas networks. Storage facilities for electrolysers are likely to be located close to renewable power sources or power plants close on the electricity network. However, hydrogen may need to be aggregated from smaller suppliers over a gas network.

Defining interactions and Methodology

This section explores how the Value Chains will impact the electricity system

Defining Electricity System Interactions Ancillary/Flex

The analysis considered different ancillary services available now to consider the potential ability for electrolysis /power generation to provide flex response of different speeds /durations.

We have considered the different ancillary services as they operate currently. This will involve electrolysers or power generation using hydrogen either turning up or down depending on requirement. However, we anticipate the different ancillary/flex services will change over time out to 2050.

Fast-acting ancillary service: Short duration with automatic activation

a) **Frequency containment reserve (FCR)** – Potential for VC’s to act as primary reserve. Typical response speed: 0-30 seconds. Duration - 15 min per incident

b) **Automatic frequency restoration reserve (aFRR)** – Potential for VC’s to act as secondary reserve. Typical response speed: 30 seconds to 5 minutes. Duration – at least 15 min.

“Slow” ancillary services: Manual activation with commitment ahead of time, respond when asked

a) **Manual frequency restoration reserve (mFRR)** – Potential for VC’s to act as tertiary reserve. Typical response speed: 5-15 minutes. Duration – 1h30 maximum

b) **b) Replacement Reserve (RR)** – Potential for VC’s to take over from aFRR and mFRR during major events (so the assets can deactivate). Typical response speed: 15-30 minutes. Duration – at least 2h.

Market Trading

- **Balancing Market** – Potential for VC’s to engage in day ahead/intra day trading. Response speed: 30 minutes. Duration – at least 30 min
- **Spot Wholesale Market Trading** – Potential for VC’s to engage in day ahead/intra day trading. Participants to be ready in 60 minutes. Duration – at least 30 min
- **Capacity Market (CM)** – Potential for VC’s to engage with long-term commitment to provide ancillary service which is more likely to be seasonal. Participants to be ready in 4 hour notice. Duration – at least 30 min

Methodology to Assess Value Chain Impacts 1/3

Analysis – Phase 1

The 10 VC's have been analysed using the following criteria to determine which VCs have the potential to engage with each interaction.

Step 1

Consideration of all the potential **interactions** between the hydrogen and the electricity network resulted in the following categories:

- **Supply/Demand of electricity** – to determine how the VC will primarily interact with the network.
- **Ancillary/flex mechanisms** – further details of these on the previous slide
- **Load shifting** – both short-term (inter/intra day) and long-term (seasonal)
- **Constraint management** – at both the DSO and TSO level

In Step 2, each VC will be analysed in relation to the interactions above, using data specific to the VC which is relevant to the interaction. This are determined by whether or not the VC includes:

- **Electrolysis**
- **Storage**
- **Power generation**

Step 2

Supply/Demand:

- Electrolysis – Demand driven, as uses electricity
- Power generation – Supply driven, as generates electricity

Ancillary/flex mechanisms:

- Electrolysis – potential to turn electrolyser up/down to use more/less electricity
- Power generation – potential to turn up/down and generate more/less electricity from hydrogen

Load shifting:

- Electrolysis – potential to move peaks in demand on request
- Storage – potential to provide additional fuel to smooth peaks in demand on request

Constraint management:

- Electrolysis – potential to reduce demand at times of constraint on request
- Storage – potential to provide additional fuel to generate more power on request
- Power generation – potential to up/down and generate more/less electricity from hydrogen on request

Methodology to Assess Value Chain Impacts 2/3

Flow Diagram

Phase 1

Step 1: **Interactions between hydrogen and the electricity network**

- Supply/Demand of electricity
- Ancillary/flex mechanisms
- Load shifting
- Constraint management

Step 2: **Each VC's contains specific assets which are to relevant to different interactions.**

- Electrolysis
- Storage
- Power generation

Supply/Demand:
- Electrolysis
- Power generation

Ancillary/flex mechanisms:
- Electrolysis
- Power generation

Load shifting:
- Electrolysis
- Storage

Constraint management:
- Electrolysis
- Storage
- Power generation

Outputs: Tables showing Yes/No for which VC's will engage with which interactions

Phase 2

Step 3: **Using market sizing data, analysis of each VC capacity (MW)**

- Total capacity of electrolysis
- Total storage capacity
- Total power generation capacity

Step 4: **VC's analysed to assess % availability for each VC for each interaction.**

Technical Capability (%): What percentage of the asset's capacity is used within the VC

Variation Capability (%): What percentage of the asset's capacity could be changed

Calculation for each VC consists of multiplying Capacity (MW) by Technical % by Variation %

Results will be non-additive, so **interactions between VC's are not considered inter-dependently**.

Results provide total potential availability for each interaction

Outputs: Charts showing capacity (MW) available from each VC for each interaction. Also cumulated by FES

Methodology to Assess Value Chain Impacts 3/3

Analysis – Phase 2

Following Phase 1, the 10 VC's have been further analysed using the market sizing data to determine size of impact.

Step 1

Using the market sizing data, an in-depth analysis of each VC was undertaken. The key pieces of information for each VC considered are:

- Total capacity of **electrolysis**
- Total **storage** capacity
- Total **power generation** capacity

The market sizing includes a low and high range, therefore a Low Analysis and High Analysis has been conducted to consider the impacts of both.

The market sizing provides the total capacity within the VC but the total capacity will not be available for the interaction. For example, a VC may state 100MW of capacity for an asset, but in practice only 10MW is available at any given time.

Step 2

Following the determinisation of whether or not a VC will engage with a given interaction, the VC's will be analysed in further detail. This involves assessing the % of availability from each VC for each interaction.

To do this two questions were considered:

- **Technical Capability**: What percentage of the asset's capacity is used within the VC, for example the utilisation rating of an electrolyser
- **Variation Capability**: What percentage of the asset's capacity could be changed, for example percentage that could be available for flex/ancillary services.

Step 3

Results will be non-additive, **so interactions between VC's and interactions are not considered inter-dependently.**

The results will be linked back to FES to provide a total potential availability for each interaction within each FES, for both a Low Analysis and a High Analysis.

Value Chain Impacts: Phase 1

This section shows the results of the Phase 1 analysis, to determine which Value Chains have a role within the different parts of the electricity system.

Value Chain Impacts and Interactions 1/3

How hydrogen can provide flex from electrolysis

Table shows VC's which include green hydrogen production and have the potential for electrolysers to be turned up/down as required.

Inclusion within a flex mechanism/ market is determined by VC's technical specification and end use.

VC's which use electricity for electrolysis and can engage with Flex/ancillary services* by turning up/down through a grid connection. This is the same for both High and Low Analysis.

No.	Value chain description	FCR	aFRR	mFRR	RR	Capacity Market	Balancing Market	Spot Trading
VC4	Centralised nuclear hydrogen for injection into hydrogen networks	No	No	No	Yes	Yes	Yes	Yes
VC5	Electrolysis for curtailment mitigation	No	No	No	Yes	Yes	Yes	Yes
VC6	Centralised green hydrogen at onshoring point for transport near industrial clusters or ports	Yes	Yes	Yes	Yes	Yes	Yes	Yes
VC7	Decentralised green hydrogen production for use in heavy road and rail transport	Yes	Yes	Yes	Yes	Yes	Yes	Yes
VC10	Centralised green hydrogen production for industrial use in a cluster	No	Yes	No	Yes	Yes	No	No

VC11: Centralised marine electrolysis piped back from offshore wind (floating or fixed).
This VC has been deliberately excluded as it has no grid connection so will not engage directly with the electricity system

*Ancillary services given here represent speed/duration of response required by electrolysers, with the anticipation that exact requirements will change in the future.

Value Chain Impacts and Interactions 2/3

How hydrogen can provide flex from power generation

Table shows VC's which include electricity generation using hydrogen and have the potential for fuel cells/turbines or engines to be turned up/down as required.

Inclusion within a flex mechanism/ market is determined by VC's technical specification and end use.

VC's which generate electricity using hydrogen as a fuel and can engage with Flex/ancillary services by turning up/down. This is the same for both High and Low Analysis.

No.	Value chain description	FCR	aFRR	mFRR	RR	Capacity Market	Balancing Market	Spot Trading
VC2	Peaking electricity generation for peaking power (high MWs)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
VC3	Mid-merit electricity generation using green hydrogen	No	No	Yes	Yes	Yes	Yes	Yes

VC1: Centralised blue hydrogen production for industry provision and early hydrogen network injection.
VC9: Hydrogen production from bioenergy with carbon capture and storage (BECCS).

These two VC's do not use or generate electricity as all hydrogen is for industrial purposes with a small amount going into the gas grid.

Value Chain Impacts and Interactions 3/3

VC's by FES

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Table shows which Value Chains have been included within which FES scenarios in the following analysis.

The team determined that the majority of VCs were applicable to CT, ST and LW, but very few were likely to appear in SP.

No.	Value chains	Consumer Transformation	System Transformation	Leading the Way	Steady Progress
VC1	Centralised blue hydrogen production for industry	Yes	Yes	Yes	Yes
VC2	Peaking electricity generation for peaking power (high MWs)	Yes	Yes	Yes	No
VC3	Mid-merit electricity generation using green hydrogen	Yes	Yes	Yes	No
VC4	Centralised nuclear hydrogen for injection into hydrogen networks	Yes	Yes	Yes	No
VC5	Electrolysis for curtailment mitigation	Yes	No	Yes	No
VC6	Centralised green hydrogen at onshoring point for transport near industrial clusters or ports	Yes	Yes	Yes	No
VC7	Decentralised green hydrogen production for use in heavy road and rail transport	Yes	Yes	Yes	No
VC9	Hydrogen production from bioenergy with CCS (BECCS), for industry	Yes	Yes	Yes	No
VC10	Centralised green hydrogen production for industrial use in a cluster	Yes	Yes	Yes	Yes
VC11	Centralised marine electrolysis piped back from offshore wind	Yes	Yes	Yes	No

As per slide 10 above, VC8: Electrolysis for frequency ancillary services, has been excluded

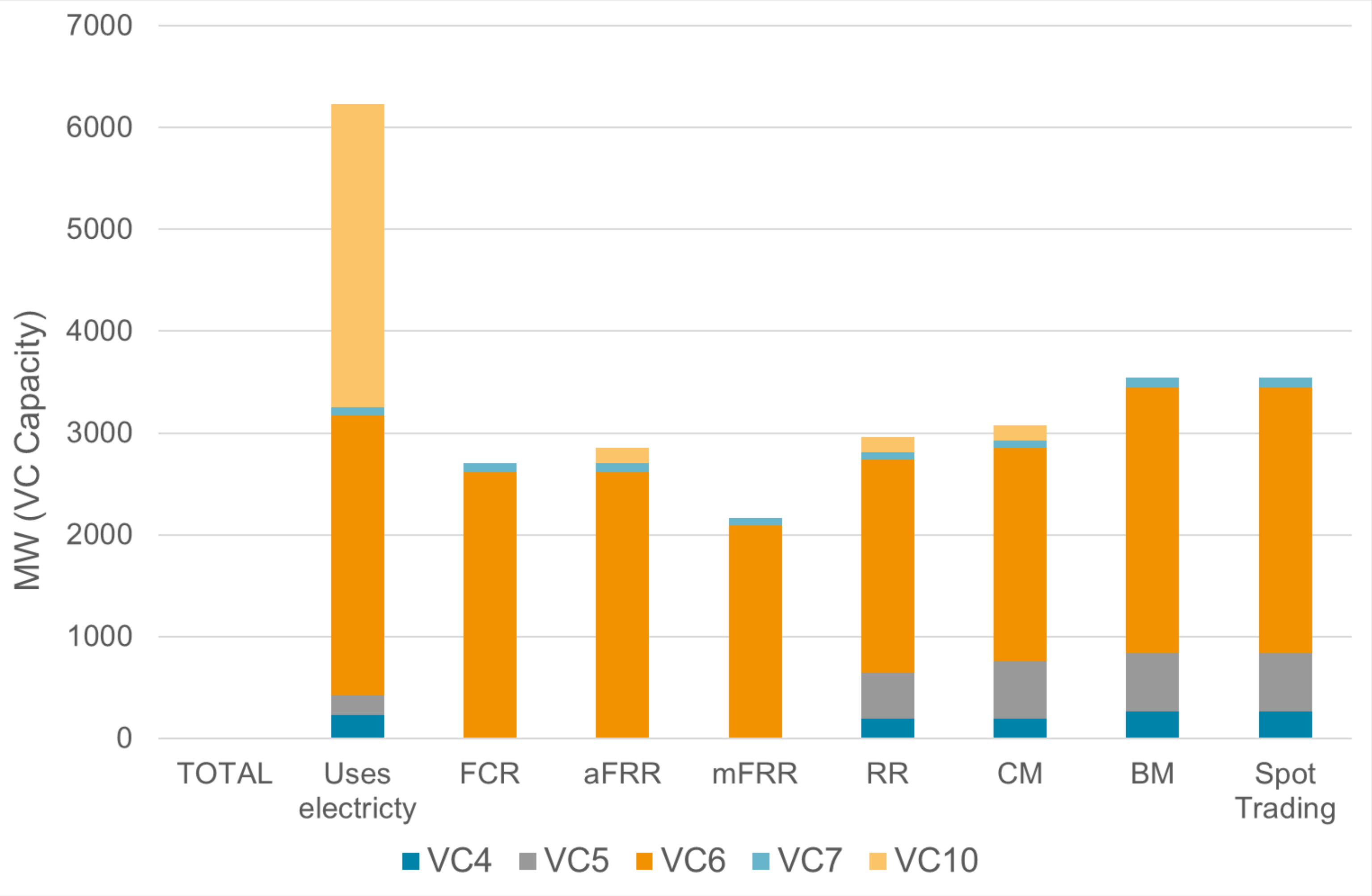
Electrolyser Value Chain Impacts: Phase 2

This section shows the results of the Phase 2 analysis, to determine the scale of the electrolyser VCs impact within the electricity system.

Results: Electrolysis VCs – ancillary/flex impacts 1/5

Low Analysis : Total impact to electricity network by VC

VC10 is green hydrogen for industry and in the low scenario is one of the highest users of electricity due to the high demand for hydrogen. Conversely, VC10 provides very little in terms of flex/ancillary services, as a continuously high utilisation rate is required that prioritises hydrogen production.



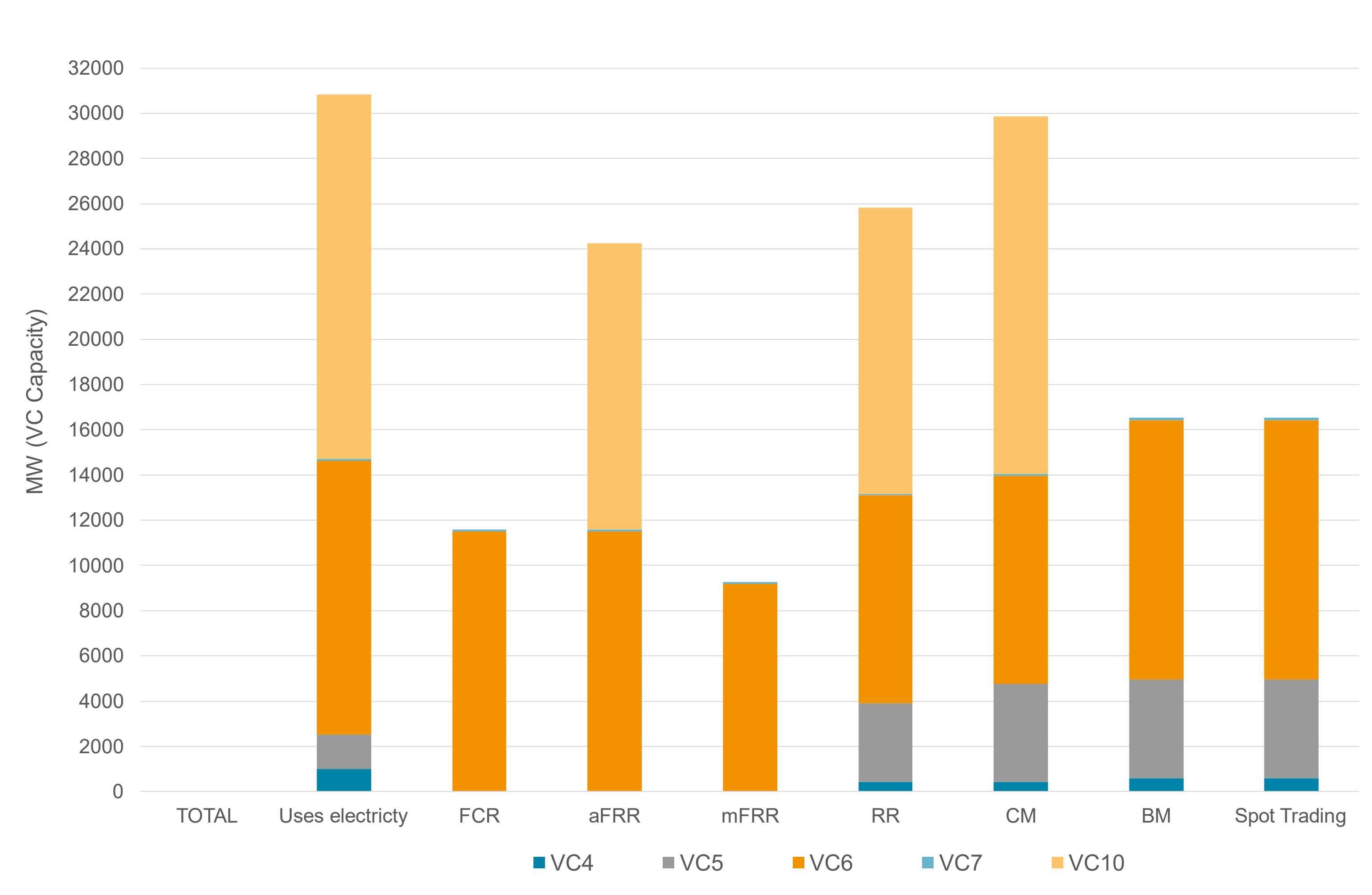
VC6 is centralised electrolysis from offshore wind power with an end use in transport. This VC has one of the largest total electrolysis capacities and offers the most flex potential across all ancillary services.

VC5 is electrolysis for curtailment and offers the second highest capacity.

Results: Electrolysis VCs – ancillary/flex impacts 2/5

High Analysis : Total impact to electricity network by VC

In the high analysis, VC10 is still proportionally one of the highest users of electricity. However, VC10 offers much more in terms of flex/ancillary services in the high analysis due to oversized electrolysers meaning the large quantities of hydrogen required for industry continue to be produced despite a lower overall utilisation rate.



VC6 offers a similar proportion of flex in the high scenario, although the total capacity is much higher. VC10 offers more than VC6 on aFRR, RR and CM but does not engage with other services where VC6 dominates, as it does in the low analysis.

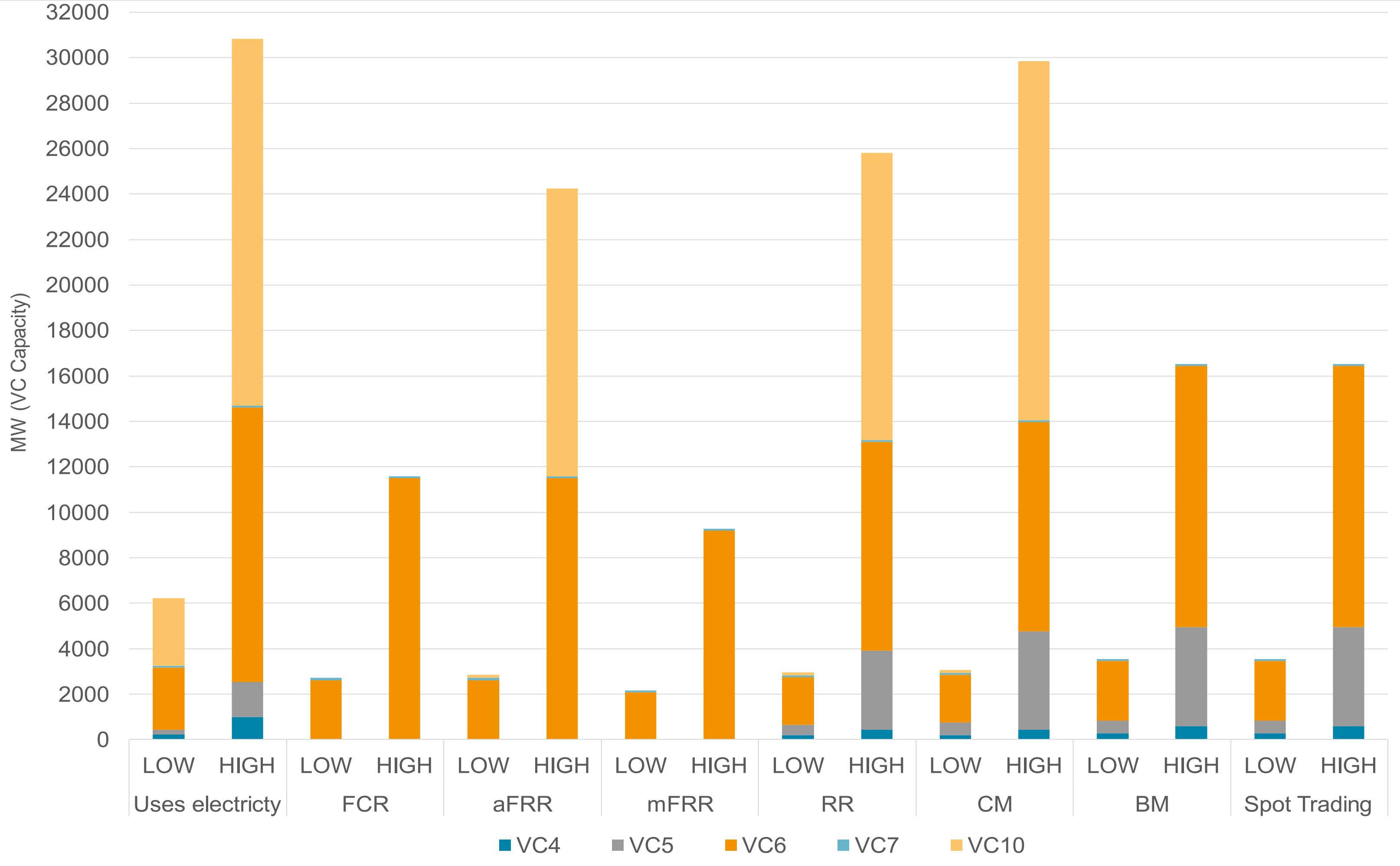
VC5 still offers the second highest capacity across the different services.

Results: Electrolysis VCs – ancillary/flex impacts 3/5

High and Low Analysis: Total impact to electricity network by VC

This chart highlights the different capacities offered between the low and high analyses.

The total size of the hydrogen market will significantly affect the total flex/ancillary capacity available.



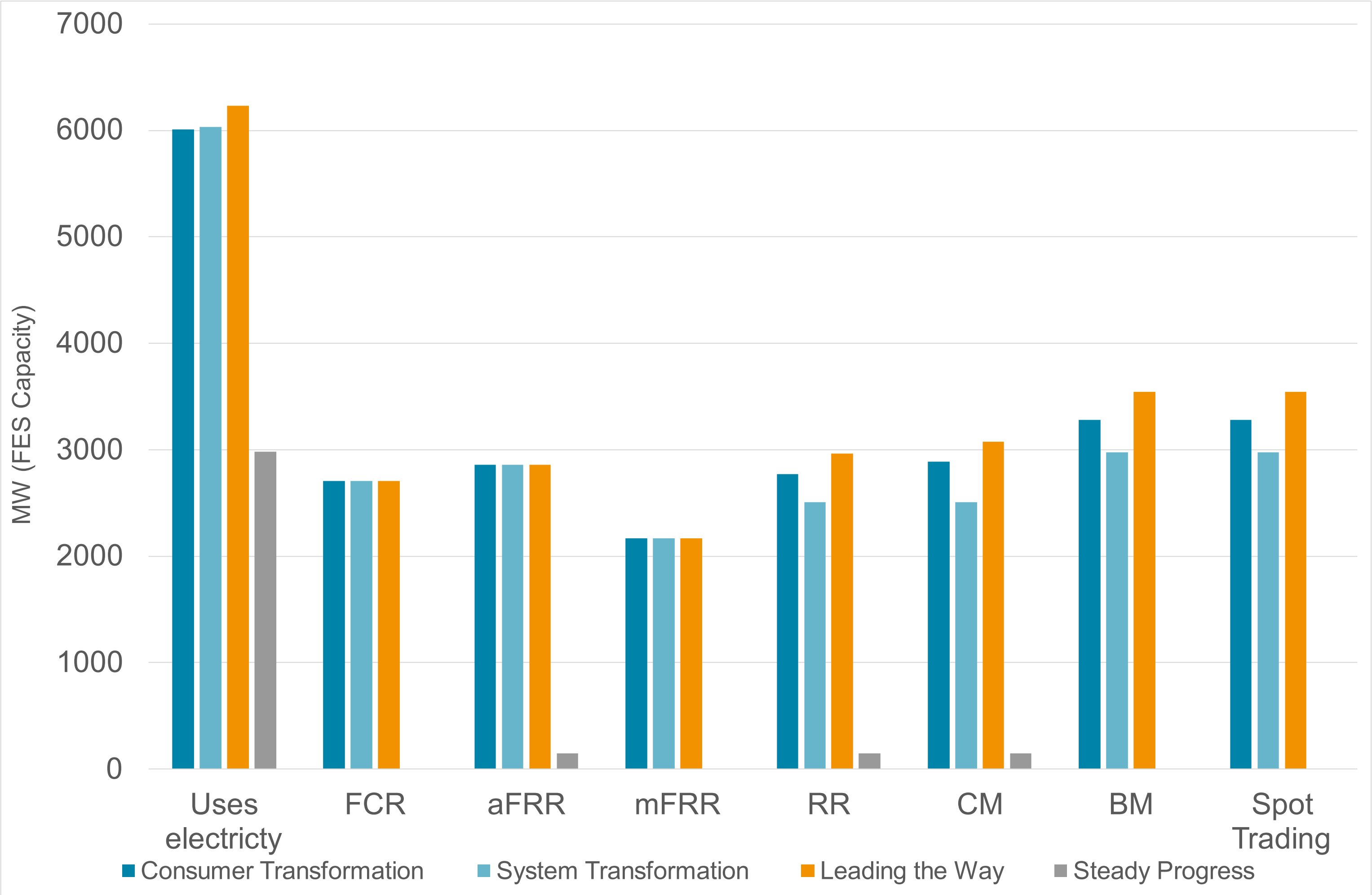
In both the low and high analyses both VC6 and VC5 have the potential to significantly impact the flex market.

In the high analysis, VC10 changes from having a very low level of interaction to the highest of all the VCs. This demonstrates the difference of electrolyser over-sizing.

Results: Electrolysis VCs – ancillary/flex impacts 4/5

Low Analysis: Total impact to electricity network by FES

The low analysis shows the CT, ST and LW as very similar. This is due to the analysis focusing on hydrogen capabilities. CT will have a higher electricity demand overall and a greater need for flex which the VCs can provide. Although the ST scenario has a comparatively lower electricity demand, the VCs are also applicable here and can equally provide flex in this scenario.

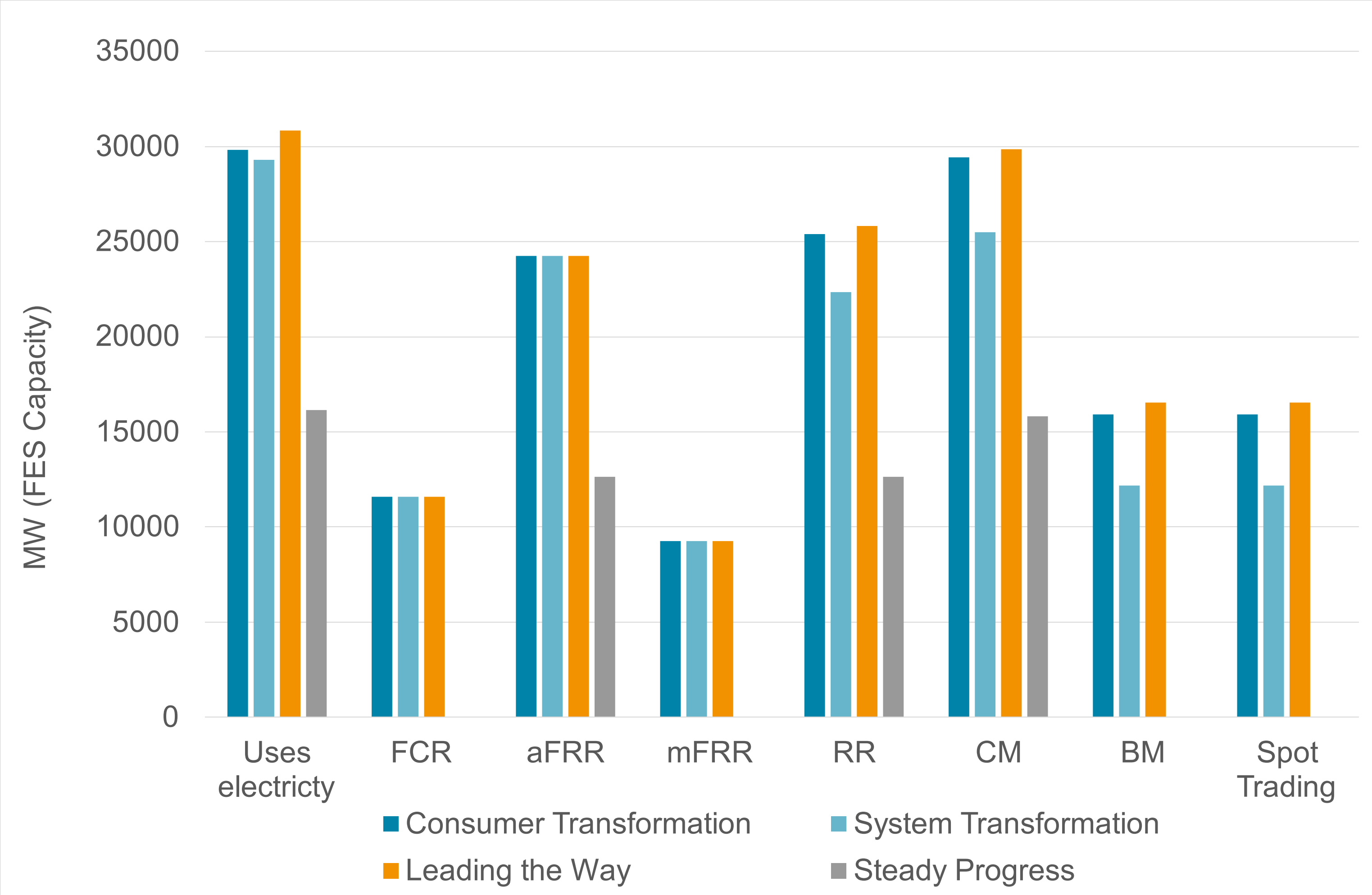


Results: Electrolysis VCs – ancillary/flex impacts 5/5

High Analysis: Total impact to electricity network by FES

The high analysis also shows a similar level of flex provision in both CT and LW, although the total capacity available is much higher. ST still includes a significant amount of flex but the difference between CT/LW is more pronounced.

The noticeable increase compared to the low analysis is in the SP scenario. This is primarily due to the increase in flex provision from VC10 in the high analysis.



Power Generation Value Chain Impacts: Phase 2

This section shows the results of the Phase 2 analysis, to determine the scale of the power generation VCs impact within the electricity system.

Results: Power generation VCs – ancillary/flex impacts 1/3

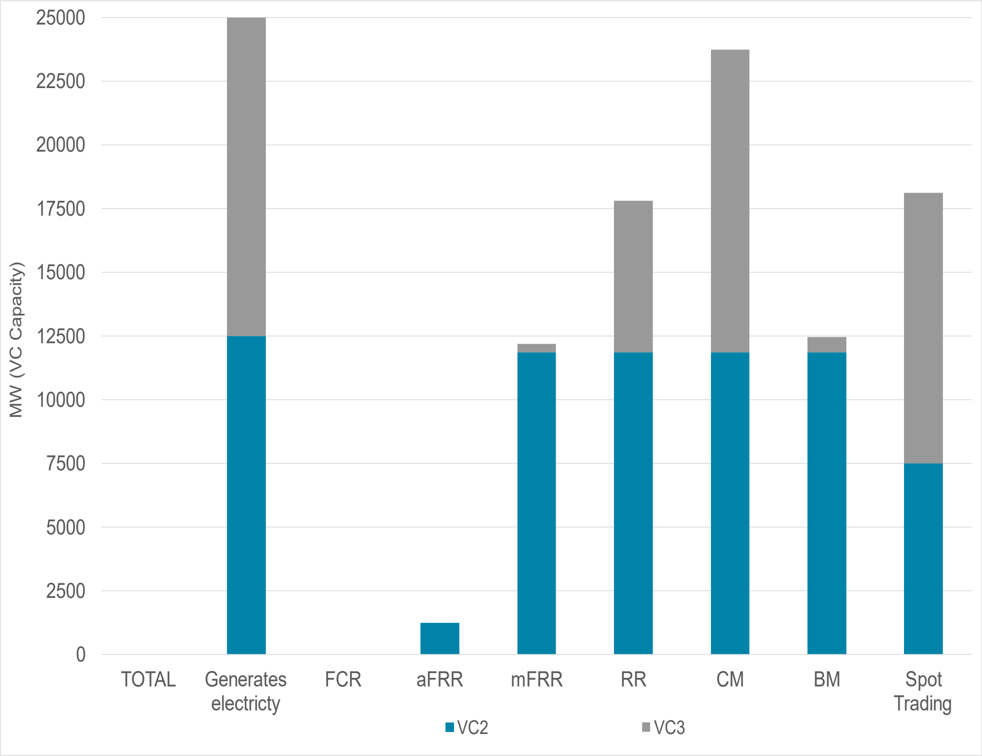
Low and High Analysis: Total impact to electricity network by VC

DELTA-EE

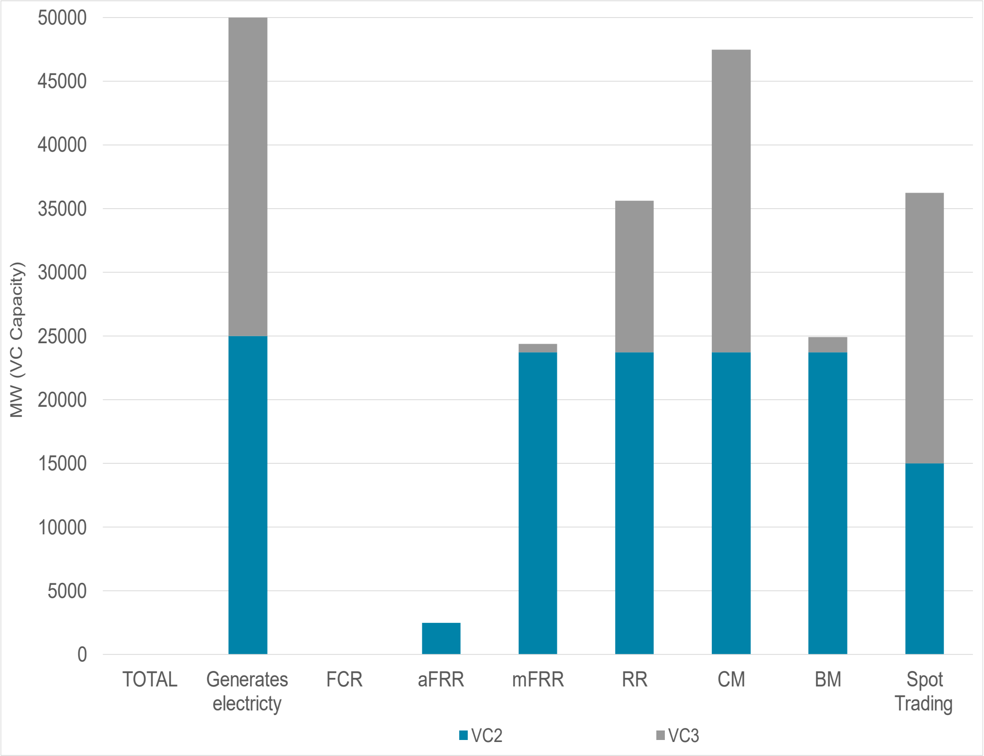
The assumptions for the two power generation VC's are the same for both the low and high scenario, so the charts look the same except the scale is larger in the high scenario.

The two power generation VC's cover peaking (VC2) and mid-merit (VC3). Neither VC is deemed suitable for FCR as the response time for this type of ancillary services is too rapid.

Low Analysis



High Analysis



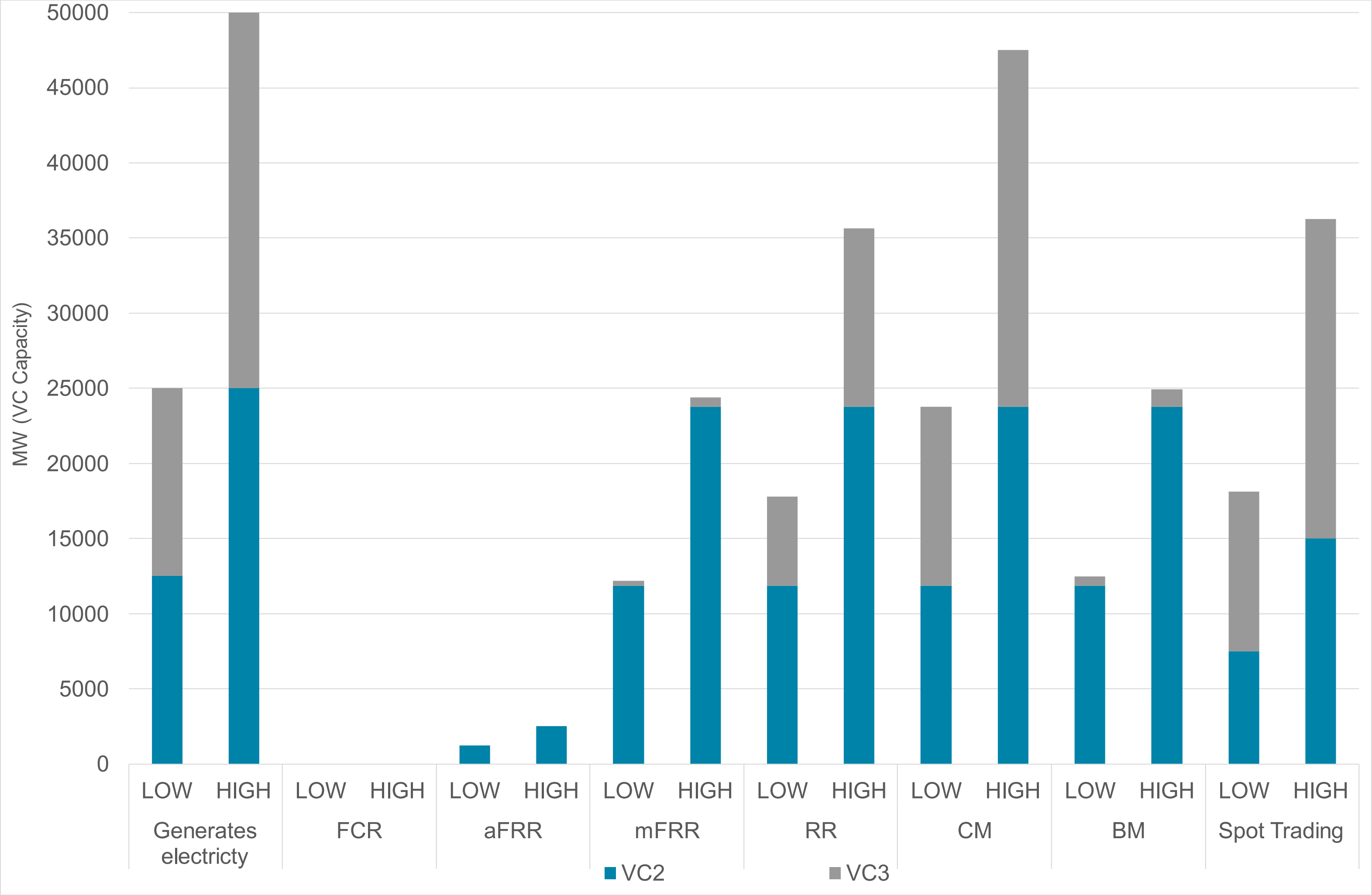
There are a small number of opportunities where VC2 hydrogen could provide power generation. The majority would be from upgraded OCGT for hydrogen combustion, with gas engines or fuel cells representing a small % of the total hydrogen peaking. VC3 will predominantly rely on upgraded CCGT's. Due to the warm-up times for CCGT's we have predicted a lower contribution to flex services for VC3 than VC2, with the CM and Spot trading the most likely markets for participation, as these give the highest rates of return with sufficient notice periods.

Results: Power generation VCs – ancillary/flex impacts 2/3

High and Low Analysis: Total impact to electricity network by VC

This chart highlights the difference in scale between the low and high analyses seen in the previous two slides.

The total size of the hydrogen market will significantly affect the total power generation capacity available.



VC2 (peaking) contributes more total capacity to flex and ancillary services, with a large % of the total VC capacity being made available for mFRR, RR, CM and the BM.

VC3 (mid-merit) makes a smaller contribution to flex services.

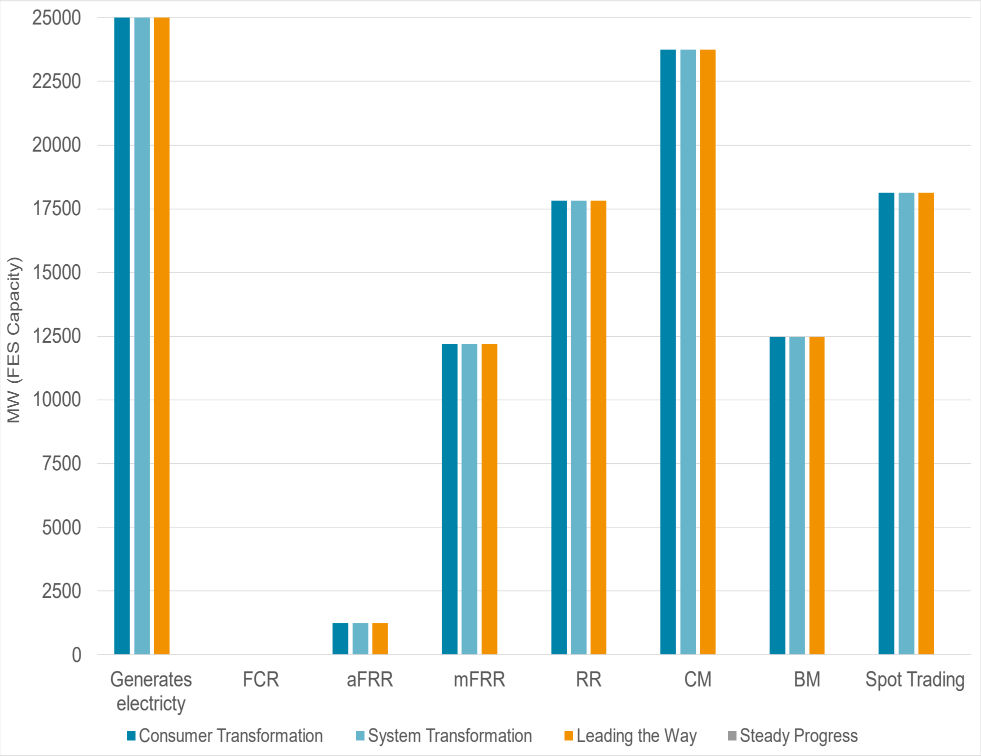
Results: Power generation VCs – ancillary/flex impacts 3/3

Low and High Analysis: Total impact to electricity network by FES

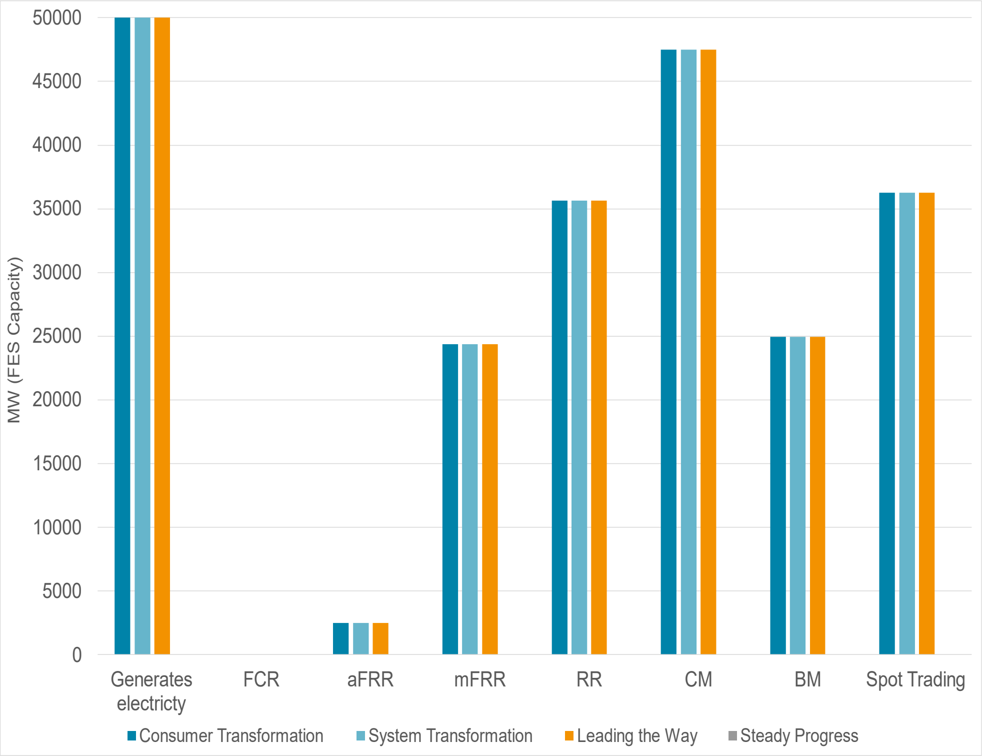
The charts show VC2 and VC3 aggregated by FES. Therefore the potential for hydrogen to provide ancillary and flex services is the across all three scenarios. Similarly to the VC slides, the charts look the same except the scale is larger in the high scenario.

The CT, ST and LW scenarios all include peaking and mid-merit power generation from hydrogen. In practice, CT will have the highest electricity supply and demand profile so will benefit most from flex and ancillary services.

Low Analysis



High Analysis



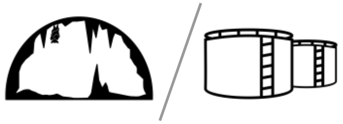
The high analysis mirrors the low (except for scale) as the same assumptions regarding FES are used in both low and high. Demand will be lower for LW and lower still for ST. However there is still a role for hydrogen peaking/mid merit power generation in these scenarios. The analysis assumes no power generation for the SP scenario, as the lower hydrogen demand in this scenario is all from other sectors such as heating and transport.

Storage and Locational Factors

This section considers storage and the level of inter-connection within the energy system. This includes consideration of geography, co-location and End Use

Hydrogen storage
Long-term vs Short-term

Scale of different storage types:



Geological scale storage, required for >2GWh of H2

Pressure vessel scale storage, required for <2GWh of H2

Four categories of storage utilisation models

- **Daily – inter & intra day:** The H2 storage asset is charged and discharged on a daily and/or within day cycle.
- **Seasonal-Quarterly:** The H2 storage asset is charged and discharged on a seasonal cycle (months in timescale).
- **Both daily and seasonal:** The H2 storage is operated on both daily, weekly and/or monthly charge and discharge cycles.
- **Strategic annual:** Used for strategic hydrogen reserves it may be held for multi-year periods.

Value chains not plotted in the table:

- VC4 (Centralised nuclear hydrogen): This VC assumes all hydrogen produced will be grid injected without need for storage.
- VC5 / 11 (Electrolysis for curtailment mitigation / Centralised marine electrolysis): Storage type and regularity of use will depend on the location, scale and end use of the H2 produced, and could be any of the above.

Scale of storage

Scale of storage	Daily – inter & intra day	Seasonal-Quarterly	Both daily and seasonal	Strategic annual
Geological		VC1: Centralised blue hydrogen production for industry VC9: Hydrogen production from bioenergy with carbon capture and storage (BECCS)	VC3: Mid-merit electricity generation using hydrogen VC6: Centralised green hydrogen for transport VC10: Centralised green hydrogen production for industrial use in a cluster	
Pressure vessel	VC7: Decentralised green hydrogen production for use in heavy road and rail transport		VC2: Peaking electricity generation using hydrogen	

Storage utilisation model (regularity of use)

Hydrogen storage

How VCs can provide load shifting/supply constraint management

Load Shifting is defined as electricity consumption that can be moved to a different time of day when demand for power is lower. Requires transmission connection to respond to price signals.

Supply constraint management is defined as providing additional power to the grid at times of localised electricity supply shortage.

Table shows VC's which have the potential to provide load shifting and constraint management.

Hydrogen storage enables electrolysers to vary their usage times and still satisfy their End Use. Geological storage facilitates the use of hydrogen for power generation, even if this is not primary End Use of the VC. However, this will only occur if power plants can offer a high enough price for stored hydrogen and the appropriate locations are available.

No.	Value chain description	Load Shifting	Supply constraint management
VC1	Centralised blue hydrogen production for industry provision and early hydrogen network injection	Does not consume electricity	**Low potential:** Stored H2 will be prioritised for industry
VC2	Peaking electricity generation for peaking power (high MWs)	Does not consume electricity	**High potential**: Stored H2 is for power generation
VC3	Mid-merit electricity generation using green hydrogen	Does not consume electricity	**High potential**: Stored H2 is for power generation
VC6	Centralised green hydrogen at onshoring point for transport near industrial clusters or ports	**High potential:** Electrolysers are likely to be transmission connected	**Low potential**: Stored H2 will be prioritised for transport
VC7	Decentralised green hydrogen production for use in heavy road and rail transport	**Low potential**: Electrolysers are unlikely to be transmission connected	**Very low potential**: Stored H2 will be prioritised for transport and is likely to be off-grid in pressure vessels
VC9	Hydrogen production from BECCS for use in industry	Does not consume electricity	**Low potential:** Stored H2 will be prioritised for industry
VC10	Centralised green hydrogen production for industrial use in a cluster	**High potential:** Electrolysers are likely to be transmission connected	**Low potential**: Stored H2 will be prioritised for industry

VC5 electrolysers may be grid connected to provide ancillary services but will be directly powered by previously curtailed renewables. VC11 is not connected to the electricity network.

Hydrogen storage

Hydrogen gas network implications

Some VCs are more impacted by the presence/absence of a H2 network than others:

VCs that are strongly impacted by network scenario: VCs 2, 3, 5, 7. The decentralised nature of these VCs imply that H2 networks will influence the need for storage and H2 supply. A network makes these VCs much more viable, and much less geographically restricted, as daily small-scale storage can be avoided.

VCs hardly impacted by network scenario: VCs 1, 4, 6, 9, 10, 11 The centralised nature and scale of these VCs imply that H2 supply and storage are project requirements, irrespective of H2 network.

Nationwide network

Definition: A national distribution and transmission network carrying pure hydrogen for residential, commercial and industrial users. Relates to FES: **ST, SP (blended)**

What does this network type mean for hydrogen storage?

- Hydrogen production and end use are largely disconnected.
- Inter/intra day storage requirements are minimal, as hydrogen demand and supply swings are balanced by the network.
- Seasonal and strategic storage will still be required to support the network during peak demands.

How are value chains impacted?

- Geological scale storage is only used for seasonal or strategic use. Small scale pressure vessel storage is very rarely required (and makes little sense in most cases with the presence of a network).
- Some value chains become much more financially, and logistically viable, and much less geographically restricted, as daily small-scale storage (and distribution) can be avoided. Applies to **VCs 2, 3, 5 and 7**.

Regional networks

Definition: Local transmission and distribution networks carrying pure hydrogen for residential, commercial and industrial users, usually within geographical areas around industrial clusters. Some regional networks could be linked up via transmission pipelines. Relates to FES: **LW**

What does this network type mean for hydrogen storage?

- In a scenario with regional networks, storage requirements will develop according to geographical zone.

How are value chains impacted?

- Zones with a hydrogen network will support the viability of some value chains; especially those where hydrogen supply can be disconnected, and small-scale storage requirements can be avoided. Applies to **VCs 2, 3, 5 and 7**.
- Value chains that benefit from a network, either by simplifying hydrogen supply or by avoiding small-scale storage, will be more geographically constrained in zones without a hydrogen network (see column to the right).

Private local networks/pipelines

Definition: Private networks carrying pure hydrogen, primarily to industrial off-takers within a cluster. The pipelines link up hydrogen supply and storage resources with multiple off-takers (likely a short distance). Relates to FES: **CT**

What does this network type mean for hydrogen storage?

- Hydrogen will only be produced, stored and distributed at scale where it's needed (primarily within industrial clusters).
- Wherever possible, demand centers will utilise large-scale geological assets for storage to buffer hydrogen supply swings.

How are value chains impacted?

- There is no public network to fall back on for daily swings in hydrogen demand. Therefore, storage becomes essential for supporting both short- and long-term demand profiles.
- Value chains that would also exists outside of industrial clusters (in a scenario with a national or regional hydrogen network) are much more geographically restricted to areas with existing storage assets (e.g., a salt cavern by an industrial cluster). Applies to **VCs 2, 3, 5, and 7**.

Hydrogen storage

Geography and co-location

VC summaries

VC1: Centralised blue hydrogen production

VC2: Peaking electricity generation using hydrogen

VC3: Mid-merit electricity generation using hydrogen

VC4: Centralised nuclear hydrogen

VC5: Electrolysis for curtailment mitigation

VC6: Centralised green hydrogen for transport

VC7: Decentralised green hydrogen production for transport

VC9: Hydrogen production from BECCS

VC10: Centralised green hydrogen production for industrial use in a cluster

VC11: Centralised marine electrolysis

Locational value chain considerations

Scottish region

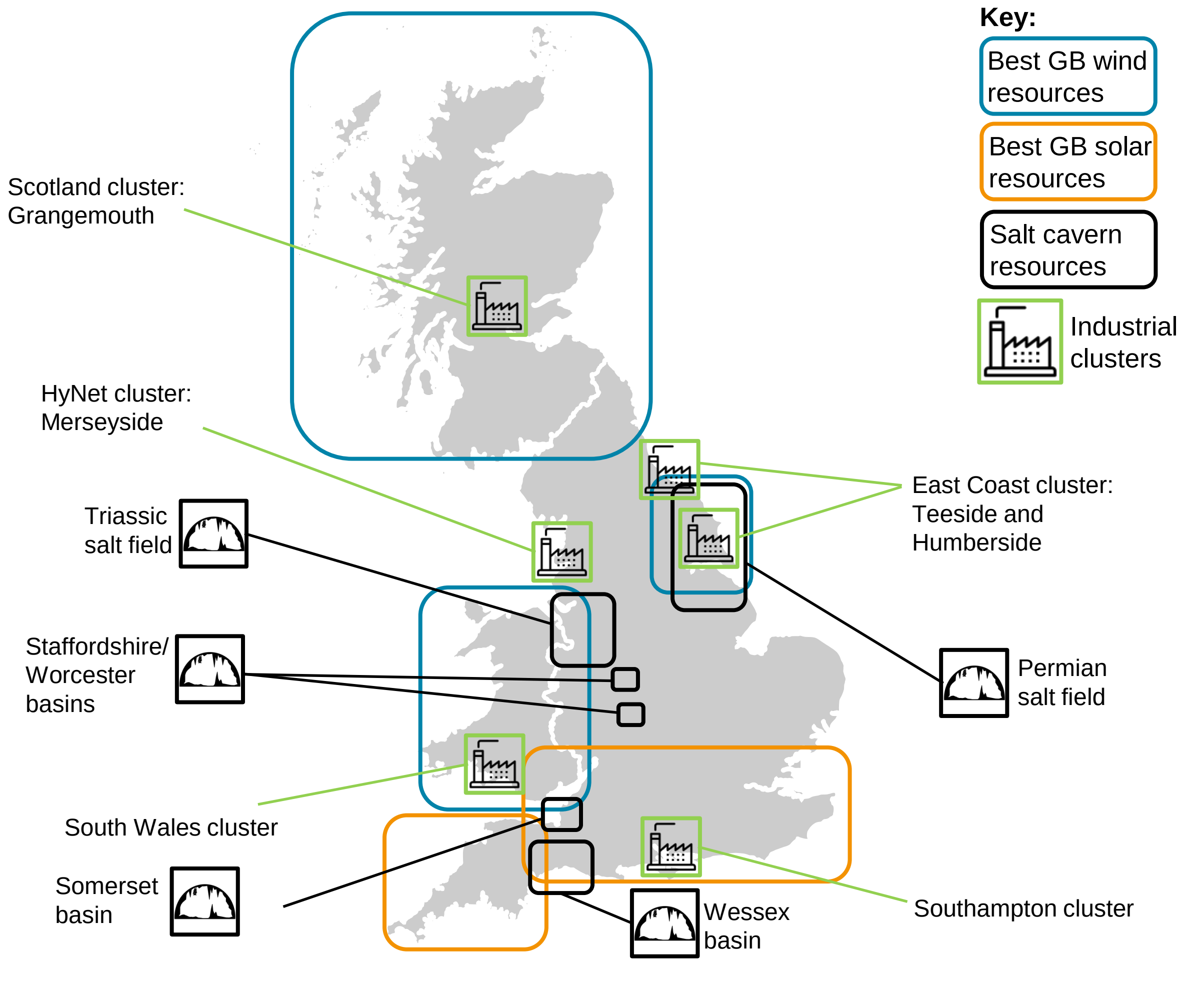
- VCs 5+11 are advantageous to this region, due to the large wind resources. However, limited geological storage resources imply that distribution networks and purpose-built storage will be vital.
- Without a network, co-location of H2 production and end use will be preferred, but the limited storage potential may limit the adoption of VCs requiring larger storage volumes (e.g. VCs 3, 6, 10)

Northern England and Wales region

- This region has the best geological storage resources, alongside major hydrogen demand centres in industrial clusters. Therefore VCs 1, 6, 9, 10 are very suitable for this area. H2 production, storage and end use can be co-located for these large demand centres.
- Without a network, VCs 2, 3, 5 will likely feature more commonly in and around the major demand and storage centres because the absence of a network makes H2 supply and storage much more challenging.

Southern England region

- This region has good solar resources for H2 production and some geological storage assets. However, the larger storage assets are not located in close proximity to the industrial clusters, suggesting that (in the absence of a network) larger users will need to invest in purpose-built storage or a pipeline linking to the storage site.



Identifying interactions with all parts of the electricity system

Summary of findings

VC summaries

VC1: Centralised blue hydrogen production

VC2: Peaking electricity generation using hydrogen

VC3: Mid-merit electricity generation using hydrogen

VC4: Centralised nuclear hydrogen

VC5: Electrolysis for curtailment mitigation

VC6: Centralised green hydrogen for transport

VC7: Decentralised green hydrogen production for transport

VC9: Hydrogen production from BECCS

VC10: Centralised green hydrogen production for industrial use in a cluster

VC11: Centralised marine electrolysis

DSO: Most **electrolyser VCs will be transmission** rather than distribution connected so impacts at the DSO level are likely to be minimal. Some, such as VCs 5 and 7 are more likely to be DSO connected, likely if the electrolyser is 20MW or less. These electrolyser could also be non-networked. To provide flex support to the DSO would require new pricing mechanisms similar to those already offered by NG-ESO.

TSO: The TSO will lead engagement with stakeholders regarding **upgrades to existing power plants** in the switchover to hydrogen from natural gas. In addition, TSO will provide vital strategic insight regarding long term **salt cavern storage** to ensure the most suitable locations are used to ensure accessibility for power generation plants.

ESO

Electrolysers: VC6 has one of the largest electrolysis capacities in addition to being able to operate the most flexibly; this is because transport demand will not be constant, giving the electrolyser more operational leeway to participate in demand side flexibility markets. VC10 also has a large potential to provide flex, if the electrolysers are over-sized, as this will ensure the primary End Use is still satisfied. Support for the grid from VC4 is minimal as the focus is to provide balancing at the plant level (nuclear). Support from VC5 is minimal as the focus is supporting renewables that would otherwise be curtailed, so should indirectly reduce the need for balancing services as few renewables will redirect their power into electrolysers instead of creating congestion on the network. The workshop supported interview findings that few electrolyser owners are currently considering revenue stacking, but the teams analysis confirms that this could be an option in the future and NG-ESO should anticipate some electrolyser owners doing this in the future.

Power generation: The assumptions behind VCs 2&3 involve a shift away from burning natural gas for power generation. Using hydrogen for power generation will be expensive which is why the VCs focus only on peaking and mid-merit. Regarding flex/ancillary, the assumption is that peaking and mid-merit will operate in a similar way to natural gas currently, although the quantity coming from CCGTs/OCGTs will be significantly reduced.

Storage: Storage is inextricably linked to the question of whether or not hydrogen will be distributed via a gas network in the long term. When considering long-term, inter-seasonal storage, questions of geography (and associated geology) are similarly vital. The analysis here has determined that decisions on the gas network will have a significant impact on the storage options for some VCs but the effect will be negligible on others. Additionally, UK geography has been appraised to determine which VCs which would be most feasible for providing long-term storage and where.

Conclusions and next steps

Observations for WP5

The delivered cost of green hydrogen will heavily dependent on electrolyser sizing, utilisation and electricity price dynamics. In addition, delivered cost will also be significantly affected on storage availability, utilisation and cost of storage.

Hydrogen Production:

The market sizing has quantified the different ranges of hydrogen that can be produced for each VC. Using this data in conjunction with the cost information from WP2 the cost of producing different quantities of green hydrogen will be modelled in WP5. This will offer a range of LCOH prices according to the different electrolyser use cases in **VCs 4-7**.

This will include considering different sensitivities, relating to:

- Electrolyser utilisation,
- Electricity price,
- CAPEX

Hydrogen Storage

The storage capacities for each VC provided in the market sizing in addition to the storage analysis in the final section of report, provides insight for how storage is used within each VC. WP5 will model a range of levelised costs of storage for both pressure vessels and salt caverns for **VCs1-3, 6,7,9,10**.

Data relevant to these costs includes:

- Electrolyser sizing and utilisation will affect storage requirements
- Storage sizing
- Storage utilisation, which includes the regularity (intra-daily, inter-daily, quarterly) with which the hydrogen is used/replaced

Power Generation

The range of LCOH prices produced by the model will be the starting point for modelling the cost of using hydrogen to produce electricity. Additional information from the market sizing will provide details for **VCs2&3** to determine the cost of producing electricity using the scales stipulated. There will be a sensitivity analysis to not only the hydrogen price but also:

- Power plant capital investment/upgrades
- Load factors
- Levelised electricity costs for power generation from hydrogen
- CCGTs vs. OCGTs
- Potential distribution costs will be included dependent on the different network options outlined in WP4.