THE ROLE OF HYDROGEN AS AN ELECTRICITY SYSTEM ASSET
WP5 REPORT

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Introduction

WP5

SYNOPSIS

This report builds upon the WP4 report, which analyses market sizes and opportunities for 10 value chains considered within this study. In this report value chains are investigated through calculation of the expected financial costs. Details of the value chains assessed are presented in the WP2/3 report.

The core aims are to:

- Provide high level estimate of the levelised cost of hydrogen delivered from each key value chains.
- Identify key drivers for cost for each element of the chain, in particular hydrogen production, storage and electricity generation from hydrogen.
- Estimate the potential scale of impact of value chain design and optimisation on the resulting hydrogen and electricity prices.
- Identify further analysis opportunities to better understand the potential impact of electrolysers on the electricity market and grid.

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Glossary of terms

AEM
Anion-Exchange Membrane

CAPEX
Capital Expenditure

CCGT
Combined Cycle Gas Turbine

CCS
Carbon Capture & Storage

H2
Hydrogen

HGVs
Heavy Goods Vehicles

LCOE
Levelised Cost Of Energy

LCOH
Levelised Cost Of Hydrogen

LCOS
Levelised Cost Of Storage

LCOD
Levelised Cost of Hydrogen Delivered

LOHC
Liquid Organic Hydrogen Carrier

LRVC
Long run variable cost

OCGT
Open Cycle Gas Turbine

OPEX
Operational Expenditure

PEM
Polymer Electrolyte membrane

SOE(C)
Solid Oxide Electrolysis (Cell)

SMR
Steam Methane Reforming

Stack
Part of the electrolyser that reacts with electricity to create hydrogen

VC
Value chain

WACC
Weighted Average Cost of Capital

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Contents

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Summary of overall Project Scope & Approach 1/2

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

Stage 2: Analysis

- **WP5:** Impact analysis
- **WP6:** Summary Report

This Report is for WP5

Stage 3: Support Redispatch

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

WP7 is Project Management (ongoing)

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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.

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Introduction and Scope

Aims for WP5

Stage 2: Analysis of short-listed impacts

Stage 2

During the second stage of work, a number of topics will be explored in more detail, based around the shortlisting of impacts in Stage 1. 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.

- Quantitative analysis of each value chain in WP5 based on findings and outcomes from the WP4 market sizing analysis and market overview.
- Overview of key input assumptions and baseline decision methodology
- Levelised cost calculation for each value chain to benchmark the relative cost of hydrogen for each value chain
- Cost sensitivity analyses, to identify and quantify the primary cost drivers and greatest uncertainties in cost predictions for each value chain
- Sensitivity assessment of impact of hydrogen storage and impact on resulting cost of electricity when used in power generation
- Assessment on potential opportunity for electrolyser and storage size optimisation to reduce hydrogen costs

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Executive Summary

Key Findings

The hydrogen economy and electricity market are fundamentally linked through electrolysers dependence on large volumes of electricity.

Detailed analysis of one market without the other reduces the overall usefulness of the analysis.

Hydrogen Production

The cost of hydrogen production is dominated by fuel costs, whether via SMR or electrolysis.

A **reliable forecast of fuel costs, through project life, is critical to understanding the potential costs of hydrogen production**. For electrolysers, this directly links hydrogen markets and electricity markets.

Electrolyser oversizing does have the potential to reduce average hydrogen price. However, this relies heavily on the ability to access relatively low electricity prices at volume and to efficiently utilise hydrogen storage.

Hydrogen Storage

The impact of hydrogen storage on the cost of delivered hydrogen is highly variable.

Analysis of the levelised cost of storage varied from **~20% increase in hydrogen costs for a highly utilised storage facility to over a 300% increase** in the cost of hydrogen when used for annual seasonal storage.

Uncertainties remain on further possible storage constraints, such as location and discharge rates, which could further increase costs and reduce capability.

Power Generation

Power generation using hydrogen in CCGT or OCGT's is estimated to be relatively high.

This is primarily due to the very low load factors estimated for the baseline. **Prices drop significantly, as load factors increase.**

Cost of electricity for OCGT was less sensitive to hydrogen price or cost of hydrogen storage, than for CCGT.

At low load factors, the capital investment costs have a significant impact on LCOE. Therefore retrofitting of old plants is likely to be preferred to significantly reduce costs for peaking units.

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WP5: Impact analysis

In-depth impact analysis of each of the short-listed priority areas from WP4

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Outputs from WP4 Analysis

Key priorities identified for further analysis in WP5

Understanding the whole value chain is critical for optimisation of sizing and operation.

Impact on the electricity grid will depend greatly on predominant value chains in industry, their location and key operating drivers.

Hydrogen Production:

- Market sizing in WP4 showed that, while there is significant uncertainty on the exact amount and proportion for each value chain, the scale of electrolyser capacity needed in 2035-2050 will be at a minimum in the 10's GW range. This will have a substantial impact on the electricity system and market.
- Cost of hydrogen for different value chains will impact their uptake and therefore critical to estimate the costs and key sensitivities.
- Electrolyser sizing is key to understanding their operation and load factors, in conjunction with storage.

Hydrogen Storage

- Hydrogen storage is essential for both load shifting and constraint management, both of which can have substantial impacts on the electricity grid and market.
- The cost of storage and its contribution to the cost of delivered hydrogen will be key to determine the cost for these services.
- Optimising the size of storage is key to minimising costs – but determining where and how storage can save money is key.
- The impact of storage utilisation on the cost of stored hydrogen and how this could impact operation.

Power Generation

- Power generation from hydrogen is mainly seen as peaking/load balancing plant, providing large range of flexibility/ancillary services.
- Hydrogen prices from different value chains and storage scenarios is the starting point for potential hydrogen electricity generation costs.
- Main technologies expected are retrofitted CCGTs and new build OCGTs. The variance in LCOE cost between these will be important for their utilisation.
- The impact of capex or retrofitting on the resulting cost of electricity.

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Analysis completed in WP5

The priority areas are examined through detailed analysis on a range of factors and drivers which form the value chains

Value Chain Baselining

- Select key base line assumptions for each value chain, with regards to operational (use case) and financial inputs
- For each value chain calculate the levelised cost of:
  - Hydrogen produced
  - Hydrogen storage
  - Hydrogen distribution
  - Hydrogen delivered
  - Electricity generated using hydrogen

Hydrogen Production:

- Measure the sensitivity of the levelised cost of Hydrogen to key input parameters such as:
  - Electricity price
  - Utilisation rate of electrolysers
  - Cost of investment

Hydrogen Storage

- Sensitivity of levelised cost of hydrogen delivered to:
  - Storage size
  - Storage use intensity(e.g. daily vs. seasonal cycling)
- Investigation of lowest levelised cost of hydrogen with variable electrolyser and storage sizing and utilisation and electricity pricing.

Hydrogen Generation

- Sensitivity of levelised electricity price to utilisation factor of the generation asset.
- Impact of retrofit of existing power plants e.g. CCGTs, OCGTs, on the levelised cost of electricity

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Levelised Cost Modelling: Baseline

Methodology and baseline levelised cost results for key hydrogen value chains.

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Value Chains for analysis in WP5

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Value chains 9 and 11 have been further removed from WP5 analysis due to limited direct impact on the electricity system and not being networked.

VC1 is included to baseline SMR cost for comparison with Electrolysers.

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 collocated with refuelling stations / transport hubs.
VC9	*REMOVED: 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. (not included in WP5)*
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	*REMOVED: Centralised marine electrolysis*	*Piped back from offshore wind (floating or fixed). (not included in WP5)*

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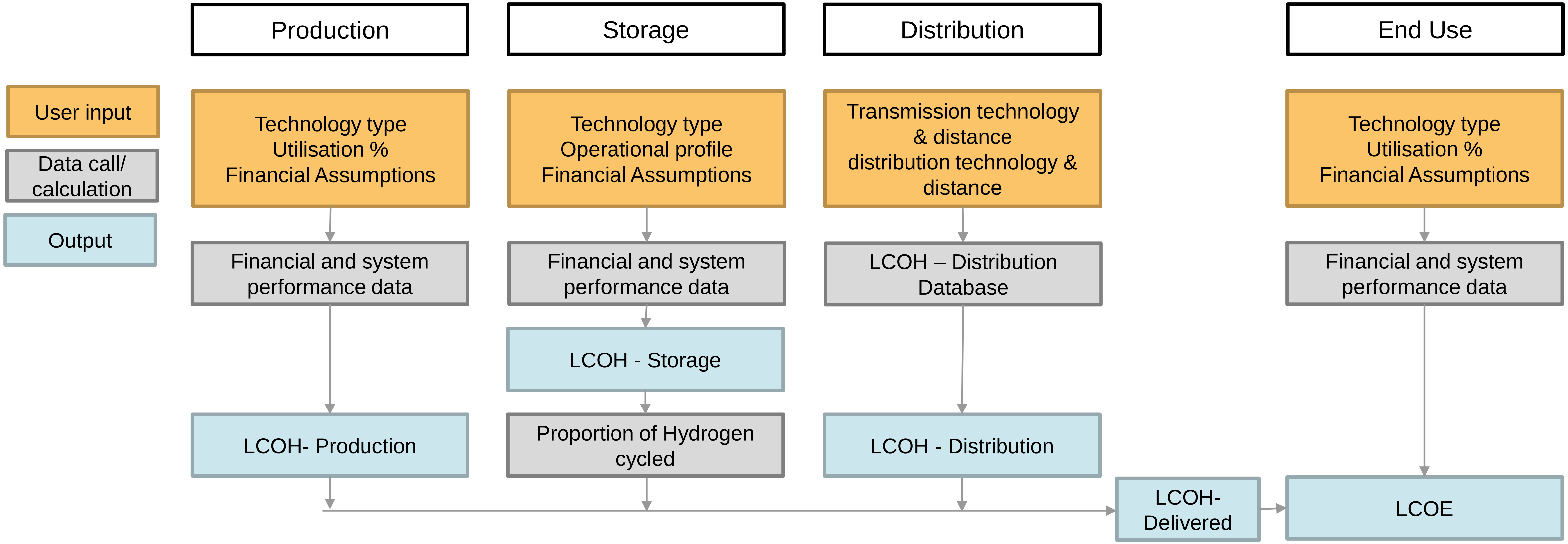
Levelised Cost Modelling Value Chains
Methodology

Systematic approach to calculation of levelised cost of hydrogen delivered and the levelised cost of electricity from subsequent end user in power generation



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Levelised Cost Modelling Value Chains

Methodology

Understanding the key drivers for hydrogen and electricity costs can be accomplished by considering the average loads per year.

Dynamics can be modelled within average values and simulated indirectly.

Key assumption/modelling decisions to calculate levelised cost for each chain element

Steady state modelling

- Static operation, meaning the load profile of electrolysers/storage/utilisation is calculated as an average for every year of operation. Dynamics are implicitly captured within the average but not explicitly modelled.
- Static commodity prices, meaning, natural gas, electricity, water prices are averaged over duration of projects.
- Degradation of performance has not been modelled

Weight Average Capital Cost to capture the cost of equity and debt

- In this modelling the WACC was estimated directly with equity and debt not considered separately.

Nominal pricing

- Inflation has not been included

Tax

- Tax benefits have not been included

Production

- Stack costs included within capex costs – discounted
- Variable costs are simplified to water costs
- Economies of scale not simulated

Storage

- Fixed average compressor efficiency by technology
- Pressure dynamics not simulated
- Storage maximum injection/discharge rates have not been modelled – annualised approach assumes these are sufficient/balanced over the necessary time.
- Economies of scale not simulated

Distribution

- Costs for distribution of hydrogen per MWh are estimated through public source data and not explicitly calculated.

Power Generation

- Focused on 100MW OCGT to cover peaking plant and 1200MW CCGT H Class for “mid merit”
- No income from ancillary services included, e.g. no subsidies(e.g. capacity market payments) from grid operator that may reduce levelised electricity costs.

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Levelised Cost Modelling Value Chains

Key input Data

Core to the model is fixed input data source defining the system performance, (e.g. energy efficiency, system life time) and financial performance (CAPEX, fixed OPEX)

Production Performance and economic data
Primary source:
- BEIS Hydrogen production costs 2021.

Secondary sources:
- IEA 2019 – Future of Hydrogen
- IRENA – Green Hydrogen costs 2020
- ICCT 2020, Assessment of Hydrogen Production Costs for Electrolysis United States and Europe

Storage performance and economic data
Multiple sources used:
- BNEF Hydrogen Outlook 2020
- Hydrogen supply chain evidence base, BEIS 2018
- IRENA –Green Hydrogen Supply 2021
- RMI -Accelerating Cost-Competitive Green Hydrogen
- DOE Hydrogen and Fuel Cells Program Record
- Review of the current technologies and performances of hydrogen compression for stationary and automotive applications
- Lowering Energy Spending Together With Compression, Storage, and Transportation Costs for Hydrogen Distribution in the Early Market

Distribution economic data
Primary source:
- BNEF Hydrogen Outlook 2020

Utilisation performance and economic data
Primary source:
- BEIS Electricity Generation Costs (2020)

Secondary sources:
- GE Hydrogen for power generation
- Energy and Economic Costs of Chemical Storage
- BNEF Hydrogen Economy Outlook 2020

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Levelised Cost Modelling Value Chains

Methodology

Value Chain scenarios are defined based on the following key financial and operational parameters

Key scenario

Weight average cost of capital:

- The weighted average cost of capital has been estimated to be at a baseline of 5% for all value chains – with a variation of 3-7%.
- This aligns with the current WACC used for other renewable projects and the typical values for the process industries. Sources:
  - IEA – Cost of Capital in clean energy transitions
  - Fraunhofer - The impact of risks in renewable energy investments and the role of smart policies
  - Stern School of Business at New York University

It is noted that increases in inflation in 2022 may lead to increased WACC due to higher interest rates, but that has not been considered in this study due to commissioning dates assumed to be 2025 or later.

Electricity costs:

- Electricity cost are tailored for each value chain depending on the specific market – further details are presented in the next slide.

System sizing:

- As this study is levelised without specific economies of scale, the key element is the balance of the electrolyser size and storage size as determining factors for the average cost of hydrogen delivered. This has been defined through Work Package 4 market sizing.

Technology choice:

- This has been defined in work package 2 for each value chain.

Storage utilisation:

- This has been defined in work package 2 for each value chain.

Production utilisation rate & utilisation load factor:

- This has been defined in the market sizing exercise in WP4

Water cost:

- A value of £0.0015/l has been assumed for all cases.

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Levelised Cost Modelling Value Chains

Methodology

Electricity baseline assumptions for each electrolyser value chain

No.	Value Chain	Electricity Cost Calculation
VC4	Centralised nuclear hydrogen for injection into hydrogen networks (smaller scale)	Assumed to be at new nuclear facilities and therefore competing with CFD supported power – Using the current Strike prices of £106.12 – no discount assumed for electrolysers, to ensure cost parity with electricity production.
VC5	Electrolysis for curtailment mitigation	Electricity cost assumed to be £20/MWh. This is determined through current CfD prices and balanced benefit for wind farm, network operator and electrolyser. Further details on this approach are on following slides.
VC6	Centralised green hydrogen at onshoring point for transport near industrial clusters or ports	Low long run variable cost industrial (BEIS) – medium utilisation, centralisation and consistent industrial user base requiring long fixed power purchasing agreement to ensure delivery.
VC7	Decentralised green hydrogen production for use in heavy road and rail transport	Central long run variable cost industrial (BEIS) – decentralised nature and relatively smaller will reduce ability to ensure consistent low prices – high value use case should also accept high hydrogen prices.
VC10	Centralised green hydrogen production for industrial use in a cluster	Low long run variable cost (BEIS) – medium utilisation, centralisation and consistent industrial user base requiring long fixed power purchasing agreement to secure power.

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Levelised Cost Modelling Value Chains
Methodology

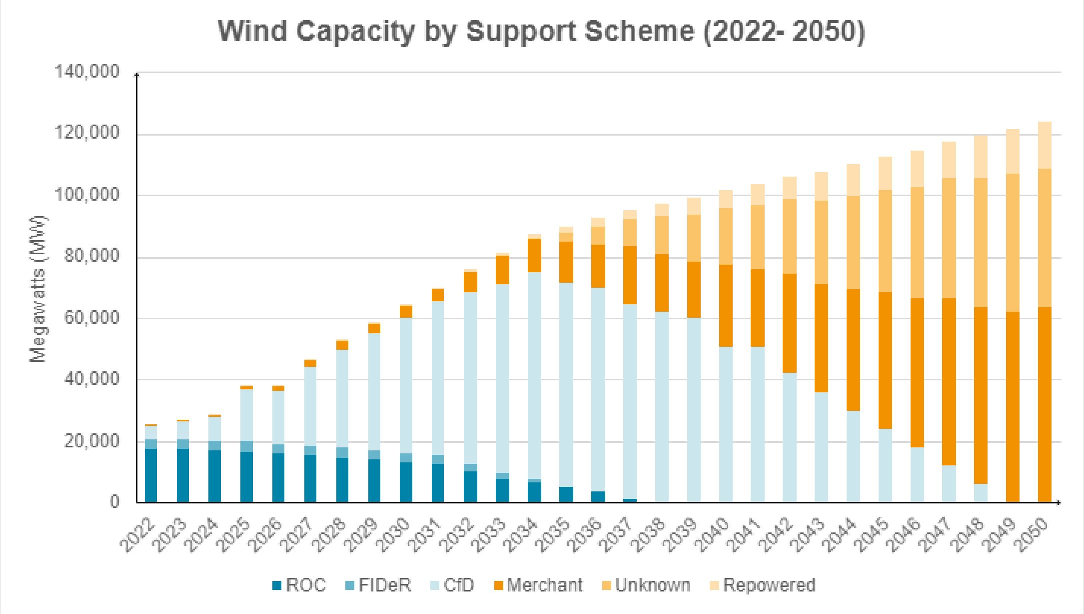
The volume of very low and negative electricity prices from over capacities of large wind farms remains uncertain, along with the causes due to subsidies

Electricity cost for electrolyser through curtailment

Many studies assessing the cost of green hydrogen through only curtailment assume a £0 cost of electricity for the electrolyser due to large future wind installations driving down the cost including possible negative electricity prices.

There is a risk that this will underestimate the cost of electricity for these systems as it is still uncertain if very low or negative pricing will be significant. In the current market very low and negative pricing is driven significantly by subsidy support which impacts the majority of wind capacity.

An approximate forecast of wind capacity until 2050 is considered; at least 50% of wind farms no longer backed by subsidies and a large amount of capacity forecasted with no new subsidies.



Source: Delta-EE forecast wind installations and planned subsidy scheme
Based on Ofgem installation data.
CfD forecast on planned auctions until 2030.
Wind farm life assumed 25 years
Final wind capacity in 2050 assumed to be 125MW following CCC6 guidance, linear installations from 2030 assumed.

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Levelised Cost Modelling Value Chains

Methodology

Electricity cost for electrolyser during curtailment must be assumed to consider potential future market dynamics.

Electrolyser is assumed to pay half the cost of typical offshore wind electricity costs.

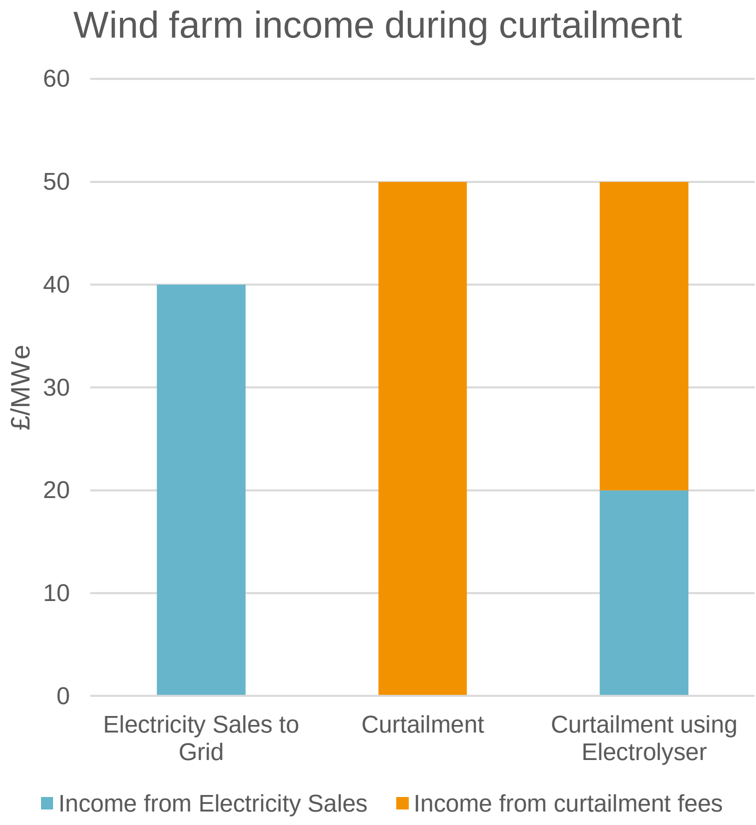
In future this cost will be highly dependent on the competition within the electricity market and curtailment needs.

Further, zero or negative electricity pricing for the electrolyser implies all of the benefits of excessive wind capacity are realised by the electrolyser, rather than the shared with the market. As renewable curtailment is a competitive process, benefits may need to be split between wind farm, electrolyser and the grid operator to secure the curtailment order and income.

Electrolysers can reduce the cost of curtailment for wind farms, ensuring their competitive edge in securing curtailment payments, while also benefiting grid operators reducing the cost of system balancing.

In VC5 is assumed the electrolyser pays half the expected electricity costs.

- Normal operation – wind farm sells electricity and receives £40/MWh (Round 3 CfD pricing)
- Curtailed – wind farm turns off - receives £50/MWh from grid operator
- Curtailed with electrolyser – wind farm diverts power to electrolyser, receives £20/MWh from electrolyser and £30/MWh from grid operator – no impact on wind farm profitability but lower cost to grid operator and more competitive bidding position.



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Levelised Cost Modelling: Baseline

Results by Value Chain

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Value Chain 1 – Levelised cost analysis

Asset Structure and Scenario inputs

Infrastructure Components	Production	Storage	Distribution
Assets	Asset: SMR w/ CCS Year: 2025 Size (MWe): 300	Storage Asset: Salt Cavern Size (GWh): 101	Local Distribution: Pipeline
Use cases	Utilisation Rate: 95%	Utilisation Type: Both Inter-day and seasonal	Distribution Distance: 100 km

VC1 Centralised blue hydrogen production for industry provision and early hydrogen network injection
Starting as isolated blue plants for specific users, and as more plants and users come online they will all be linked to a pipeline network.

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Value Chain 1 – Levelised cost analysis

Base line key outputs and assumptions

Baseline Financial Inputs Values

Natural gas Cost - Production (£/MWh)	22.9
Electricity Cost – Storage* (£/MWh)	90.9
Weighted Average Capital Cost	5%

*Compression costs

Baseline Levelised Costs(£/MWh)

Production	49
Storage (contribution to average price)	35(6)
Distribution	9
Average hydrogen cost delivered	63

Key assumptions

This value chain provide the SMR case for comparison to the electrolyser costs using the same methodology.

- The most critical input parameter is the natural gas price. This has been based on Long run variable cost average from 2025 based on figures from BEIS in June 21. However considering raising gas prices through 2022, there is significant uncertainty on wholesale price of natural gas.
- Electricity cost for compression in storage is LRVC – 2025-2055 Central Industrial
- SMR was assumed to relatively close to it's end use, but also have a relatively large service area, hence distribution pricing at 100km distance.
- CO_2 transport, storage and carbon costs have been included - estimated from BEIS calculations from "Hydrogen Production costs 2021"

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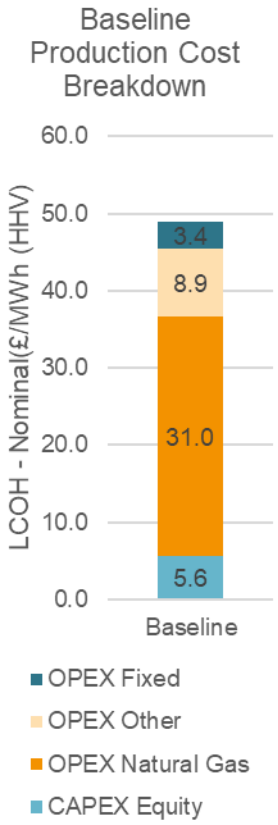
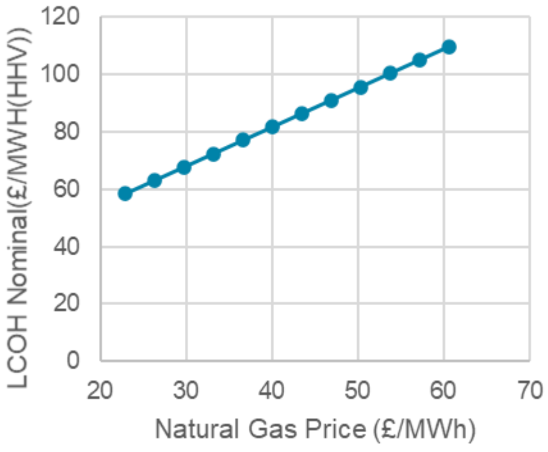
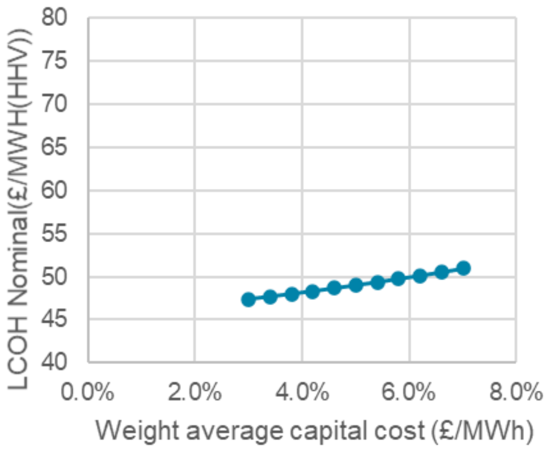
Value Chain 1 – Levelised cost analysis
Sensitivity analysis

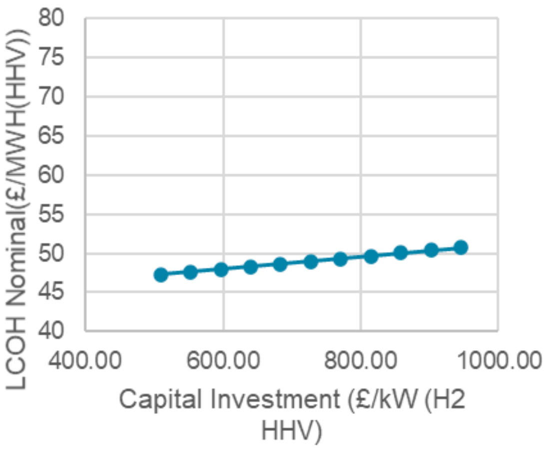
Key variables defining the average cost of Hydrogen produced



- Production breakdown (left) shows levelised cost of hydrogen production are dominated by natural gas prices at 63% of the costs, second is “OPEX other” which includes water, CO_2 T&S and carbon costs.
- Natural gas prices have risen to over £60/MWh* in the start 2022, at this level the cost production alone is estimated at 109 £/MWh >200% more expensive than our baseline.
- Weighted average capital cost and capital investment have a relatively smaller impact on the resulting end cost.
- The largest uncertainties in hydrogen production cost from SMR are the operating costs, natural gas, and CO_2 T&S and carbon cost.







*OFGEM Forward delivery contracts (January and February 2022)

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Value Chain 2 – Levelised cost analysis

Asset Structure and Scenario inputs

Infrastructure Components

End Use

Assets

Asset	OCGT
Year	2035
Size(MWe)	100 MW

Use cases

Load Factor	0.5%

VC2 Peaking electricity generation using hydrogen
Peaking electricity generation using commodity market hydrogen supplied via a hydrogen network.

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Value Chain 2 – Levelised cost analysis

Base line key outputs and assumptions

Key Financial Inputs Values

Weighted Average Capital Cost	5%
Hydrogen Cost Delivered	130

Baseline Levelised Costs(£/MWh)

Cost of Electricity	3220

Key assumptions

- Hydrogen costs has been estimated at a central cost of £130/MWh, based on VC6 considering VC5 curtailment cases has more uncertainty.
- Calculated as a small 100MW OCGT turbine, considering very low load factor of 0.5% plant for very in frequent peaking support (50 hours per year).
- Load factor is based on market sizing from WP4.
- Baseline assumption is new build OCGT, while a large number of OCGT currently operate that could potentially be retrofitted. It is uncertain if these will be suitable 2035 and beyond.

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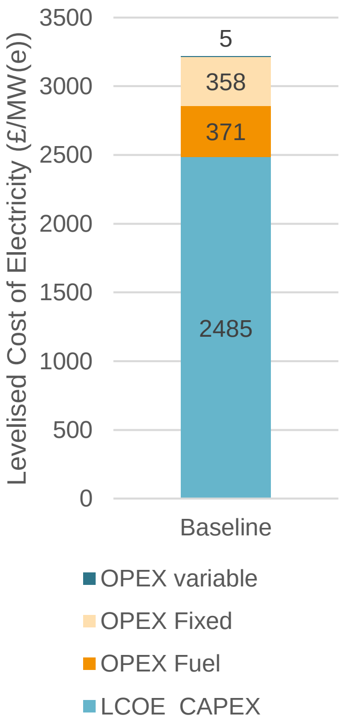
Value Chain 2 – Levelised cost analysis

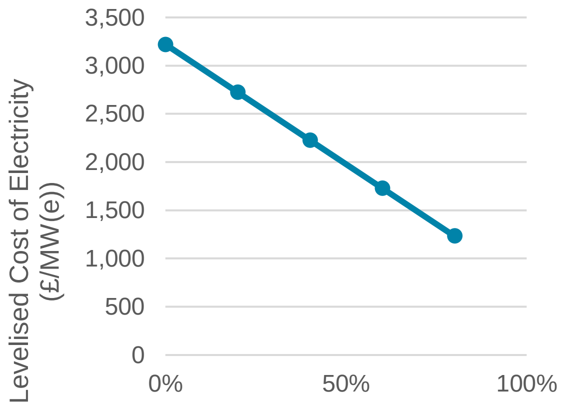
Sensitivity analysis

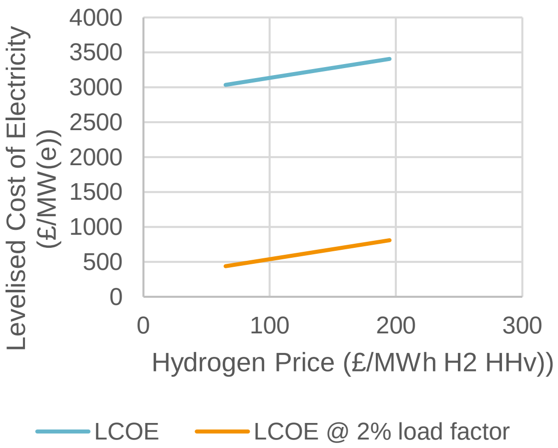
Key variables impacting the levelised cost of electricity for peaking OCGT

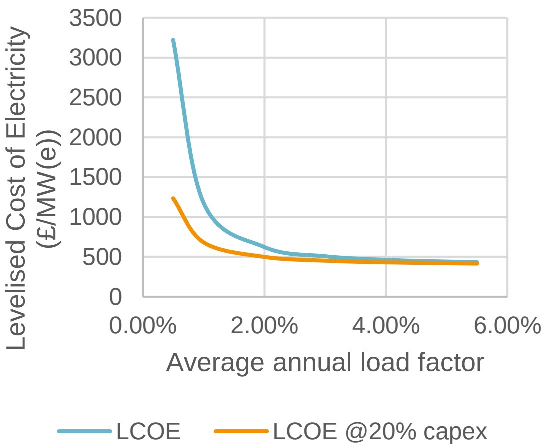
Breakdown of baseline LCOE



- Capital cost play a large role determining the ultimate cost of electricity for this value chain – this is due to the low load factor assumed at 0.5%. Reducing capex has direct proportional impact on the LCOE.
- Increasing the load factor even by very small margins, greatly reduces the levelised cost of electricity. As load factor increases to around 3%, electricity price stabilises at approximately £380/MWh(e) (hydrogen price of £130/MWh)
- At low load factors the relative impact of hydrogen price on the LCOE is limited, but relatively more significant at higher load factors, +/-50% change in hydrogen cost had a only 5% impact to the baseline, but 30% impact at 2% load factor.







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Value Chain 3 – Levelised cost analysis

Asset Structure and Scenario inputs

Infrastructure Components

End Use

Assets

Asset	CCGT (Class H)
Year	2035
Size(MWe)	1200

Use cases

Load Factor	5%

VC3 Mid-merit electricity generation using hydrogen
Mid-merit electricity generation using commodity market hydrogen supplied via a hydrogen network.

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Value Chain 3 – Levelised cost analysis

Base line key outputs and assumptions

Key Financial Inputs Values

Weighted Average Capital Cost	5%
Hydrogen Cost Delivered	130

Baseline Levelised Costs(£/MWh)

Cost of Electricity	530

Key assumptions

- Hydrogen costs has been estimated at a central cost of £130/MWh, based on value chain 6 considering SMR and curtailment cases with more uncertainty.
- Calculated as a 1200MW CCGT turbine, analogous to current mid-merit gas power plants.
- Low load factor of 5% is based on market sizing from WP4 – considering the large wind capacity 2035-2050.
- Baseline assumption is new build CCGT, similar to VC2 while a large number of CCGT currently operate that could potentially be retrofitted. It is uncertain if these will be suitable 2035 and beyond.

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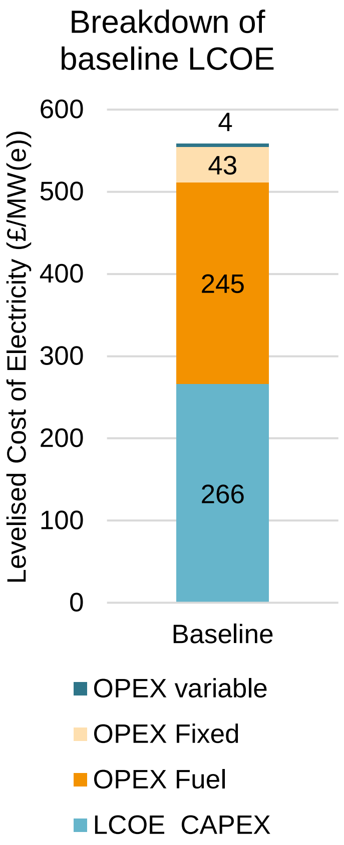
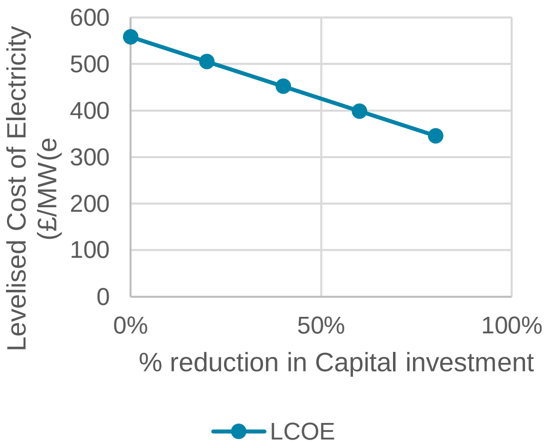
Value Chain 3 – Levelised cost analysis

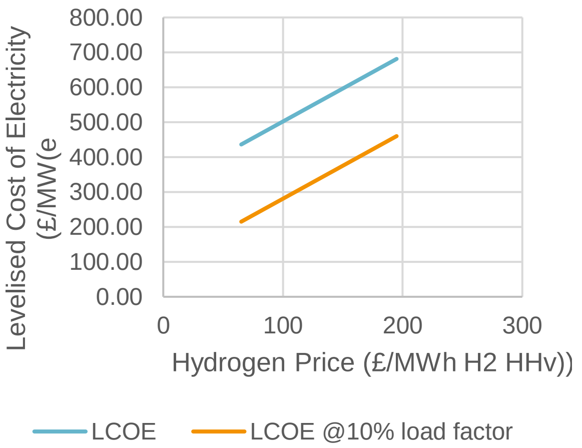
Sensitivity analysis

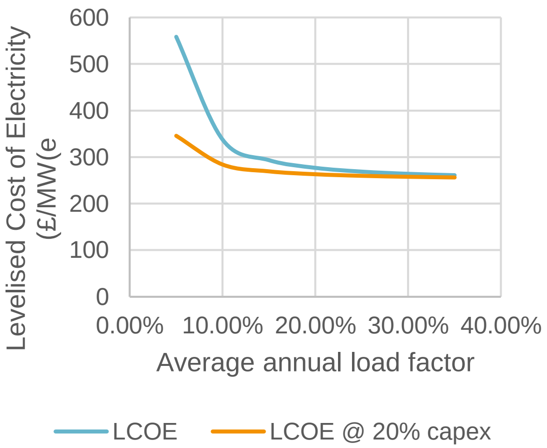
Key variables impacting the levelised cost of electricity for “mid-merit” CCGT



- For the VC 3 baseline, the primary drivers to LCOE is split approximately 50:50 between hydrogen costs and capital recovery.
- Similar to VC 2, small increases in the load factor greatly reduce the levelised cost of electricity. As load factor increase from 5-20%, electricity price stabilises at approximately £250/MWh(e) (hydrogen price of £130/MWh)
- LCOE is more sensitive to hydrogen price compared to VC2, with +/- 50% change in hydrogen price causing 20% change in LCOE, this increase to 35% change at a 10% load factor.
- Capital investment reduction, through retrofit or other means will have a substantial impact on the LCOE.







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Value Chain 4 – Levelised cost analysis

Asset Structure and Scenario inputs

Infrastructure Components	Production	Storage	Distribution
Assets	Asset: SOE Year: 2025 Size (MWe): 500	Storage Asset: None/ Linepack	Transmission Asset: Pipeline Local Distribution: Pipeline
Use cases	Utilisation Rate: 50%		Transmission Distance: 100 km Distribution Distance: 50 km

VC4 Nuclear hydrogen for injection into hydrogen networks
Electrolysers that are being installed at existing or new large-scale nuclear power stations built isolated locations.

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Value Chain 4 – Levelised cost analysis

Base line key outputs and assumptions

Key Financial Inputs Values

Electricity Cost Production (£/MWh)	106.1
Water Cost (£/L)	0.0015
Electricity Cost Storage* (£/MWh)	106.1
Weighted Average Capital Cost	5%

*Compression costs

Baseline Levelised Costs(£/MWh)

Production	130
Storage	0
Distribution	3.9
Average hydrogen cost delivered	134

Key assumptions

- Electricity cost of Nuclear is assumed to be matching the current CfD price (Hinkley Point C) – on the basis that operating the electrolyser has no impact on nuclear plant profitability.
- Due to heat integration opportunities at nuclear facility, the electrolyser is the SOE design, which has a high electrical efficiency, but higher capital and operational maintenance costs.
- The electrolyser is assumed to be used to improve the flexibility of the nuclear plant (e.g. allowing turn down of power export without impact nuclear operation). Based on this utilisation is assumed to be 50%, balancing flexible operation, while ensuring enough operation to offset higher SOE capital investment.
- This value chain is assumed co-located to the nuclear facility without storage but rather direct injection into a gas distribution network.

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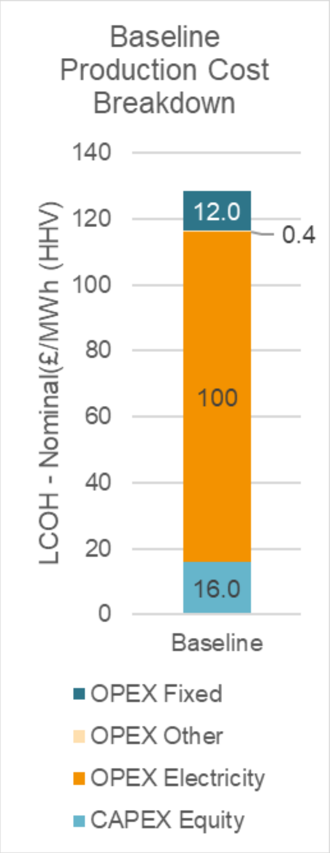
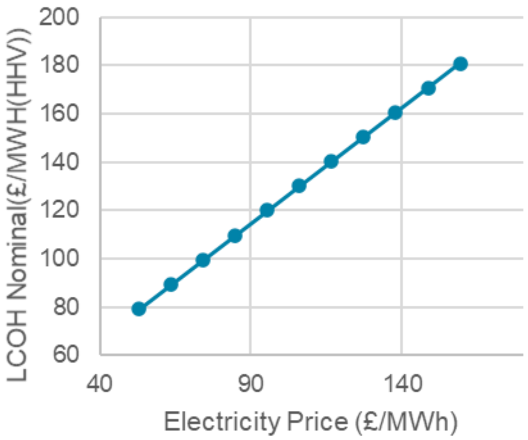
Value Chain 4 – Levelised cost analysis

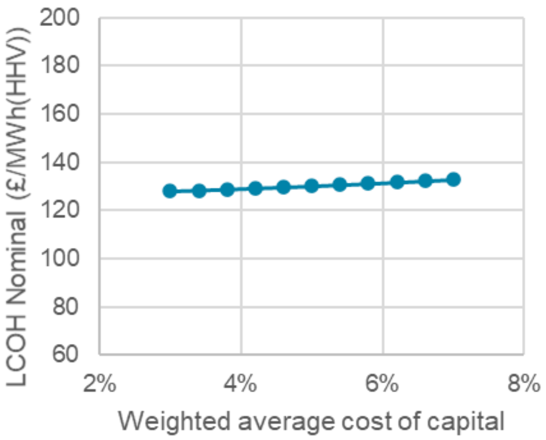
Sensitivity analysis

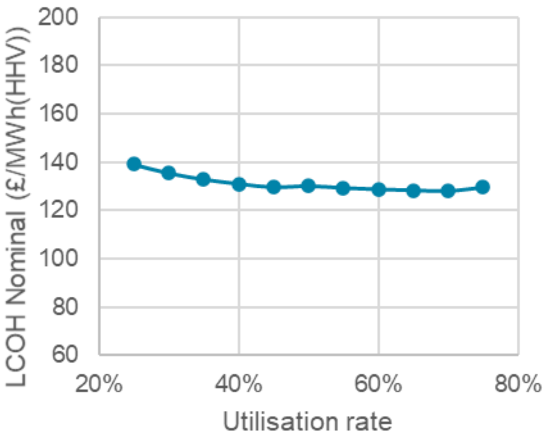
Key variables defining the average cost of Hydrogen produced



- The production cost breakdown (left) shows that the levelised cost of hydrogen production in this case is dominated by the electricity cost, accounting for 78% of the total costs.
- Relatively high electricity costs from Nuclear (when considering subsidy level), means relatively high production costs of £130/MWh. Base assumption on electricity price provides great uncertainty – Nuclear plant may accept significantly lower electricity price when it can't sell electricity to the grid. (e.g. in scenarios when Nuclear plant would not normally be operating).
- Changes in the WACC and utilisation rate have a minimal impact on the LCOH when compared to changes in the cost of electricity.







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Value Chain 5 – Levelised cost analysis
Asset Structure and Scenario inputs

Infrastructure Components	Production	Storage	Distribution
Assets	Asset: PEM Year: 2035 Size (MWe): 200	Storage Asset: Salt Cavern Size (GWh): 19	Transmission Asset: Pipeline Local Distribution: Pipeline
Use cases	Utilisation Rate: 25%	Utilisation Type: Both Inter-day & seasonal	Transmission Distance: 100 km Distribution Distance: 50 km

VC5 Electrolysis for curtailment mitigation
Electrolyser directly connected to renewable generation asset producing hydrogen using renewable energy that would otherwise be curtailed. The hydrogen produced is then sent onto the hydrogen network.

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Value Chain 5 – Levelised cost analysis
Base line key outputs and assumptions

Key Financial Inputs Values

Electricity Cost Production (£/MWh)	20
Water Cost (£/L)	0.0015
Electricity Cost Storage* (£/MWh)	90.9
Weighted Average Capital Cost	5%

*Compression costs

Baseline Levelised Costs(£/MWh)

Production	45
Storage (contribution to average price)	35(8)
Distribution	7
Average hydrogen cost delivered	59

Key assumptions

- Electricity cost is estimated at £20/MWh – this is half the current contract for difference awards for large offshore wind farms(£40/MWh)
- PEM electrolyser is used, due to relatively balanced capex, performance and flexibility
- Electrolyser utilisation factor is assumed to be 25% on average on the basis that the electrolyser is sized such that it can achieve this consistently based on the wind power available.
- It is assumed operation will have very high variability, therefore both long periods without operation and daily variations, therefore requiring both seasonal and daily storage requirements, but overall large storage capacity necessitating salt cavern storage.
- Assumed co-located with renewables, therefore significant transmission and distribution distance necessary.

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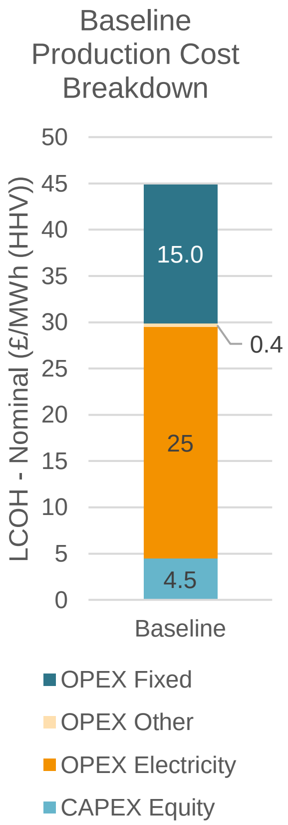
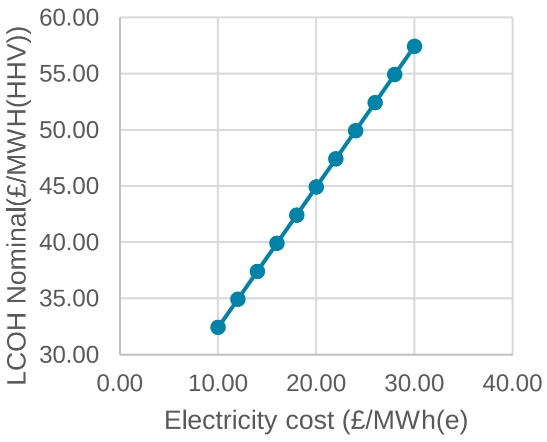
Value Chain 5 – Levelised cost analysis

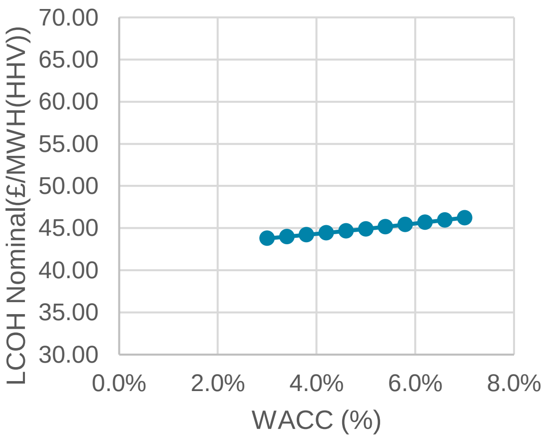
Sensitivity analysis

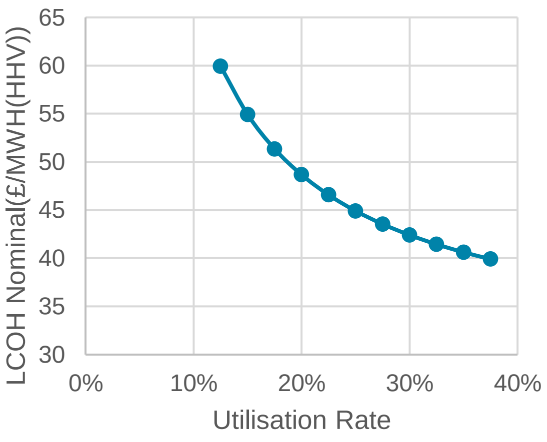
Key variables defining the average cost of Hydrogen produced



- Production costs are primarily driven by electricity prices, however, with low utilisation rates, fixed operational costs have a significant role at around 33% of the costs.
- Production cost of hydrogen is sensitive to utilisation rate when the electricity costs are relatively low. Halving the utilisation rate from 25% to 12.5%, increased hydrogen production costs by 33%(when electricity price is fixed). At low electricity costs, the capital cost components and therefore the utilisation rate becomes high significant driver for overall costs.
- Cost of capital is relatively low impact resulting in +/- 5% in the cost of hydrogen over the range analysed.







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Value Chain 6 – Levelised cost analysis

Asset Structure and Scenario inputs

Infrastructure Components	Production	Storage	Distribution
Assets	Asset: PEM; Year: 2025; Size (MWe): 200	Storage Asset: Salt Cavern; Size (GWh): 38	Transmission Asset: Pipeline; Local Distribution: Pipeline
Use cases	Utilisation Rate: 50%	Utilisation Type: Both Inter-day and seasonal	Transmission Distance: 50 km; Distribution Distance: 10 km

VC6 Centralised green hydrogen at onshoring point for transport near industrial clusters or ports
Transport distribution hubs (including HGVs, trains, forklifts etc) near industrial clusters or ports.

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Value Chain 6 – Levelised cost analysis

Base line key outputs and assumptions

Key Financial Inputs Values

Electricity Cost Production (£/MWh)	76.5
Water Cost (£/L)	0.0015
Electricity Cost Storage* (£/MWh)	90.9
Weighted Average Capital Cost	5%

*Compression costs

Baseline Levelised Costs(£/MWh)

Production	117
Storage (contribution to average price)	35(8)
Distribution	5
Average hydrogen cost delivered	130

Key assumptions

- Electricity cost for production is assumed to be based on long term agreements to control the risk and cost and provision of energy to ensure demand provision is met. BEIS LRVC - industrial low 2025-2055.
- Utilisation of the electrolyser is assumed 50% - broadly matching the availability of offshore wind to ensure continuous green hydrogen production.
- Assumed to be relatively closely located to storage and demand therefore limited transmission and distribution distance via pipeline.
- Storage is assumed to be salt cavern to provide both daily and seasonal balancing. Electricity price is assumed to be less secured for storage therefore central LRVC industrial 2025-2055.

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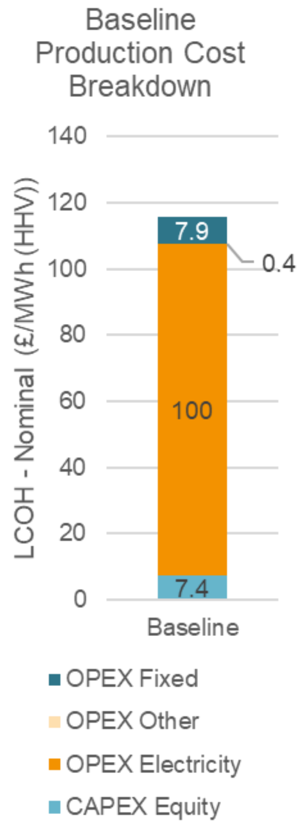
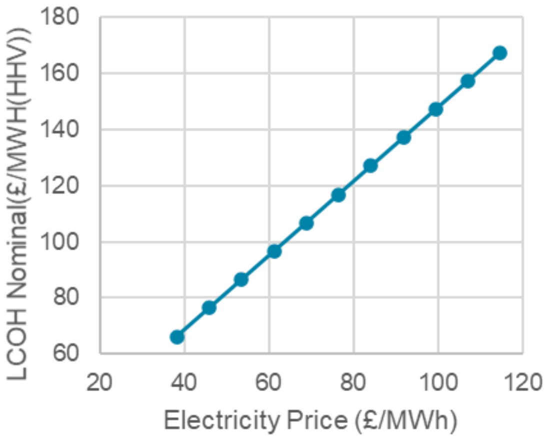
Value Chain 6 – Levelised cost analysis

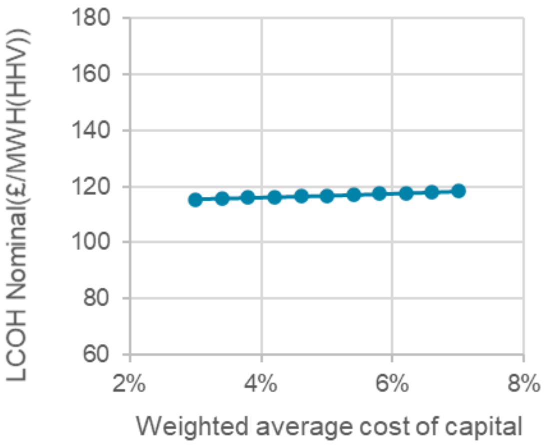
Sensitivity analysis

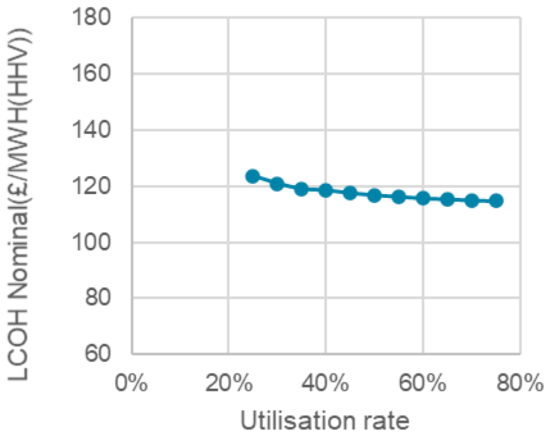
Key variables defining the average cost of Hydrogen produced



- Hydrogen production costs in value chain 6 are heavily linked to electricity price, which accounts for 85% of the cost hydrogen produced.
- Increasing utilisation rate has negligible impact on the cost of hydrogen(~2% decrease at fixed electricity prices), reducing utilisation by half to 25% increased LCOH by 6%.
- Financial cost of capital have relatively small impact +/- 2% on the cost hydrogen produced







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Value Chain 7 – Levelised cost analysis

Asset Structure and Scenario inputs

Infrastructure Components	Production	Storage	Distribution
Assets	Asset: PEM Year: 2025 Size (MWe): 2	Storage Asset: Pressure vessel Size (GWh): 0.06	Local Distribution: Truck
Use cases	Utilisation Rate: 40%	Utilisation Type: Inter-day	Distribution Distance: 10 km

VC7 Decentralised green hydrogen for use in heavy road and rail transport
Distributed electrolysers that will be collocated with hydrogen refuelling stations.

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Value Chain 7 – Levelised cost analysis
Base line key outputs and assumptions

Key Financial Inputs Values

Electricity Cost Production (£/MWh)	76.5
Water Cost (£/L)	0.0015
Electricity Cost Storage* (£/MWh)	90.9
Weighted Average Capital Cost	5%

*Compression costs

Baseline Levelised Costs(£/MWh)

Production	117
Storage (contribution to average price)	(31)31
Distribution	0
Average hydrogen cost delivered	148

Key assumptions

- Electricity cost for production is assumed to be based on long term agreements to control the risk and cost and provision of energy to ensure demand provision is met. BEIS LRVC- industrial low 2025-2055.
- Utilisation of the electrolyser is assumed 50% - broadly matching the availability of offshore wind to ensure continuous green hydrogen production.
- Assumed to co-located with demand, therefore no distribution
- Storage is assumed to be local high pressure vessels(430 bar) to providing daily balancing services. Electricity price is assumed to be less secured for storage therefore central LRVC industrial 2025-2055.

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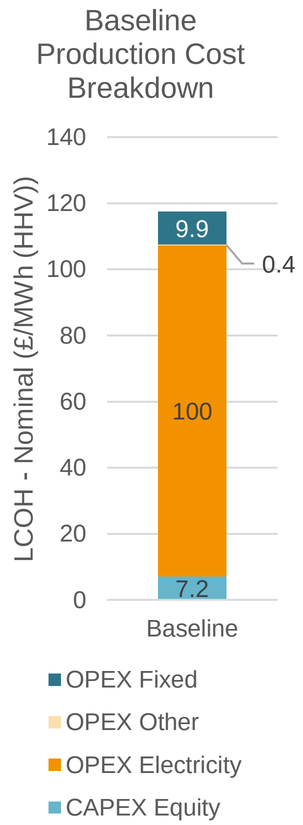
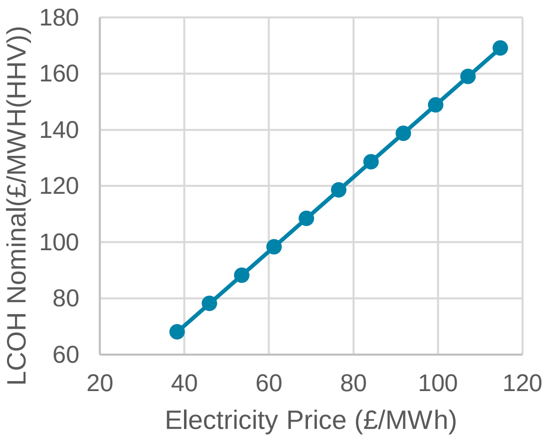
Value Chain 7 – Levelised cost analysis

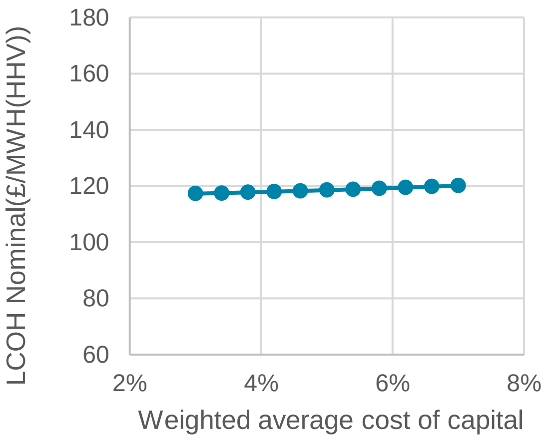
Sensitivity analysis

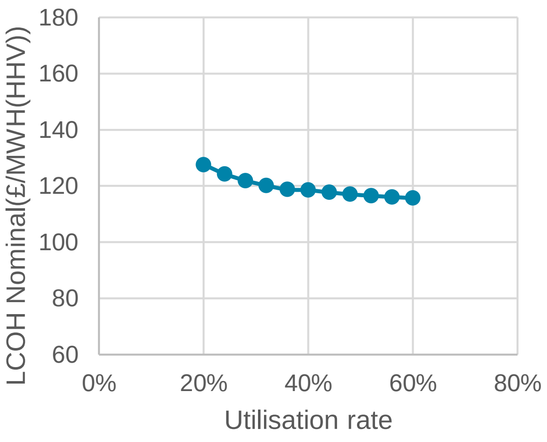
Key variables defining the average cost of Hydrogen produced



- Hydrogen production costs in value chain 7 are heavily linked to electricity price, which accounts for 83% of the cost hydrogen produced.
- Increasing utilisation rate has negligible impact on the cost of hydrogen(~3% decrease at fixed electricity prices), reducing utilisation by half to 25% increased LCOH by 7%.
- Financial cost of capital have relatively small impact +/- 2% on the cost hydrogen produced







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Value Chain 10 – Levelised cost analysis

Asset Structure and Scenario inputs

Infrastructure Components	Production	Storage	Distribution
Assets	Asset: PEM Year: 2035 Size (MWe): 500	Storage Asset: Salt Cavern Size (GWh): 447.8	Local Distribution: Pipeline
Use cases	Utilisation Rate: 75%	Utilisation Type: Both Inter-day and seasonal	Distribution Distance: 50 km

VC10 Green hydrogen production for industrial use in a cluster

Large-scale green hydrogen provision for industrial end use, potentially replacing blue hydrogen in a cluster.

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Value Chain 10 – Levelised cost analysis

Base line key outputs and assumptions

Key Financial Inputs Values

Electricity Cost Production (£/MWh)	91.7
Water Cost (£/L)	0.0015
Electricity Cost Storage* (£/MWh)	91.7
Weighted Average Capital Cost	5%

*Compression costs

Baseline Levelised Costs(£/MWh)

Production	126
Storage (contribution to average price)	35 (24)
Distribution	6
Average hydrogen cost delivered	156

Key assumptions

- Electricity cost is long run variable cost (BEIS) – medium utilisation, centralisation and consistent industrial user base requiring long fixed power purchasing agreement to secure power, but due to higher utilisation consistently lower prices harder to achieve.
- Utilisation is assumed to be higher at 75% due to the requirement to provide very consistent demand to industrial users.
- As a centralised location close to industry, but with distribution to reach all customers.
- Requirement of both seasonal and daily storage cycling to ensure demand is met.

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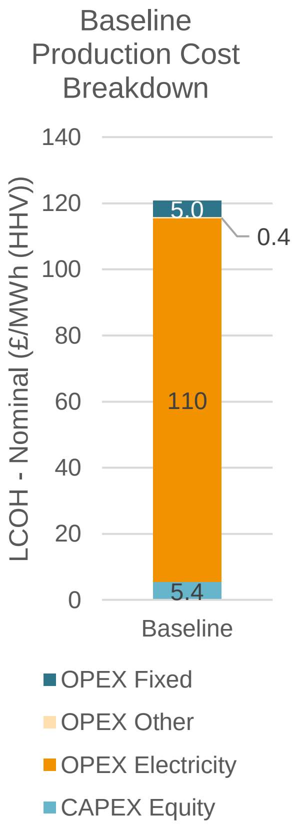
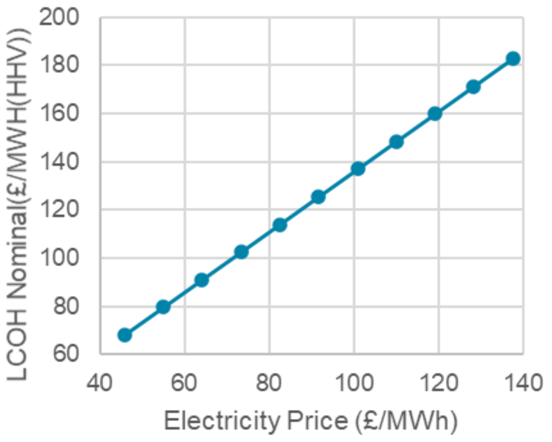
Value Chain 10 – Levelised cost analysis

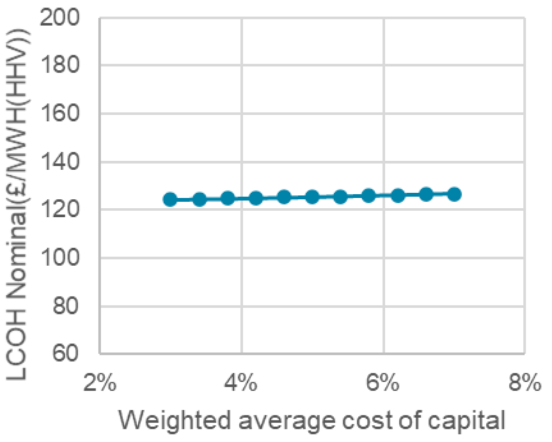
Sensitivity analysis

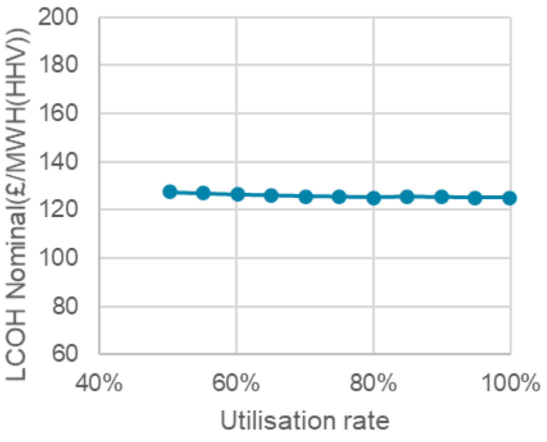
Key variables defining the average cost of Hydrogen produced



- Hydrogen production costs in value chain 10 are heavily linked to electricity price, which accounts for 87% of the cost hydrogen produced. As this is produced hydrogen, rather than delivered, it does not include storage costs.
- Increasing utilisation rate has negligible impact on the cost of hydrogen(~2% decrease at fixed electricity prices), reducing utilisation by half to 25% increased LCOH by 6%.
- Financial cost of capital have relatively small impact +/- 2% on the cost hydrogen produced







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Summary Baseline results

Breakdown of levelised cost by value chain

The table presents the baseline values for the levelised cost of hydrogen, broken down by production, storage, distribution.

The delivered value is the average cost of hydrogen for end use, taking into account average of produced and directly distributed hydrogen and the cost of produced, stored and distributed hydrogen.

LCOE is based on key baseline assumptions on load factor and hydrogen cost.

The levelised costs are highly sensitive to input assumptions and should considered be used with respect to the input assumptions.

		LCOH (£/MWh H2 HHV)				LCOE (£/MWh(e))
Value chain#	**Value Chain Description**	**Production**	**Storage (contribution to delivered)**	**Distribution**	**Delivered**	**Generation**
VC1	Blue Hydrogen	49	35(6)	9	**63**	
VC2	Peaking Electricity					**3220**
VC3	Mid-merit electricity generation using hydrogen.					**558**
VC4	Centralised Nuclear-no storage	130	0(0)	4	**134**	
VC5	Electrolysis for curtailment mitigation	45	35(8)	7	**59**	
VC6	Centralised green hydrogen at onshoring point	117	35(8)	5	**130**	
VC7	Decentralised green hydrogen production	117	31(31)	0	**148**	
VC10	Centralised green hydrogen production for industrial use	126	35(24)	6	**156**	

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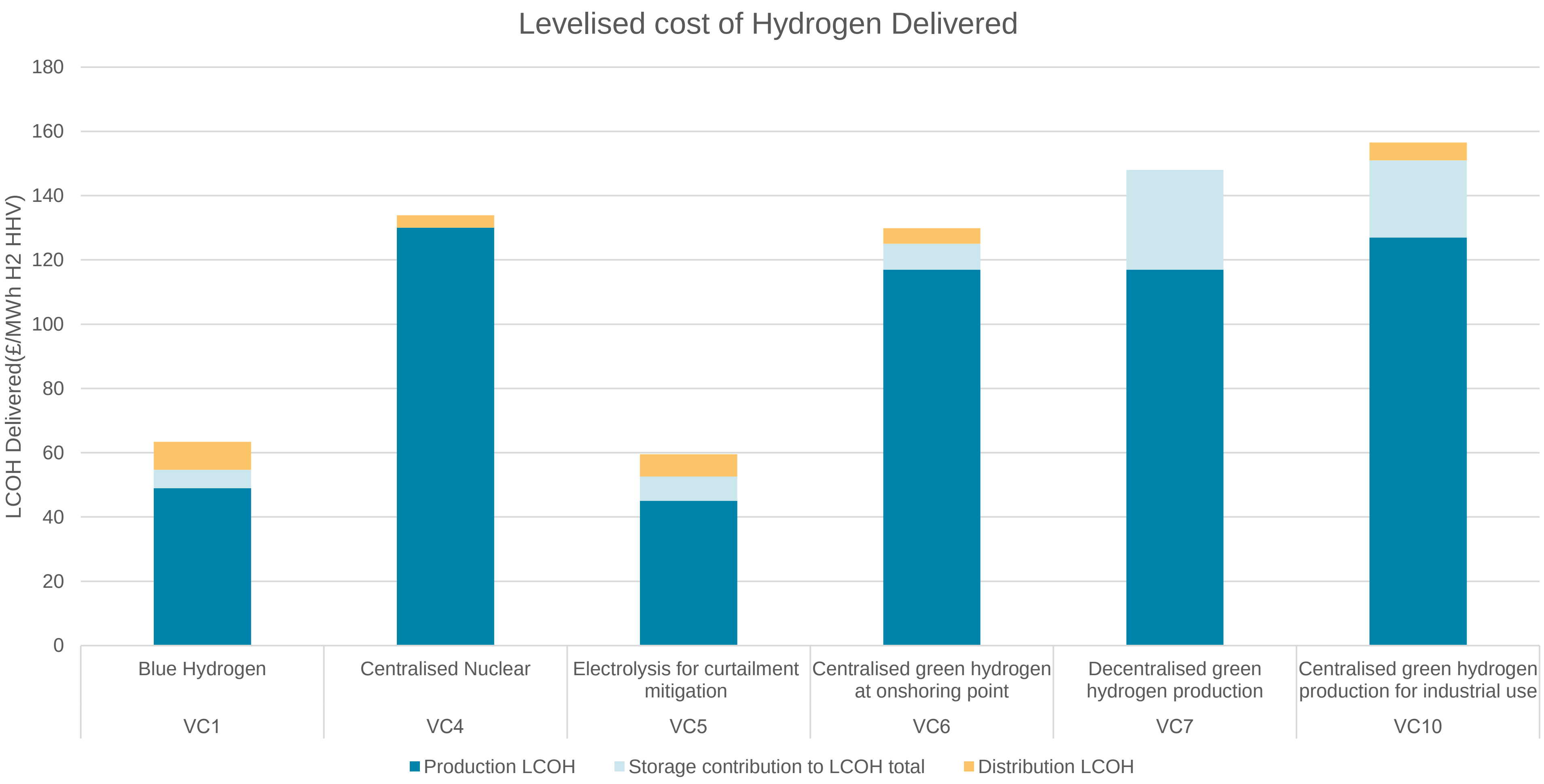
Summary Baseline results

Break down of baseline

This graph shows the levelised cost of hydrogen delivered.

This is average cost between stored and directly produced hydrogen.

The costs are broken down by production, storage contribution and distribution.



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Cost of Seasonal Storage

Impact of seasonal storage on cost of electricity

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Key drivers for levelised cost of storage

What makes the biggest difference in storage costs

The levelised cost of storage is driven by how efficiently it is used. This is driven mainly by two key aspects:

- The intensity of usage, measured as the number of storage/discharge cycles per year
- The size of the store relative to the required usage.

Intensity of usage or utilisation of the store means a greater volume of hydrogen gas is processed per year. This increases the operational costs, mainly any necessary compression required; however it splits the capital costs over greater amount of material, thereby reducing the cost per MWh(or kg) of hydrogen stored and discharged.

In addition – more intensely used storage facilities can be smaller, as there is less need for storage over long periods.

It is hard to accurately forecast the exact size of storage needed. Therefore a degree of storage oversizing is a likely contingency, this will mean increased capital costs.

To understand the impact of these two drivers on levelised cost of storage, cost of hydrogen delivered and the cost of electricity a sensitivity analysis has been completed using value chain 6 as the baseline.

The following key storage usage intensity and storage size input have been used:

Cycles/annum	Size as % of electrolyser annual production volume
1	50.0%
2	33.3%
4	16.7%
8	8.3%

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Levelised cost of Storage

How much does storage cost per MWh of Hydrogen?

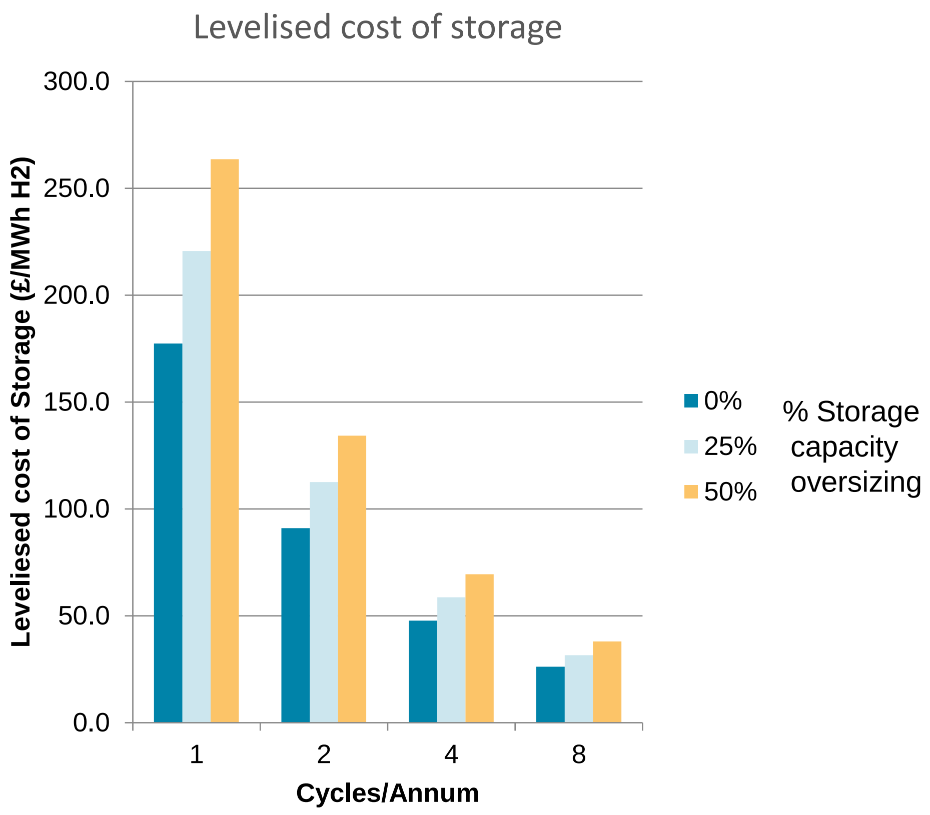
Levelised cost of storage per MWh, with three levels of storage oversizing: 0%, 25%, 50%

Oversizing will likely be necessary to provide system contingency, but the precise amount required is uncertain and case dependent. In all scenarios a proportion of gas is considered to be operating gas (cushion gas) which is not available for cycling.

The graph shows the greatest impact on the LCOS is the number of full cycles per annum.

- Seasonal storage, e.g. production in summer and usage in winter is equivalent to 1-2 cycles per annum.
- Daily/weekly cycling is broadly equivalent 4-8 cycles/annum. Note this requires complete discharge and recharge of the store every 1-3 months.

Oversizing has an almost proportionate impact on LCOS, e.g. 25% oversizing resulting in ~20-25% additional cost per MWh Hydrogen stored.



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Cost of Hydrogen Delivered

Impact of stored hydrogen on final hydrogen price

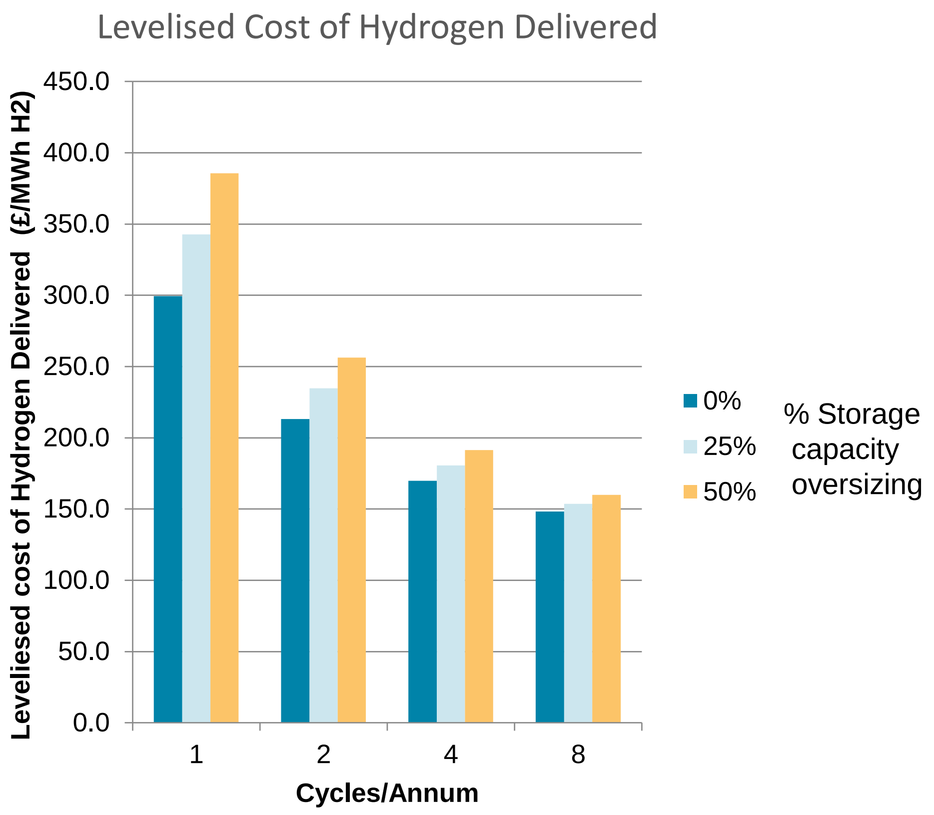
Levelised cost of hydrogen delivered considering fixed production and distribution cost, but variable storage duration and sizing

In this study the cost of production and distribution is assumed to be unaffected by the storage, however as further analysed in the value chain size optimisation. Operation of the electrolyser can impact the production costs.

For value chain 6 the cost of hydrogen production and distribution is estimated at ~£122/MWh.

In the case of a single cycle per year at 50% oversized, the hydrogen delivered is >300% more expensive than direct utilisation at ~ £400.0/MWh.

Whereas with the most intensely used storage at 8 cycles per year, the increase in Hydrogen cost is only ~21% at ~£150/MWh.



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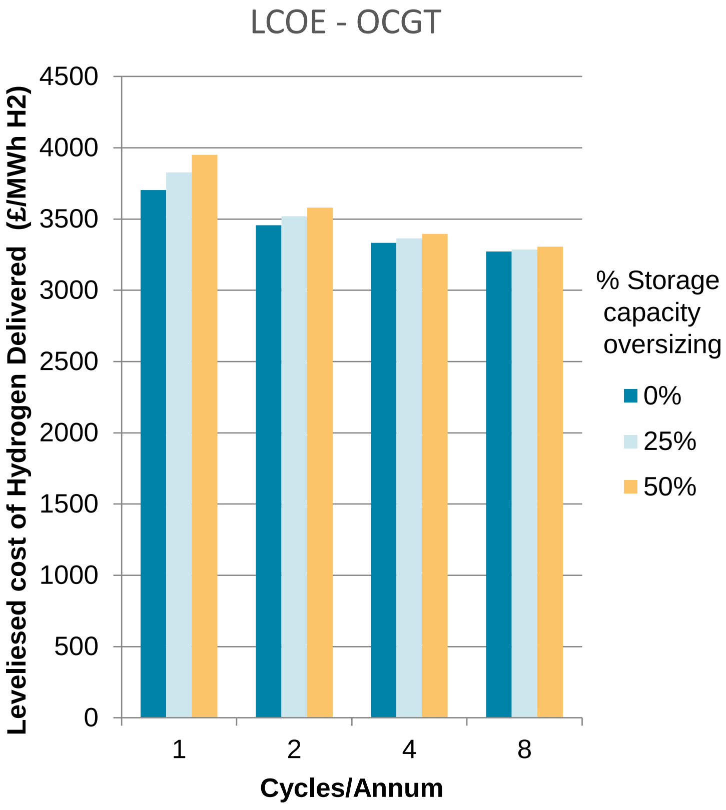
Impact on cost of electricity

How much does storage duration impact LCOE

Value Chains 2 and 3 have been used to estimate impact on cost of electricity on both OCGT and CCGT plants operating either as peakers or mid-merit load balancers.

OCGT plant has a very low load factor of 0.5%. As such it would only operate ~50 hours per year, and would be expected to use relatively secure sources of long stored hydrogen.

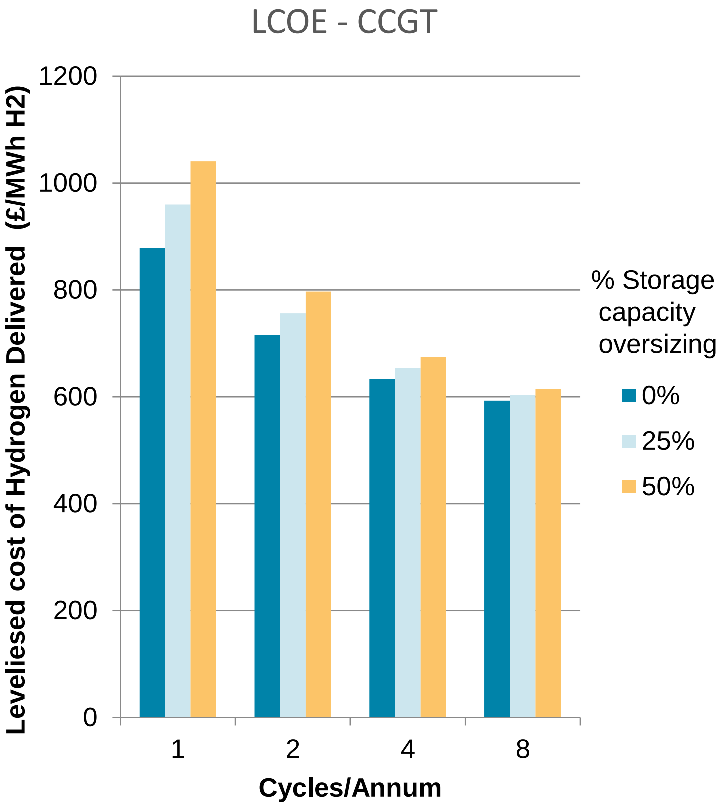
LCOE of OCGT range from ~£4000MWh(e) to ~£3200/MWh(e) for cheapest stored hydrogen, relatively low impact of hydrogen price.



CCGT plant in value chain 3 has a load factor of 5% and a relatively large capacity for 1200MW.

It would therefore also require large reliable stores of hydrogen to ensure operation for around 500 hours/year.

Costs range from ~£900/MWh(e) to ~£600/(MWh(e).



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Value chain size optimisation

Analysis of impact of electrolyser over sizing on storage requirements and levelised cost of hydrogen delivered.

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Value chain size optimisation

How this analysis has been approached

Value chain sizing has been analysed through a number of electricity price and electrolyser operation scenarios

A key question highlighted in the previous reports for WP2/3 and 4 is: How should electrolysers and storage sites be sized?

Within this value chain sizing optimisation, the aim is to identify the impact of storage and electrolyser sizing on the resulting levelised cost of hydrogen.

Storage aims to balance the dynamics of both supply side and demand side variability. In this analysis only supply side variability is considered. This analysis is based on value chain 6, which aims to deliver for industry with assumed stable demand.

Supply side dynamics are caused by the operating approach of the electrolyser and their approach to the electricity market.

In this analysis, sizing has been approached as means to deliver a specific annual volume of hydrogen, with different scenarios and operating use cases considered.

Key elements considered are:

- Amount of electricity available each year at different price points
- Possible operating regimes for electrolysers
- The maximum contiguity of different electricity prices
- Minimum storage sizes required
- Realistic storage sizes required.

The following slides explain in more detail the approach to the above elements; as key inputs into this analysis and the resulting impact on levelised cost of hydrogen.

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Electricity Price Scenarios and Operating Use Cases

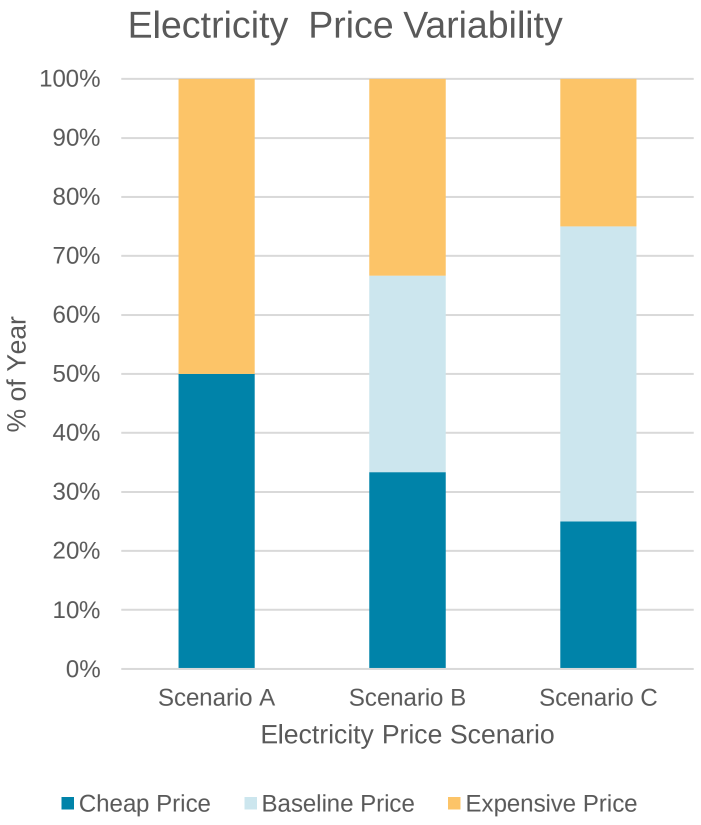
Defining the scenarios

The variability of electricity price, combined with the electrolyser operating plan define the resulting supply side variability.

Three electricity price scenarios were considered:

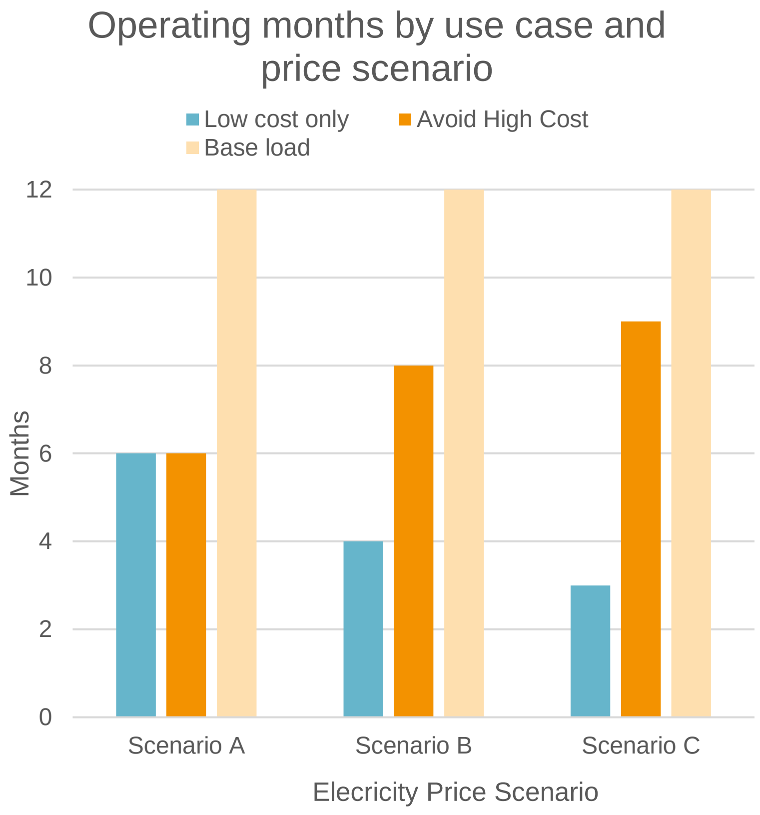
- **Scenario A** considers where half the year price is high and half the year low
- **Scenario B** is an equal split between price ranges.
- **Scenario C** scenario includes 6 months at baseline price and 3 at high and low prices

In this analysis prices are symmetric – high and low price are +/- 50% of the baseline price.



Three operating modes have been considered:

- **Low cost** - will only operate during period of low electricity pricing.
- **Avoid high cost** – operates during medium and low pricing.
- **Baseload** operates throughout the year with no regard to price.



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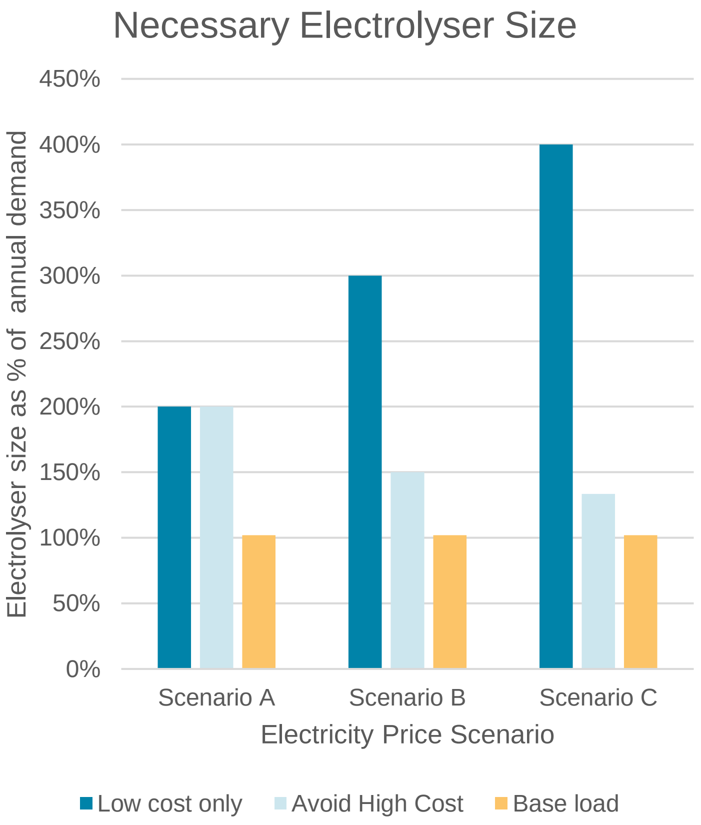
Electrolyser Size and Utilisation

Size and electrolyser utilisation are directly linked when meeting a specific annual demand

When optimising an electrolyser to meet a specific demand annually, using storage to smooth supply inconsistency, the electrolyser must be oversized to cover sufficient generation during the operational period.

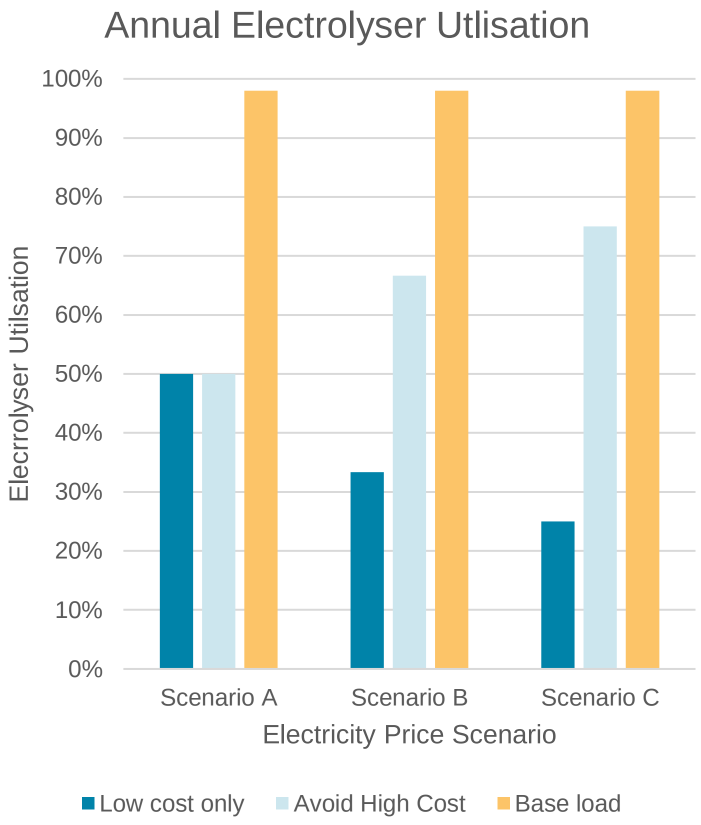
Baseload is sized at 102%, to account for 98% availability.



The effective annual utilisation is calculated to delivered sufficient annual demand.

However the average utilisation hides potentially long continuous periods of operation or idle time.

For the baseload case, final utilisation is assumed to match availability (98%), for other use cases, necessary maintenance down is assumed handled in idle periods.



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Minimum Storage sizing

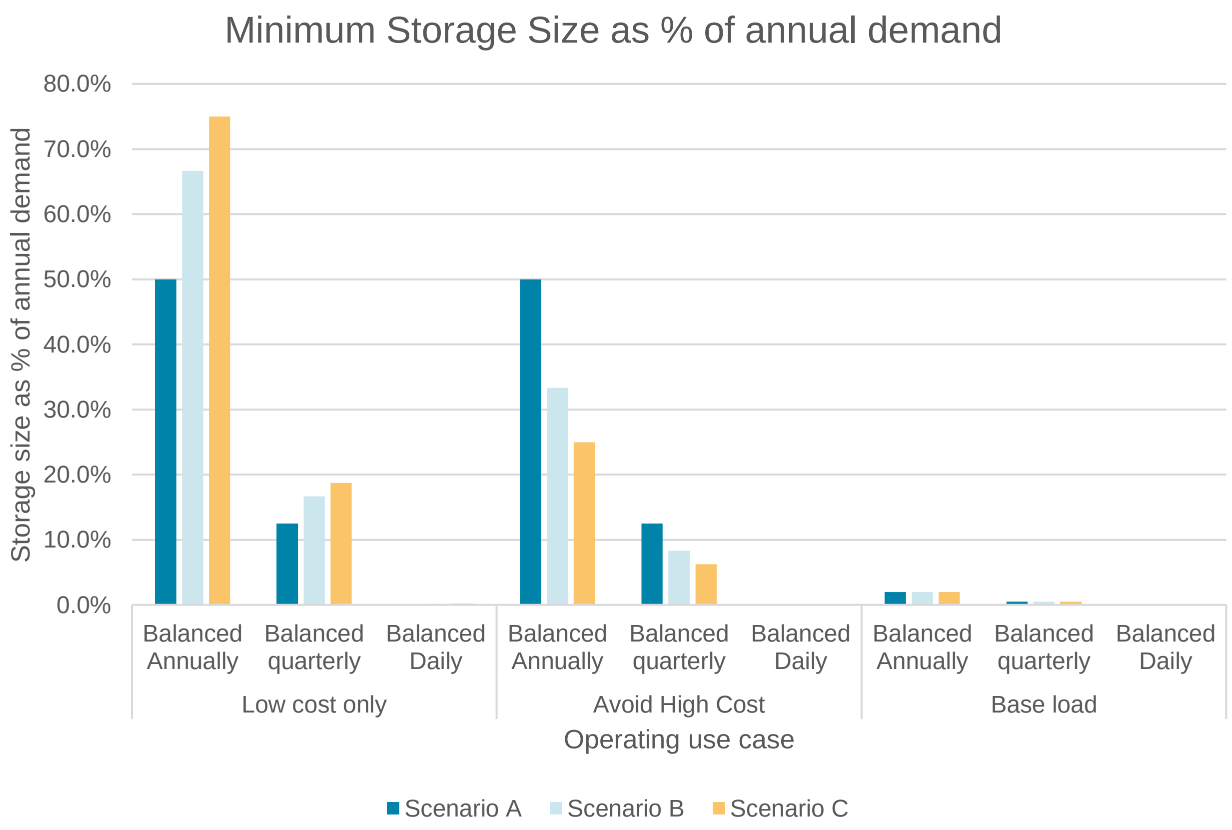
Minimum storage size is just enough to ensure capacity for the longest possible continuous storage operation.

To estimate the minimum size of storage capacity required, the main factor is the maximum duration of discharge required.

Three cases have been considered

- Balanced annually – where the storage is fully cycled only once per year.
- Balanced quarterly – where the store is cycled four times per year.
- Balanced daily – where the store is cycled every day.

The maximum size of the store is reduce, as the maximum available hydrogen that can be produced in each period.



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Adjusted Storage Sizing

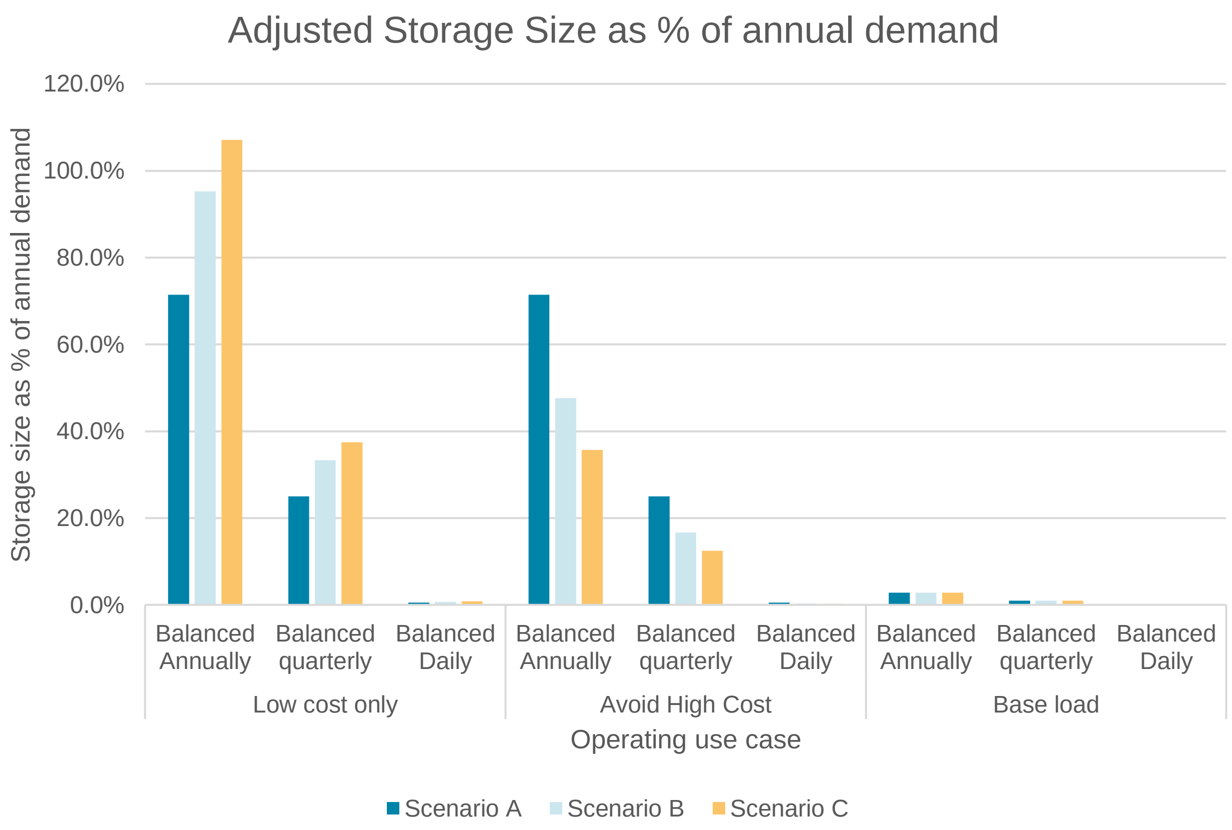
Realistic storage capacities need to account for contingency, smaller dynamics and operating gas requirements.

However – the minimum storage size is unrealistic – it does not account for significant variability in usage, e.g. smaller dynamic, in addition to the requirement to have some working gas to maintain operating pressure (known as cushion gas).

The below table shows the assumed number of cycles and depth of the store filled/discharged.

The storage sizes were adjusted proportionally to these operations.

Usage Profile	Number of cycles/ year	Cycle Depth
Balanced Annually	1	70%
Balanced quarterly	4	50%
Balanced Daily	365	25%



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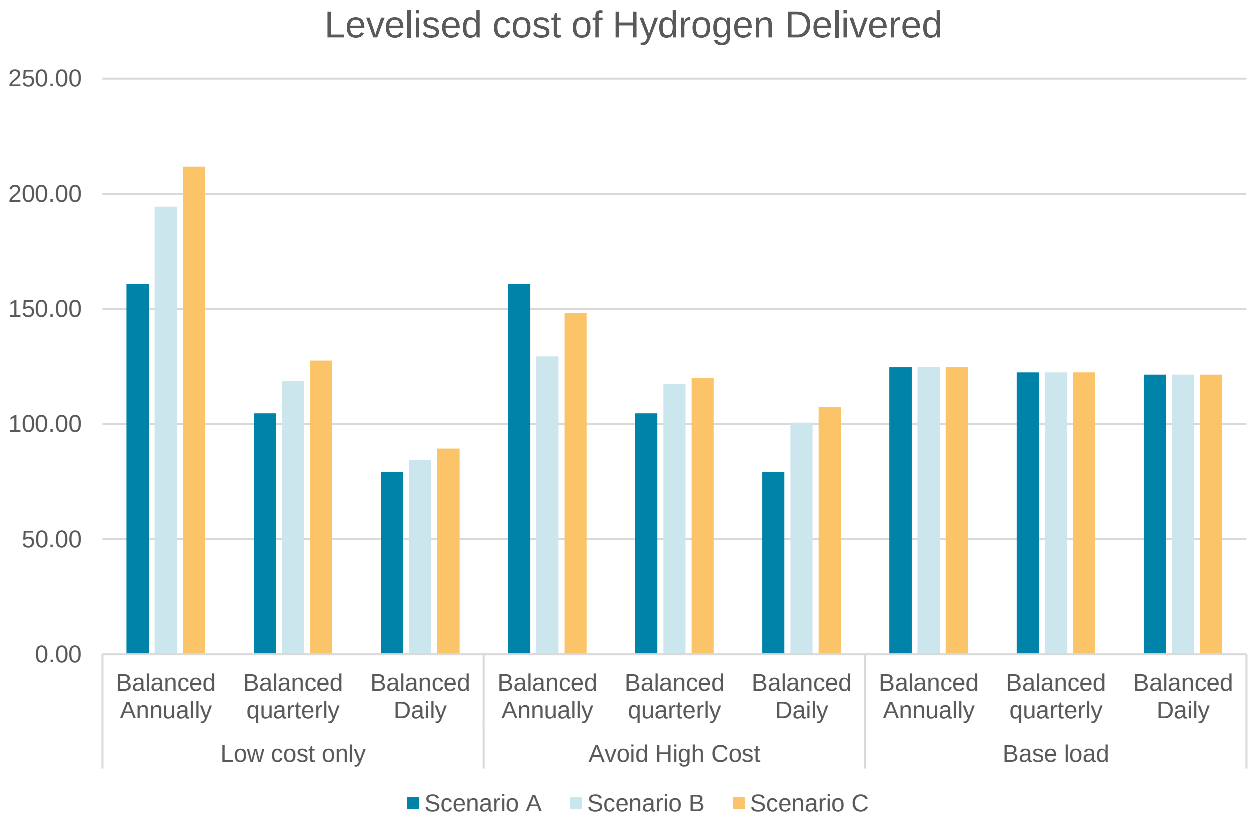
Levelised Cost of Hydrogen Delivered

Intensively utilised storage can reduce the cost of hydrogen by allowing access to low electricity price, this depends greatly on the electricity market.

The results show oversizing electrolysers to optimise use of low cost of electricity is only effective when storage is minimised and used efficiently.

Markets with high electricity price variability that allow storage to be used on daily or quarterly basis can potentially reduce cost of hydrogen compared to base load operation.

If storage is used at very low frequency (e.g. once per year), then capex from storage overshadows electricity price savings.



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Limitations and areas for further analysis

Limitations

- The study relies on symmetric low/high pricing, high prices are likely significantly further from the average than low prices, but relative volume at different price ranges are also critical.

- Storage and discharge constraints can limit the potential benefits of storage, by increase capital costs or constraining usage, which has not been assessed.

- Timing of compression and access to electricity could impact effectiveness of frequent storage.

- Demand side flexibility requirements could considerably change the profile of storage requirements depending on end use.

Further Analysis

An improved analysis will allow a more accurate estimation of electrolyser and storage size for real world scenarios. This is essentially to simulate the impact of electrolysers on the grid, importantly the potential peak loads that electrolysers will require on the grid, which could be significantly higher where electrolysers are oversized.

To achieve an improved analysis:

- Implement real hourly annual electricity price supply curves
- Implement real demand hydrogen demand potentially including demand stacking
    - Seasonal and high variability heat demand
    - Variable transportation demand
    - Variable electrical generation demand
    - Static industrial demand
- Calculation of storage requirements to meet peak annual demands

- Include constraints on storage delivery rates(charge or discharge) as limitation on performance or requiring additional investment cost.

- Include consideration of economies of scale for larger electrolyser/storage facilities or staged construction (feasible in salt cavern construction).

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Summary

Conclusions and areas for further analysis

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Conclusions and Further Analysis Opportunities

Value Chain overview and Hydrogen Production

Energy input costs dominate average hydrogen costs and hydrogen production costs more than any other factor

Value Chain baseline
Baselining shows two potential average price ranges for delivered hydrogen, with critical assumptions underlying the potential price points.

SMR and curtailed green electrolysers have the potential to provide electricity at approximately £60/MWh. However this depends heavily on the through life natural gas and electricity prices.

Other value chains are not expected to be able to access the same volume of cheap electricity and present a higher price point of £130-150/MWh.

Further analysis integrating the dynamics of supply and demand with electricity prices is critical to effectively predict both the hydrogen price and the impact on the electricity system.

Hydrogen Production
The fundamental uncertainty regarding the cost of hydrogen production is the cost of electricity the electrolysers can consistently access. At current industrial forecast rates, electricity costs account for >75% of the cost of hydrogen produced. Priority for electrolyser operators will be needed to secure predictable, lower cost electricity to ensure competitive hydrogen production.

There is potential for electrolyser oversizing when paired with appropriate storage. However, this may be niche and requires predictable electricity pricing and demand with efficiently utilised storage.

Further analysis on opportunities for electrolysers to capture electricity at volume, at lower than wholesale market price is critical to identifying real average hydrogen prices.

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Conclusions and Next Steps 1/2

Hydrogen storage and power generation

Efficient utilisation of Hydrogen storage and power generation assets are key to determining the factors in levelised cost of storage and electricity

Hydrogen Storage
Hydrogen storage costs can vary substantially depending in the specific value chain and it is critical that storage is used efficiently.

When used seasonally, the cost of storage is greatly increased and has potentially significant consequences on certain end use cases.

In the best-case scenarios, optimization of storage may enable electrolysers to access lower energy costs and reduce the average cost of hydrogen.

Further analysis can combine more detailed hydrogen production modelling with locational and performance constraints for storage facilities.

Power Generation
Power generation using hydrogen will depend highly on the source of the hydrogen delivered and the load factor achievable by power generation facilities.

Cost variance in the region of >100% is feasible, therefore significant potential optimization is necessary to minimize costs and maximize profits.

For peaking plants (OCGT) cost mitigation may be feasible by optimizing load factors and volumes required.

Even at 5% load factor, a large volume of hydrogen will be required for CCGT and therefore need reliable supply which means potentially high hydrogen storage costs.

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Conclusions and Next Steps 2/2

Final observations and next steps for WP8

The Hydrogen economy and electricity markets are fundamentally linked through the electrolysers dependence on large volumes of electricity.

Detailed analysis of one market without the other reduces the overall usefulness of the analysis.

There remains a number of key uncertainties when estimating hydrogen costs and impacts on the electricity system.

- How much will electrolysers pay for electricity vs. how much end users will be willing to pay for hydrogen.
- How will hydrogen storage costs be distributed to customers.
- Impact of hydrogen demand variability due to hydrogen price.
- Impact of existing and future subsidies on both electricity market and hydrogen market.

Critically, the significant dependence of electrolysers on large volumes of electricity means forecasting hydrogen pricing without reliable electricity market modelling is challenging. Likewise, large scale of hydrogen electrolysers will have an impact on the electricity market, therefore dynamics of both need to be analysed together.

Electrolysers for flexibility services

As electrolysers are forecast to have large, potentially flexible demands, they could play a role in the balancing market by offering electricity (by switching off or turning down) or by bidding for additional electricity(switching on or turning up).

The key determining factors, will be the fundamental cost of providing these services and how well flexibility will fit in with specific electrolyser business models.

WP8 will estimate a range of potential offer and bid prices for electrolysers, covering **VCs 4-7 and 10**, using the baseline results in WP5 as the basis for the calculations.

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