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ENERGY RESEARCH

HYDROGEN
FOR A NET ZERO GB:
an integrated energy market perspective

Foreword

Last year, UK set in legislation a bold ambition to fully decarbonise our economy by 2050. This will involve a transformation of the way we generate, store and utilise energy to heat our buildings, produce goods, and move around. Delivering on this will be a key societal challenge over the next few decades - to play our part in averting catastrophic climate change.

There are many different pathways and technologies to achieve this ambition. In this report we focus on the potential for hydrogen to enable the decarbonisation of our energy system and economy, concluding that it could satisfy up to half of total energy needs by 2050. Working closely with a group of key stakeholders in industry and Government, Aurora has leveraged its expertise in energy market modelling to produce a highly sophisticated representation of a possible future hydrogen system – and used this to derive insights on what this means for policymakers and industry.

This summary report highlights the huge potential but also some key challenges to realise a hydrogen economy in UK. Low carbon hydrogen could be used as a substitute for natural gas in homes and industry, and a fuel in transport, and can be upgraded to ammonia or other synthetic fuels, which have a wide variety of applications in industry. Our analysis demonstrates that hydrogen infrastructure can help to integrate renewables into the power system and balance their output. All of this will require significant investment into new hydrogen pipeline and storage infrastructure.

The development of a hydrogen economy, built around the UK's industrial clusters, could be part of a post-COVID recovery package – stimulating jobs and investment. The report sets out a roadmap for the realisation of this opportunity, laying the foundations in the 2020s for a scale up in the 2030s and beyond.

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About the study

The analysis in this report reflects Aurora's independent perspective as a leading energy market modelling and analytics company. The analysis in this study was originally prepared over a course of 6-months with support and feedback from a number of study participants.

In addition to the study participants, a number of private and public organisations were also consulted and informed the analysis in this study.

About Aurora Energy Research

Aurora was founded in 2013 by University of Oxford Professors and economists that saw the need for a deeper focus on quality analysis. With decades of experience at the highest levels of academia and energy policy, Aurora combines unmatched experience across energy, environmental and financial markets with cutting-edge technical skills like no other energy analytics provider.

Aurora's data-driven analytics on European and global energy markets provide valuable intelligence on the global energy transformation through forecasts, reports, forums and bespoke consultancy services.

By focusing on delivering the best quality analysis available, we have built a reputation for service that is:

- **Independent –** we are not afraid to challenge the 'norm' by looking at the energy markets objectively
- **Transparent –** all our analyses undergo further refining through a detailed consultation process across our private and public sector clients
- **Accurate –** we drill right down to the requisite level of detail and ensure results are internally consistent. In power market analysis, this means half hour granularity with complete internal consistency across energy capacity balancing and other markets.
- **Credible –** trusted by our clients, our results have proven bankability

Main contacts

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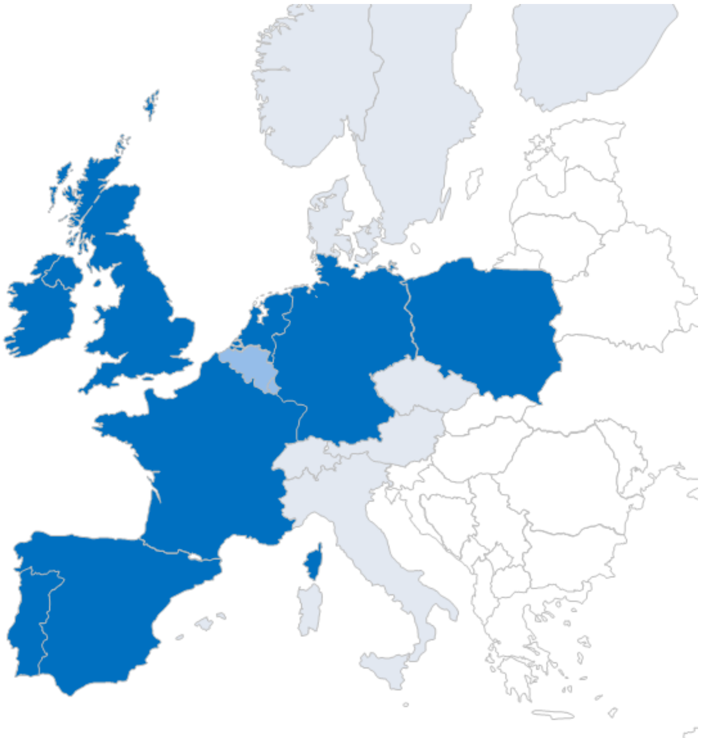
Our services cover all power markets across Western Europe and Australia



Comprehensive Power Market Services	Power Market Forecast Reports	Bespoke forecasts
✓ Power market forecast reports ✓ Forecast data in Excel ✓ Global energy market forecast reports ✓ Strategic insight reports ✓ Regular subscriber group meetings ✓ Bilateral workshops ✓ Analyst support	✓ Power market forecast reports ✓ Forecast data in Excel ✓ Analyst support	✓ Aurora can provide power market forecasts upon request

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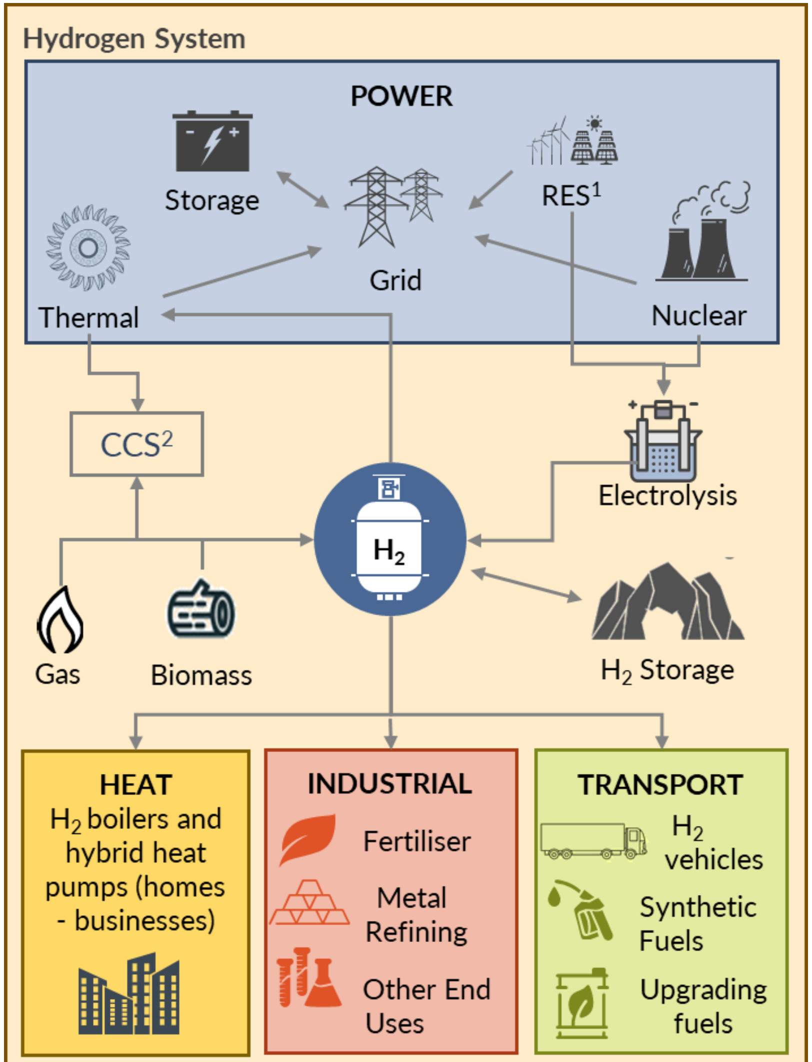
Executive summary – Hydrogen in the GB energy system

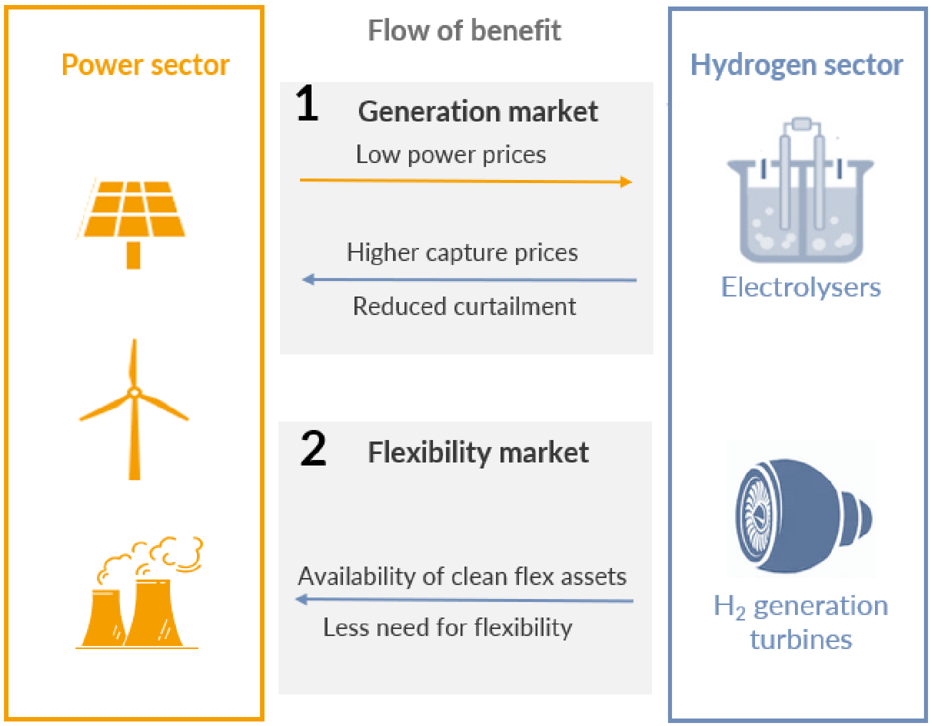


1. Renewable Energy Systems. 2. Carbon Capture and Storage

- Hydrogen (H_2) can play an important role in meeting GB's 2050 target for economy-wide Net Zero emissions by providing c.25-50% of its final energy demand by 2050, and by facilitating the decarbonisation of sectors with limited alternatives
- Aurora has developed an analytical framework that integrates the entire market-based energy system and includes different types of production, transportation and storage technologies
- The study provides a wide range of Net Zero market outcomes by assessing various scenarios and sensitivities, reflecting two pathways for low-carbon power and three levels of H_2 adoption
- Both main H_2 production technologies (electrolysis -green H_2 and natural gas reforming with CCS -blue H_2) are expected to play an important role, with blue H_2 providing the scale in high adoption scenarios and merchant green H_2 deployment accelerating with falling technological costs and power prices in the medium and long-term
- Out of the merchant market analysis, green H_2 projects are expected to be prominent in early years owing to bilateral contracts and dedicated renewables assets for industrial users
- Falling technology costs and gas prices will drive steady reduction in the market H_2 price, which is expected to go below £50/MWh H_2 by 2050 (in £2019, including production and transportation costs)

Source: Aurora Energy Research

Executive summary – Decarbonisation pathways



- Large-scale adoption of H_2 could entail synergies with the power sector, with high penetration of H_2 adding more than c. £3 billion/year to the clean energy market by 2050 and reducing the power sector requirement for flexibility during peak winter months

- All Net Zero scenarios require substantial growth in renewable generation and electrification upon which H_2 benefits are complementary in challenging sectors. Generally, H_2 scenarios require additional investments on H_2 transmission and distribution infrastructure and present higher energy costs, but lower spending on low-carbon power subsidies, power network costs and power capacity market spending

- Higher overall energy requirement due to efficiency losses in the production of H_2 and the lower efficiency of H_2 used in transport and heating when compared to electricity result in a generally larger energy system in scenarios with high H_2 adoption

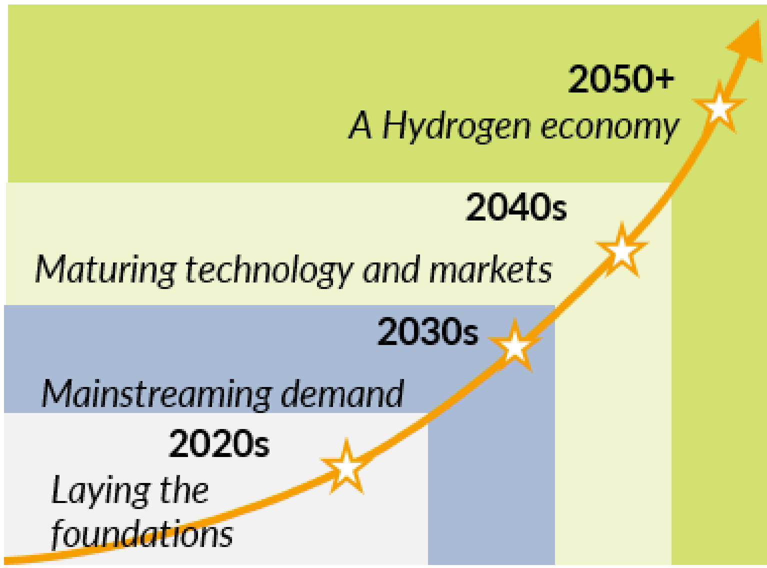
- New and repurposed gas pipelines will be the cheapest form of transportation for transmission and distribution of large volumes of H_2, while trucks will provide a means of distributing small volumes of H_2. Salt cavern storage, pressurised tanks and pipelines are likely to provide the short- to medium-term storage options, but a number of carrier fluids could become available as the market scales and costs decline

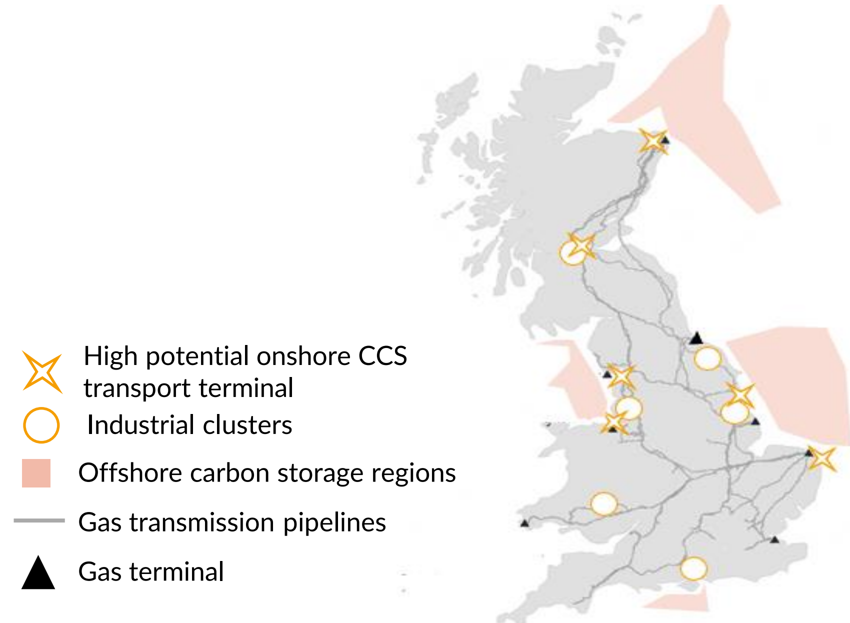
- Imports from regions with cheaper clean H_2 supply are likely to be limited in their overall role in the GB market due to high shipping costs (£40-70/MWh H_2)

Source: Aurora Energy Research

Executive summary – Policy roadmap

Roadmap to a Hydrogen Economy





- All Net Zero scenarios require intensive investment and policy development across all energy sectors, with no pathway (with H_2 or high electrification) being decisively better in terms of system cost on a net present value basis
- Multiple low-regret options for policy can anticipate challenges and tackle key uncertainties in the short term, including setting decarbonisation targets and promoting H_2 demand in key sectors, deploying CCS in strategic locations and advancing energy efficiency and network standardisation efforts
- UK has a distinct advantage compared to other countries like Germany and Denmark due to higher availability of usable CO_2 storage sites for CCS. It can rely on early market scaling through blue H_2 before cost reduction results in competitiveness of merchant green H_2
- Developing a H_2 system can thus be an important element of the UK Government's post-COVID stimulus plan, which could enable the development of globally competitive low-carbon industrial clusters

Source: Aurora Energy Research

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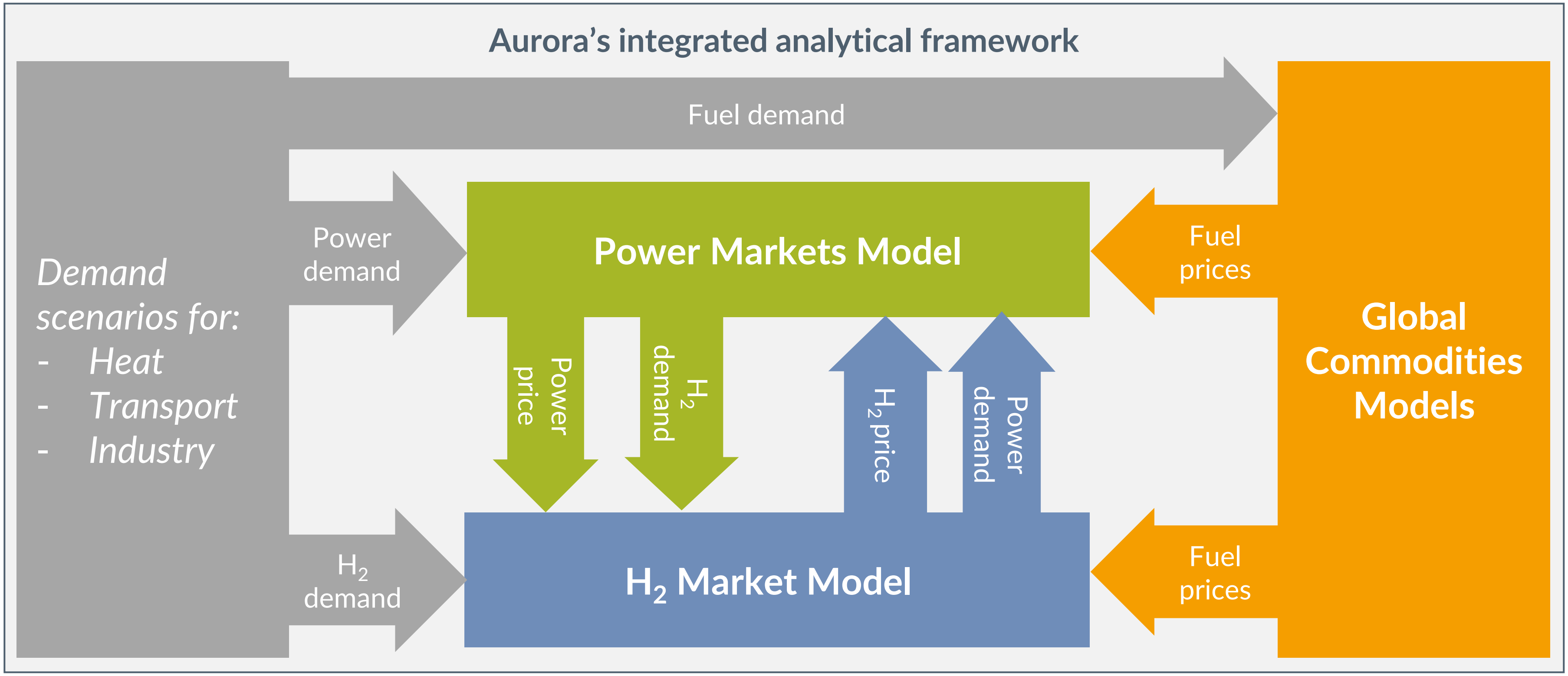
Aurora has undertaken a comprehensive modelling exercise, which integrates the entire energy system

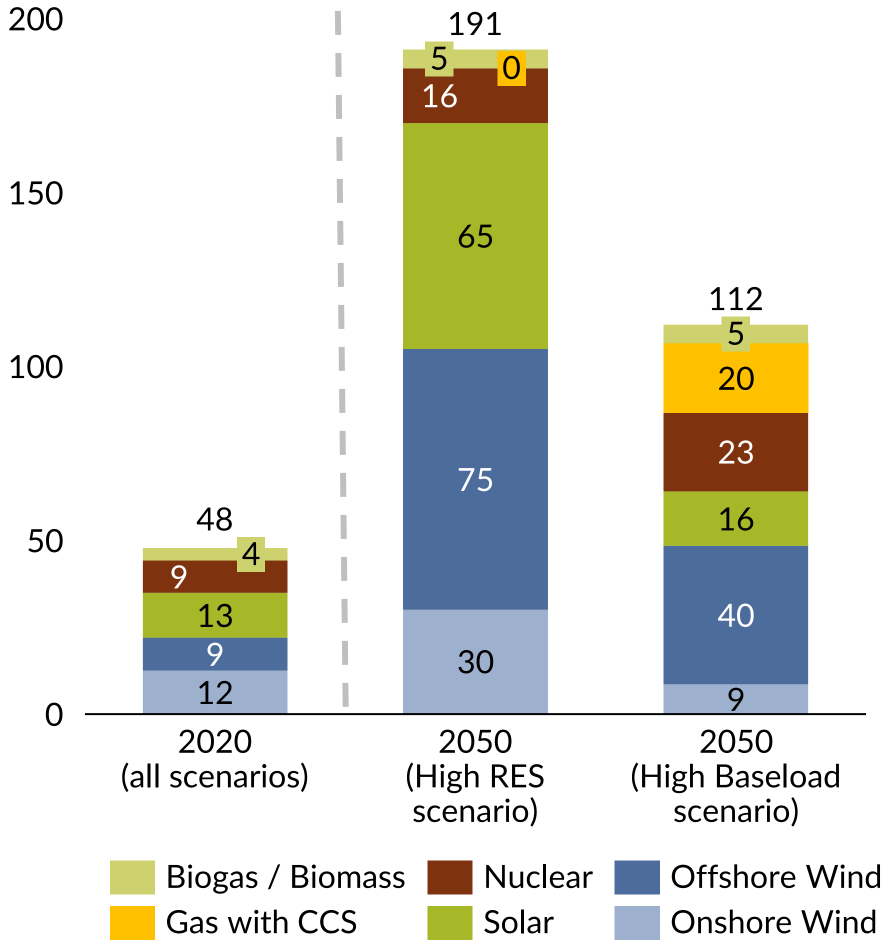


- Aurora's analytical approach is based on an integrated framework that covers the entire energy system, using:
  - internally consistent gas, power and H_2 demand scenarios for heat, transport and industry
  - commodity price forecasts that reflect a Net Zero outlook for Europe
  - a modelling suite that highlights feedback loops across H_2 and power markets
- By integrating H_2 and power market modelling, Aurora's approach captures the interactions of power and H_2, and specifically the mutual benefits of H_2 adoption and deployment of RES

Source: Aurora Energy Research

The study provides a wide range of Net Zero market outcomes by assessing various scenarios and sensitivities

Assumed[1] low-carbon capacity in the power sector,
GW

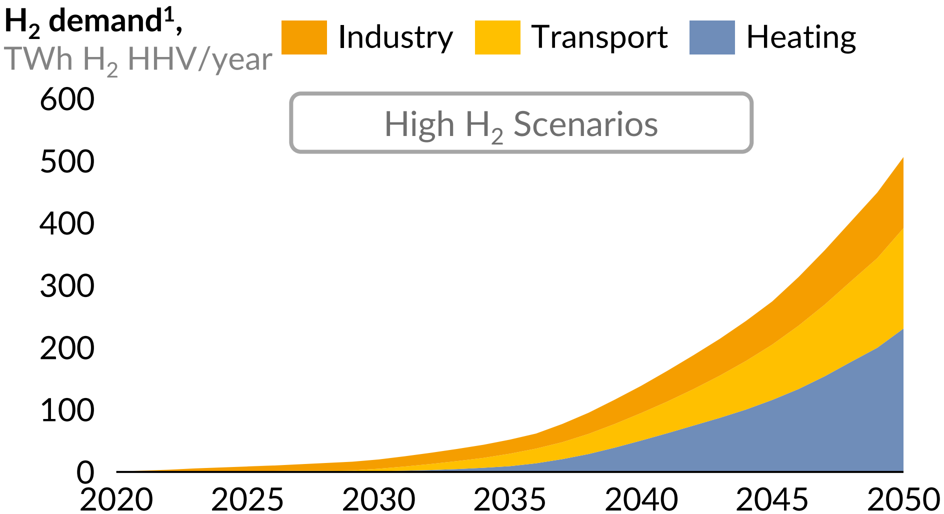


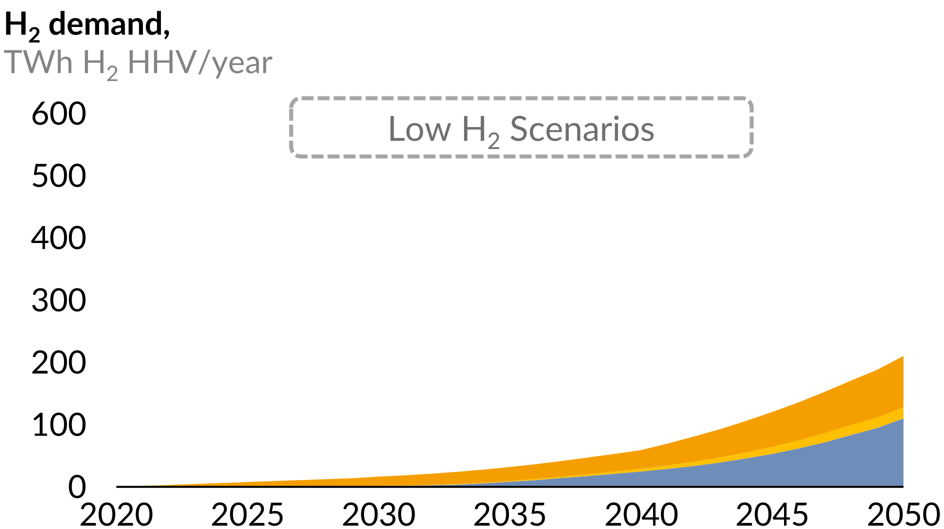
- The UK has set a challenging target for Net Zero emissions by 2050, which requires switching the economy-wide energy consumption to zero-carbon sources
- Decarbonisation of the power sector will be crucial to meet this target, and will require significant deployment of zero-carbon capacity, including renewable energy systems (RES), nuclear and carbon capture and storage technology (CCS)
- The study assesses market scenarios that reflect two alternative pathways for the power sector to meet this target, which focus on either:
  - The High RES scenario assumes accelerated penetration of wind and solar capacity, which reach a minimum of 170GW of combined installed capacity by 2050
  - The High Baseload scenario sees a policy focus on the deployment of gas-CCS and nuclear capacity, which reach a capacity of 20GW and 23GW respectively
- The study also assesses the impact of a range of sensitivities including gas prices, technology cost trajectories, volume of imports and deployment levels of renewables and storage on the H_2 supply mix

1. This reflects the minimum capacity deployment of these technologies. Aurora power modelling allows for further deployment endogenously if it is economic on a net-present value basis

Source: Aurora Energy Research

Levels of H_2 adoption in major sectors also varies with scenario





- H_2 could play an important role in reducing emissions across the energy system with direct applications in heat, transport and industry
- The level of H_2 adoption will depend on the availability of alternative decarbonisation options
- The study considers three levels of H_2 demand across the three main demand sectors:
  - The No H_2 (High Electrification) scenario sees almost complete electrification of transport and heat, and widespread use of natural gas with CCS to provide heat for industrial processes
  - The Low H_2 scenario sees H_2 use in high-grade heat applications in industry and limited penetration in private transport and heat, which are largely electrified by 2050
  - The High H2 scenario sees widespread adoption with deployment of up to 14 million hydrogen boilers and more than 75% H_2 penetration in heavy-goods vehicles, resulting in a total of more than 500TWh of hydrogen demand by 2050
- H_2 could also possibly reach the power sector, providing firm capacity to the energy mix, but this will be highly driven by policy direction and is not a part of our core demand assumptions (discussed later)

1. Hydrogen demand in the power sector was calculated endogenously in our modelling. Demand segments shown here were forecasted exogenously.

Source: Aurora Energy Research

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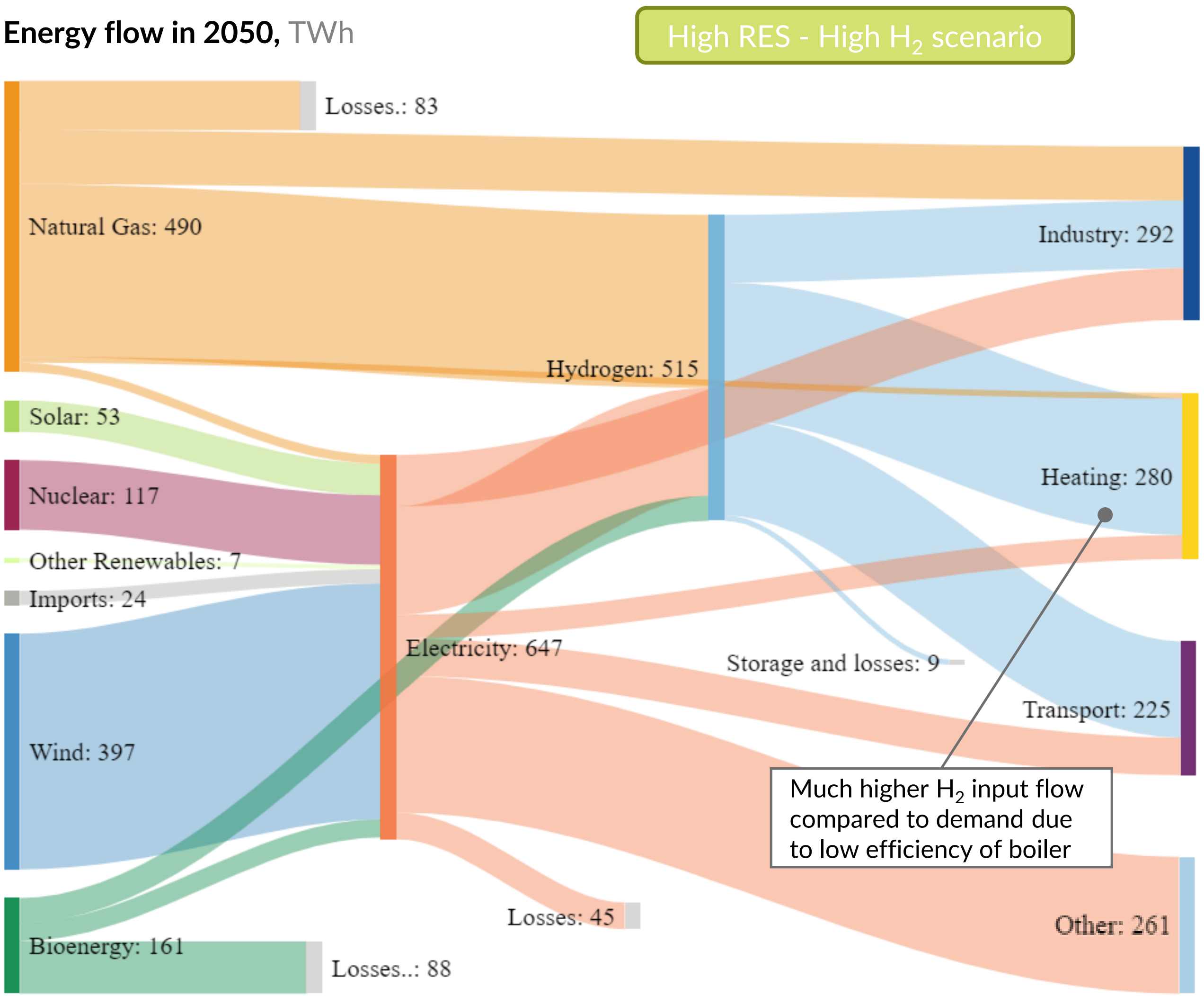
H_2 could provide c.50% of total final energy demand by 2050 in a high adoption scenario

Energy flow in 2050, TWh



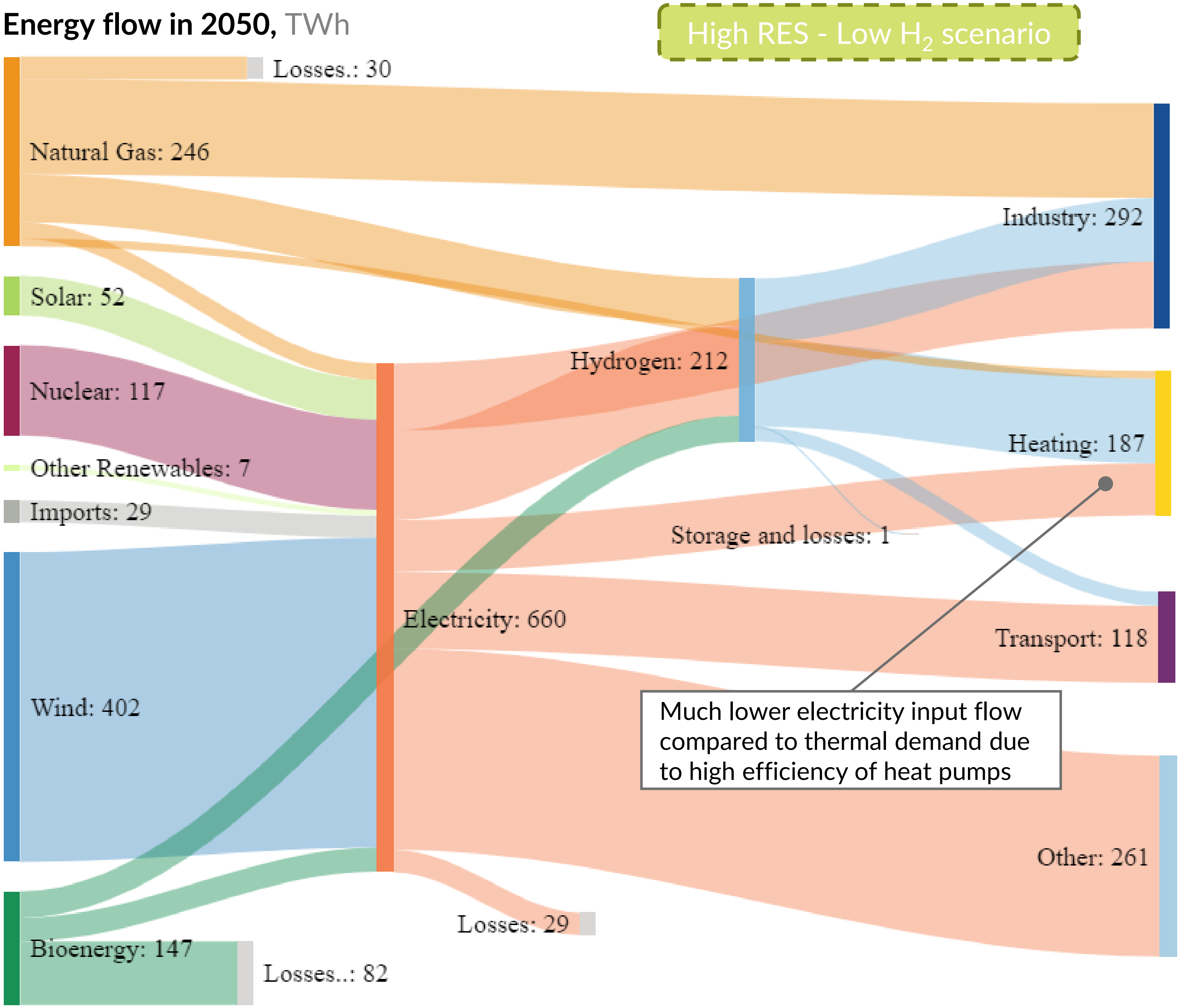
- Widespread adoption in the heat and transport sectors will result in c. 50% of the final energy demand being met by H_2 in 2050
- More than 50% of that H_2 demand is produced by natural gas, which continues to play a important role in the energy sector even in a High RES scenario
- The market scenario sees accelerated deployment of wind, which provides c. 61% of the electricity requirement in 2050
- Up to 7TWh of H_2 could also be used for power generation but this will be highly driven by policy direction, as discussed later

Note: Energy flows reaching the electricity node are in TWhel, flows reaching the H_2 node in TWh th and flows reaching final demand nodes are in source units (TWhel or TWhth for H_2 and gas)

Source: Aurora Energy Research

More targeted adoption could still see c.25% of final demand being met by H_2 in hard-to-electrify sectors

Energy flow in 2050, TWh



- H_2 could provide c. 25% of the final energy demand in 2050 if adoption is limited to hard to electrify sectors and heating applications in certain locations
- Low-cost electricity from RES will provide the bulk of this H_2 requirement, reducing the dependence of the energy system on natural gas
- High electrification of heat and transport results in a considerably smaller total energy requirement, due to more efficient applications compared to H_2 counterparts
- Biomass gasification with CCS can provide up to 31MT/year of negative emissions by 2050

Note: Energy flows reaching the electricity node are in TWhel, flows reaching the H_2 node in TWh th and flows reaching final demand nodes are in source units (TWhel or TWhth for H_2 and gas)

Source: Aurora Energy Research

Green H_2 supply will highly depend on RES penetration, while blue H_2 will be required to provide the scale

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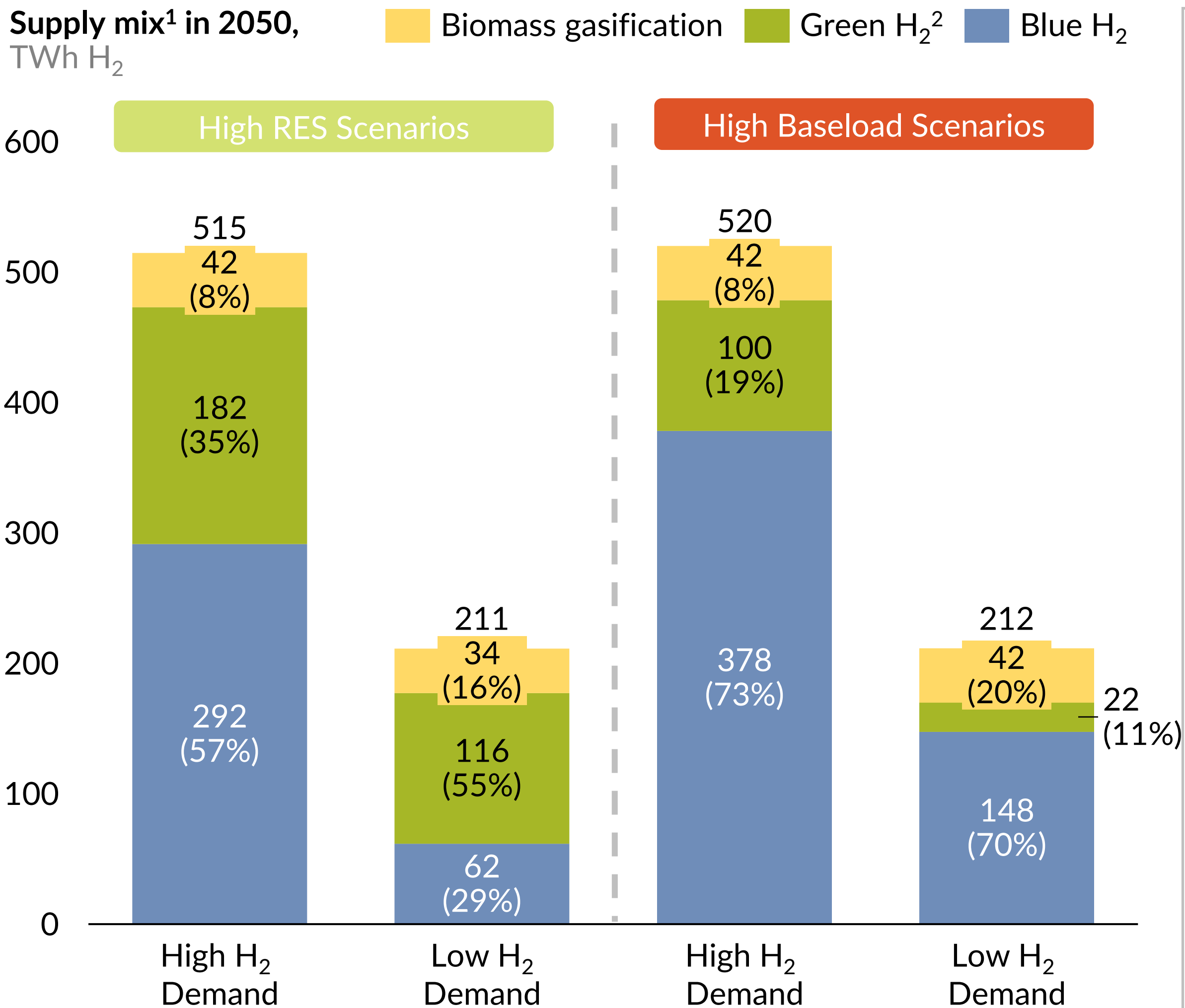

- By 2050, the relative share of blue and green H_2 will depend on two key factors: 1) availability of cheap power and 2) scale of hydrogen adoption across the economy
- The deployment of green H_2 will be highly dependant on the amount of surplus low-carbon generation and cheap power available for electrolysis, which will be driven primarily by the policy direction and other developments in the power sector
- Supply from green H_2 can meet a significant part of the H_2 demand if deployment is limited to hard-to-electrify sectors, like steel and chemicals
- Widespread H_2 adoption for sectors like heating and transport, however, would require the deployment of blue hydrogen technologies (which in turn rely on CCS) to provide the required scale of supply

1. Only merchant business models considered 2.Includes production from centralised, collocated and embedded electrolysers

Source: Aurora Energy Research

Falling costs and power prices will lead to accelerated merchant green H_2 deployment in the long term

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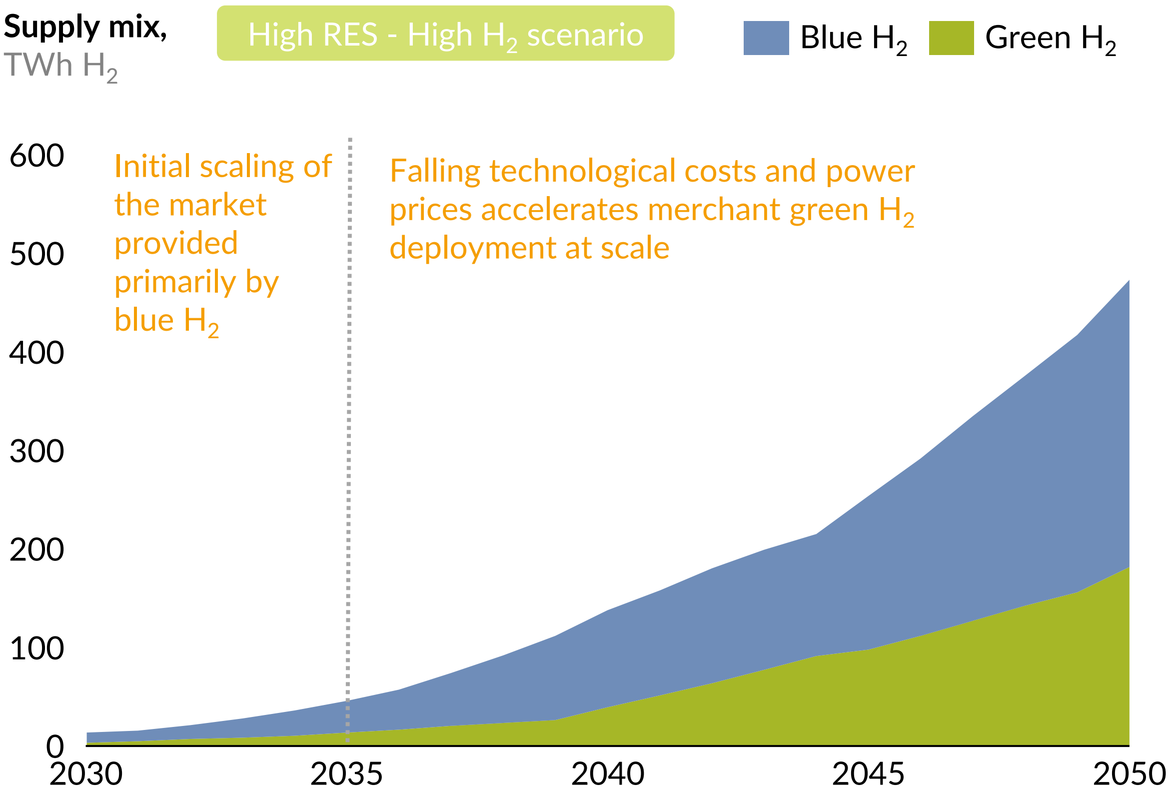


Proportion of total supply,
%

	2030	2040	2050[1]
Blue H_2	76	72	57
Green H_2	24	28	35

Need for policy support (2020-2030):

In the near-term, policy support will be required to stimulate deployment and facilitate technological learning, and is expected to target the replacement of existing grey H_2[2] with green or blue H_2

Market Scaling (2030-2035):

By 2030, falling technology costs are expected to allow development of merchant business models for both green and blue H_2. Th initial advent of green H_2 is expected to be primarily in the form of dedicated solutions in industry or transport. However, due to limited availability of surplus power, the initial scaling of the market is expected to be provided primarily by blue H_2

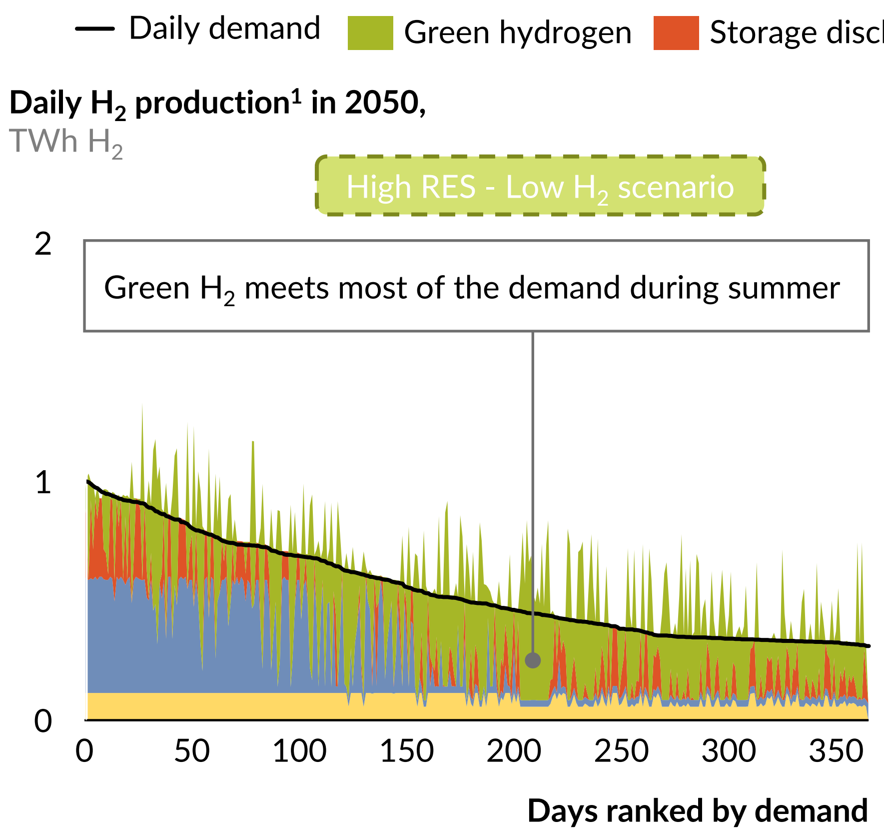
Rising green H_2 share (2035-2050):

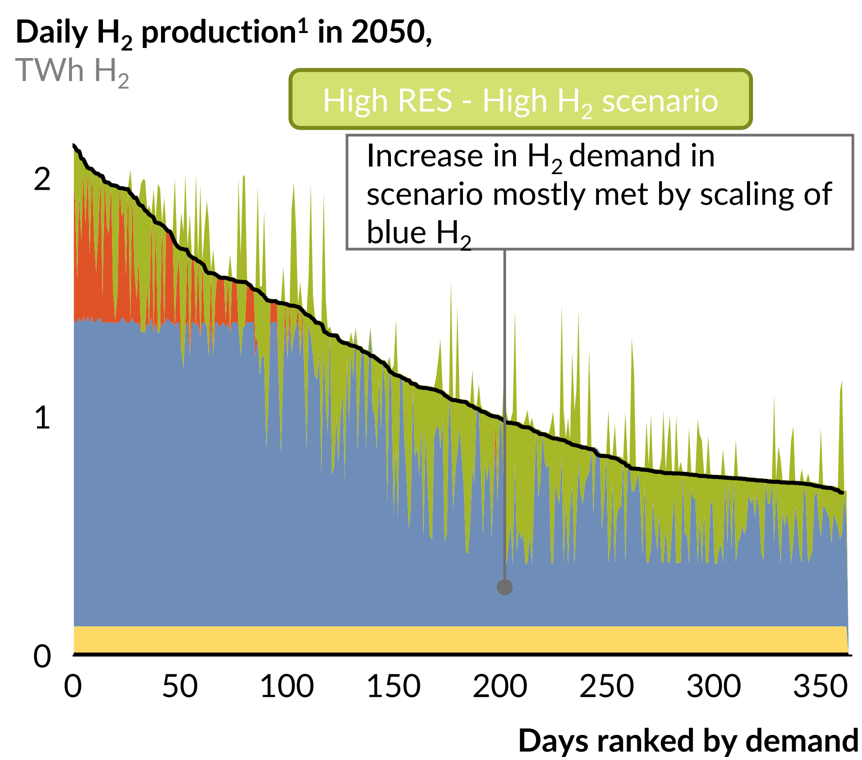
Falling technological costs and power prices enable increase in penetration of merchant market green H_2 in the long run, which is expected to continue over the horizon.

1. Remaining supply provided by BECCS 2. Hydrogen produced from gas reformation without CCS

Source: Aurora Energy Research

If H_2 adoption is limited to hard-to-electrify sectors, green H_2 could meet daily demand for most of the year





- In case of targeted deployment, green H_2, in conjunction with biomass gasification and some storage, could meet almost all of the summer demand and still shift some of generation to winter months through storage

- In a high H_2 demand scenario blue H_2 supply would be required to meet most of the heightened demand during winter, especially considering the intermittent nature of green H_2 supply

1. Does not include green hydrogen supply from embedded generation, which does not participate in the market

Source: Aurora Energy Research

H_2 Storage will be essential to provide flexibility and to shift intermittent green H_2 generation to peak demand periods

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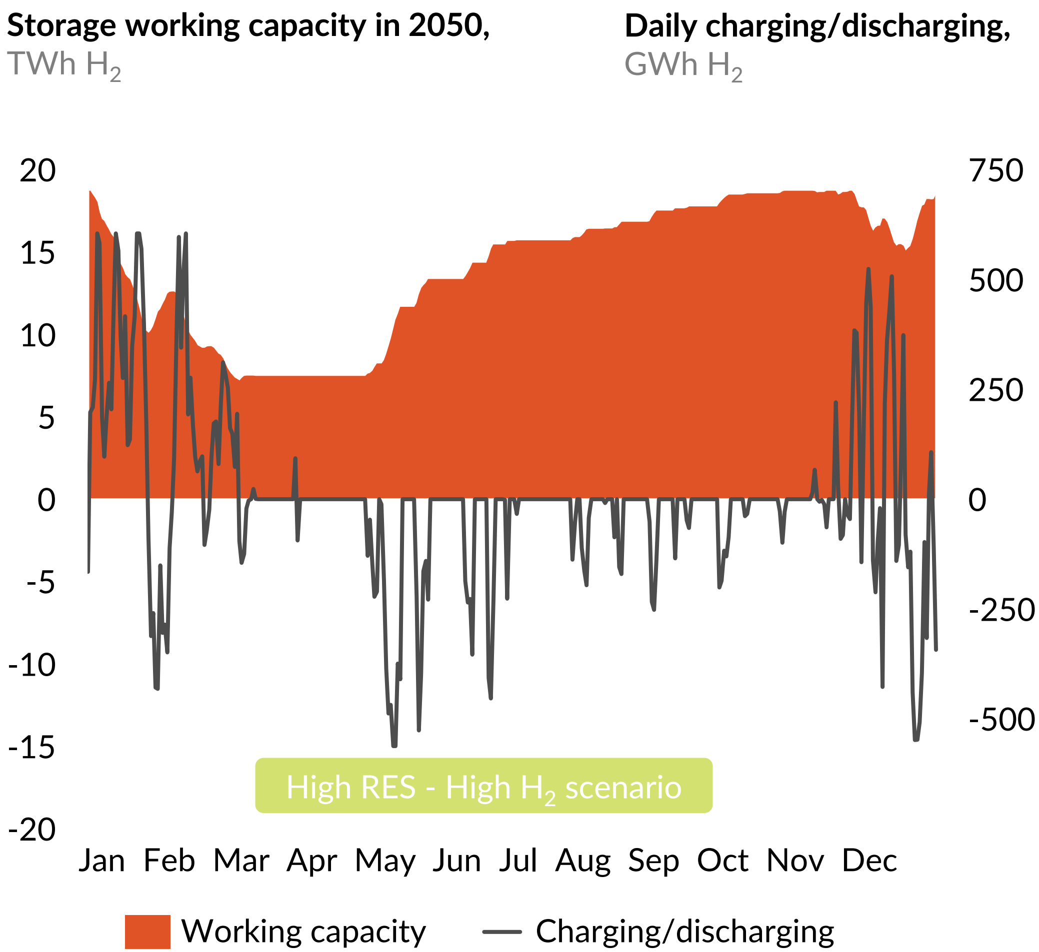
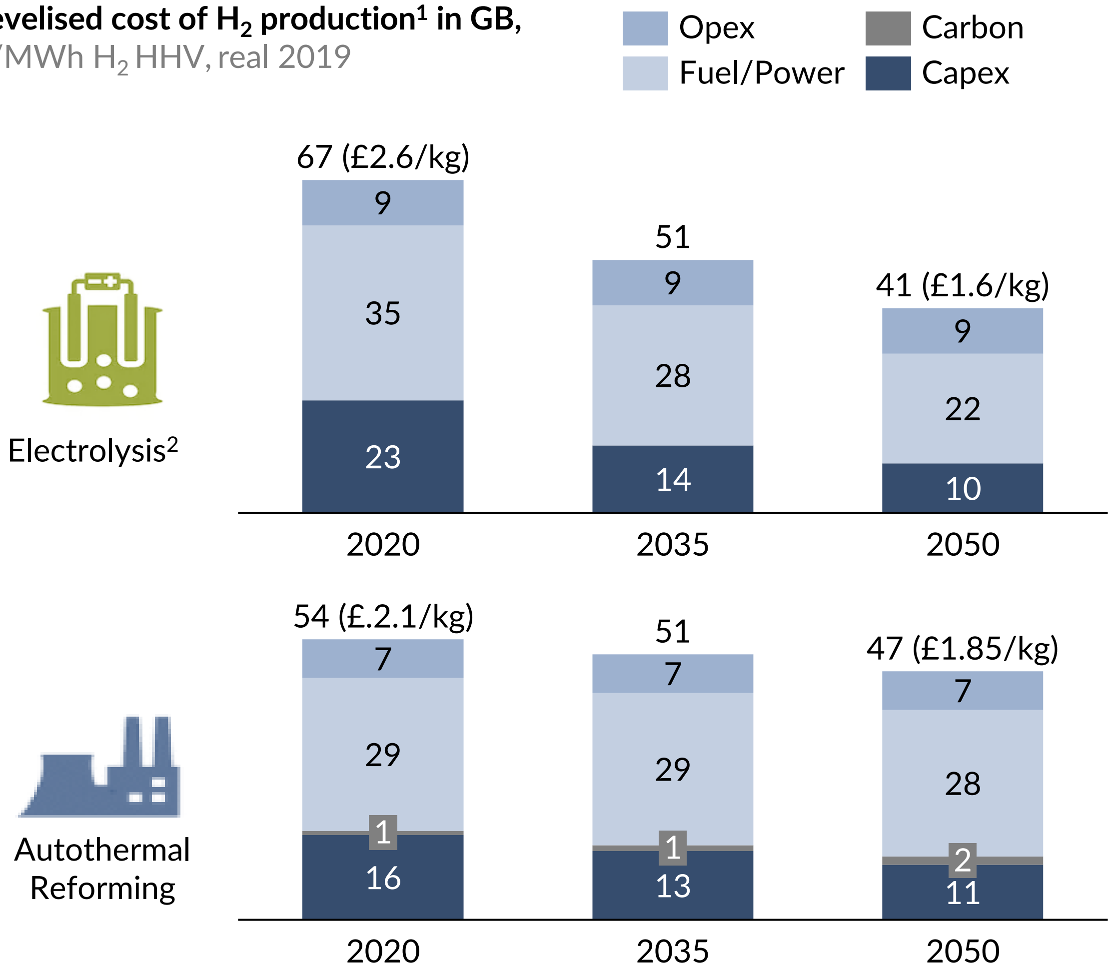


- H_2 storage will be pivotal for stocking up excess power generation especially during summer and utilising it for security of supply during winter and extreme weather months
- The cycling pattern of storage will be highly dependant on the seasonality of demand in sectors adopting H_2, with more inter-seasonality expected in scenarios with high H_2 adoption in heat
- Our analysis suggests that **19TWh** of centralised salt cavern storage will be sufficient to meet peak winter demand by 2050
- This supply could also be used for back-up baseload and flexible generation in the power sector (through H_2 turbines) to hedge against intermittent generation of renewables assets
- On a daily basis, storage can provide **0.63 TWh** supply, equivalent to **c.30%** of daily peak winter demand during a normal weather year

Source: Aurora Energy Research

Levelised cost of production will be majorly driven by operational costs

Levelised cost of H_2 production[1] in GB,
£/MWh H_2 HHV, real 2019

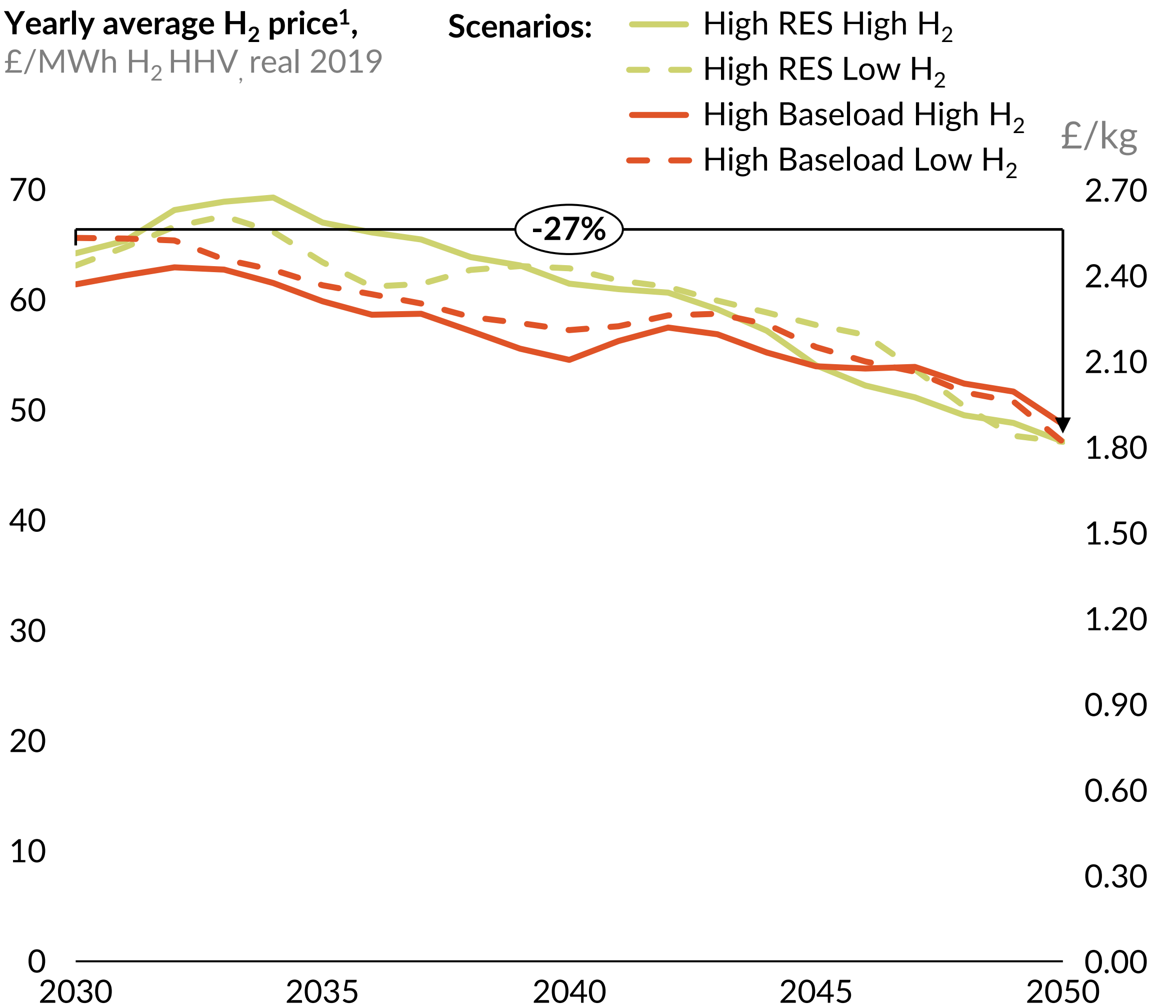


- The levelised cost of green H_2 production will be highly dependant on the business model:
  - Availability of low-cost power will be higher in assets co-located with offshore wind, which will have access to surplus generation, resulting in lower overall H_2 production cost
  - However, the cost of transportation is expected to be higher for these assets due to the higher distance from demand centres
- Similarly, for blue H_2 production, the variable cost of gas price will be the most significant factor in terms of overall production costs
- The cost of transportation (not included in the charts here), will also be a significant element of the final delivered cost

1. Does not include costs for transportation and storage 2. Alkaline electrolysers. Assuming 50% power from curtailment and rest from grid

Source: Aurora Energy Research

Market price of H_2 drops to £50-60/MWh H_2 across all scenarios once at scale by the 2040s



- Falling technology costs and lower gas prices are expected to drive a steady reduction in the market H_2 price, which is expected to go below £50/MWh H_2 by 2050
- Our H_2 price includes all costs incurred across the supply chain, from production to transportation (to end user), and is assumed to be set through daily clearing of the market at a single virtual supply point in GB
- The market is expected to follow a merit order dispatch curve, with the plants with the highest marginal cost of production setting the daily price
- We expect blue H_2 production technologies at the higher end of the merit order to be setting the price most days in such a market design

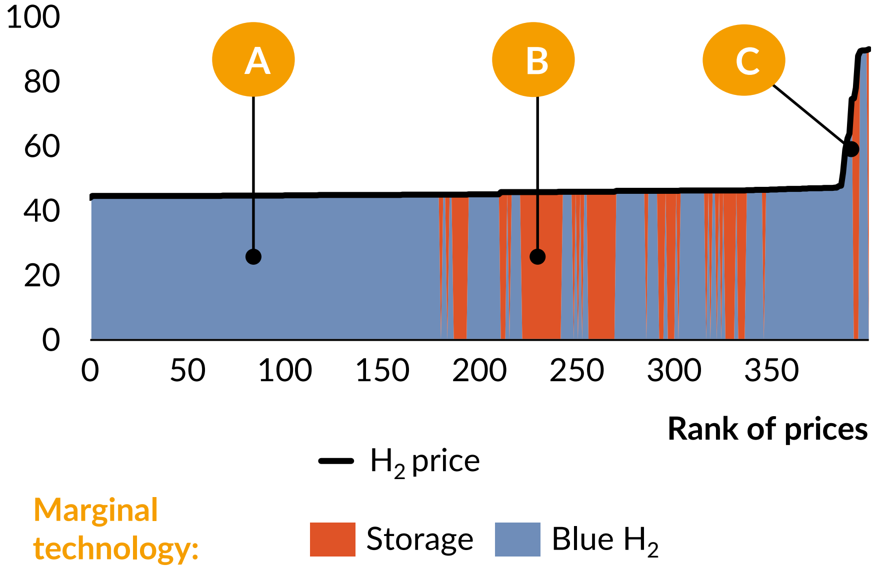
1. Yearly time-weighted average clearing price, including production and transportation costs

Source: Aurora Energy Research

Storage can provide security of H_2 supply in most years, but strategic reserve capacity will also be required

H_2 price in 2050, £/MWhH$_2$, real 2019

High RES - High H_2 scenario



A

- Blue H_2 is the marginal technology across summer when demand is lower
- Green H_2 utilising surplus RES power sits on the lower side of the supply curve, but in a High H_2 scenario is not enough to meet demand and set the price

B

- Arbitrage opportunities for storage arise during periods of higher demand and lower intermittent green H_2 supply. Storage is vital for ensuring security of supply during such periods

C

- Periods of scarcity could still arise in the system which could be exacerbated during extreme weather events, and will require some strategic reserve in the system

- With 19TWh of salt cavern storage by 2050, about 9TWh is expected to be tapped for meeting peak winter demand during a normal weather year, which leaves nearly 10TWh to supply excess demand during extreme weather scenarios
- An additional strategic reserve capacity of up to 7GW will be required to ensure system adequacy during scarcity periods
- Due to the reliance of green H_2 on highly intermittent RES, blue H_2 capacity might be better suited to provide this capacity
- The GB market could also possibly rely on H_2 imports to meet this demand, but such an approach has many challenges including very high costs of shipping and consideration for the fact that such weather events might also impact both exporting and other importing countries too, limiting the volume available for imports into GB

Source: Aurora Energy Research

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Large-scale adoption of H_2 could entail significant synergies with the power sector

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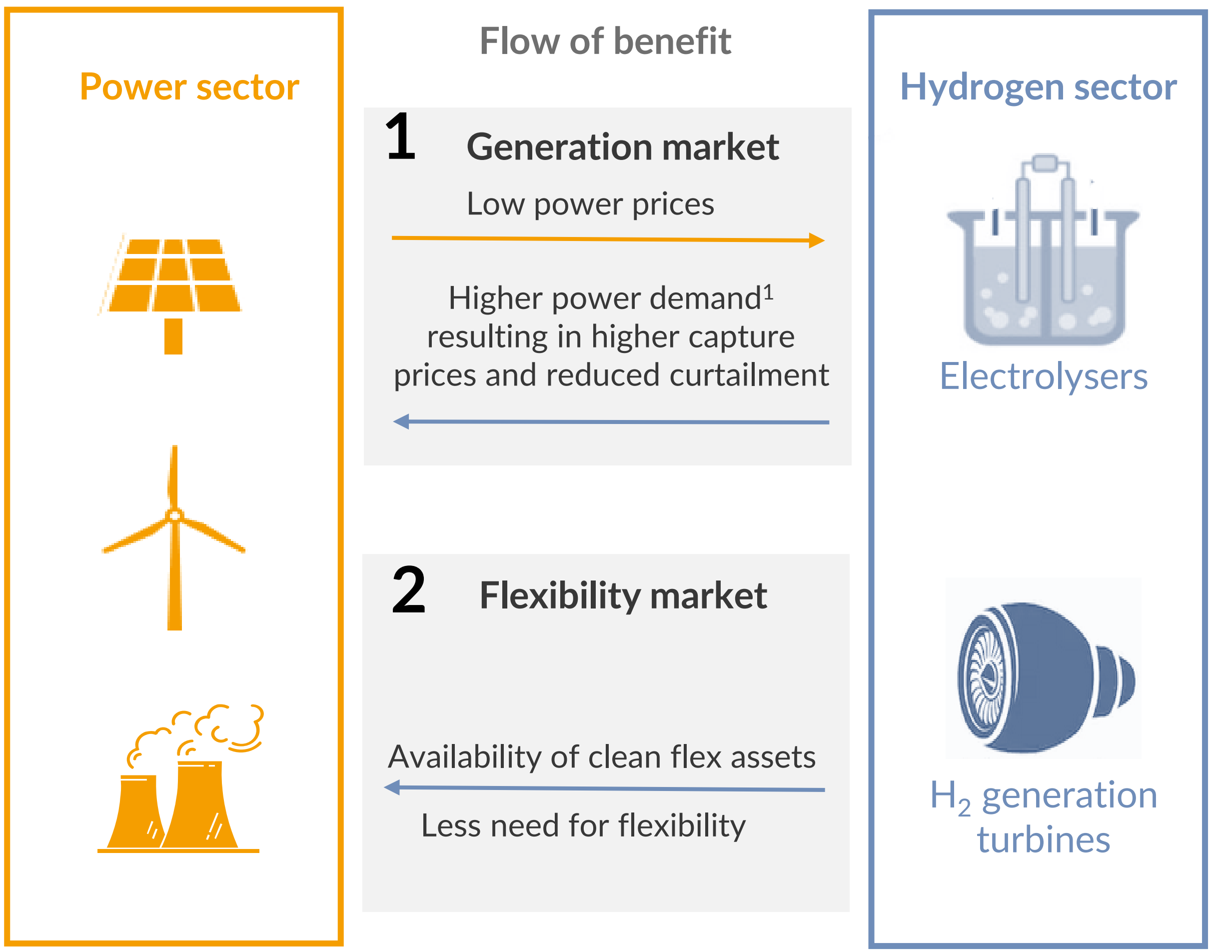
Power market – H_2 market synergies



Generation market:

- Deployment of electrolysers for green H_2 production can create demand for surplus power generation during periods when wind is very high, also increasing capture prices for RES and nuclear in the process
- Increasing RES penetration reduces power prices and increases surplus supply (during high wind periods) for green H_2 production

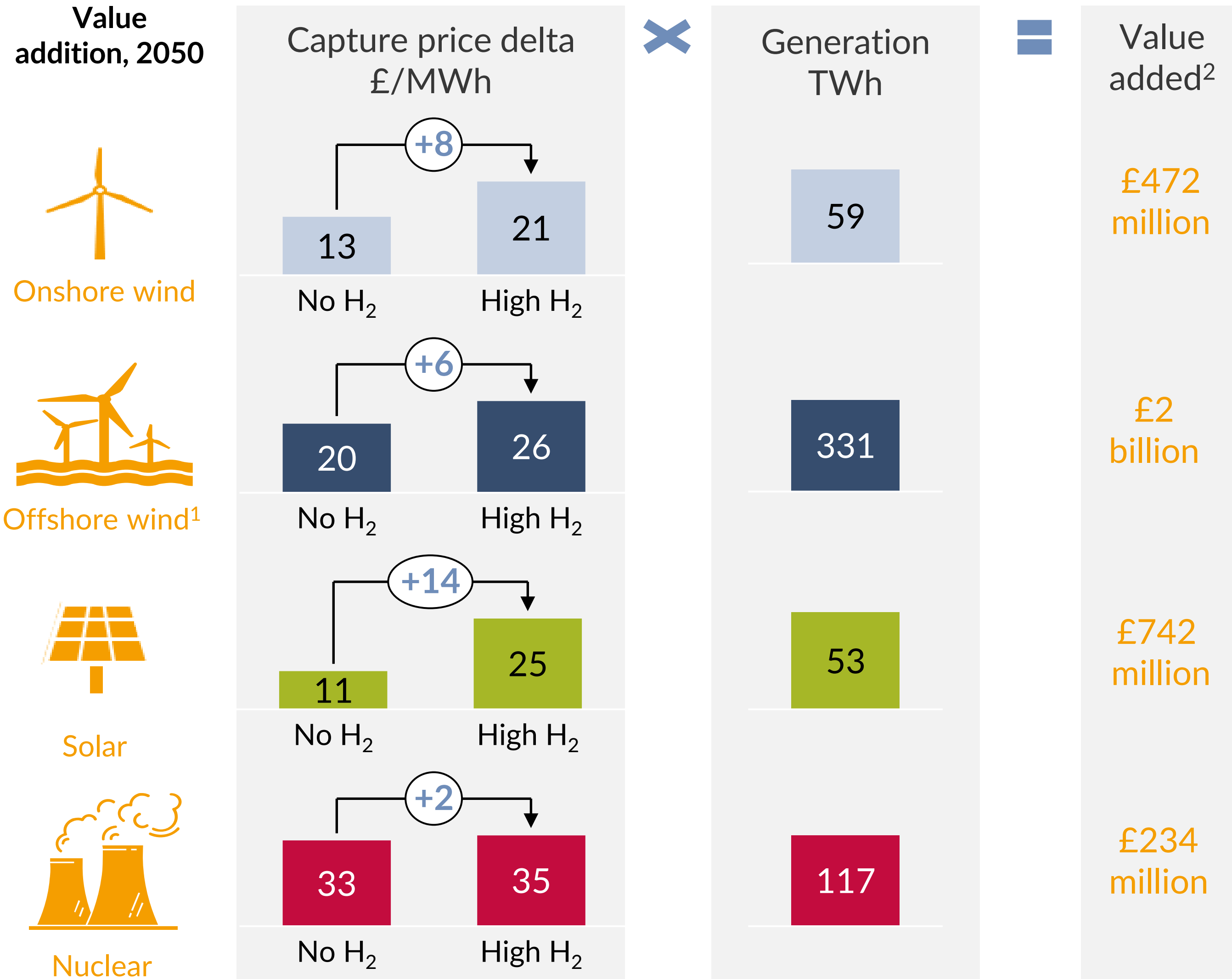
Flexibility:

- Widescale H_2 adoption for energy system decarbonisation can also reduce the burden on the power system during periods of peak demand in sectors such as heating and transport, reducing the requirement for flexibility in the power system
- Moreover, H_2 turbines and electrolysers can serve as additional sources of this flexibility

1. Due to use of hydrogen

Source: Aurora Energy Research

High penetration of H_2 could expand the clean energy market by c. £3 billion/year by 2050



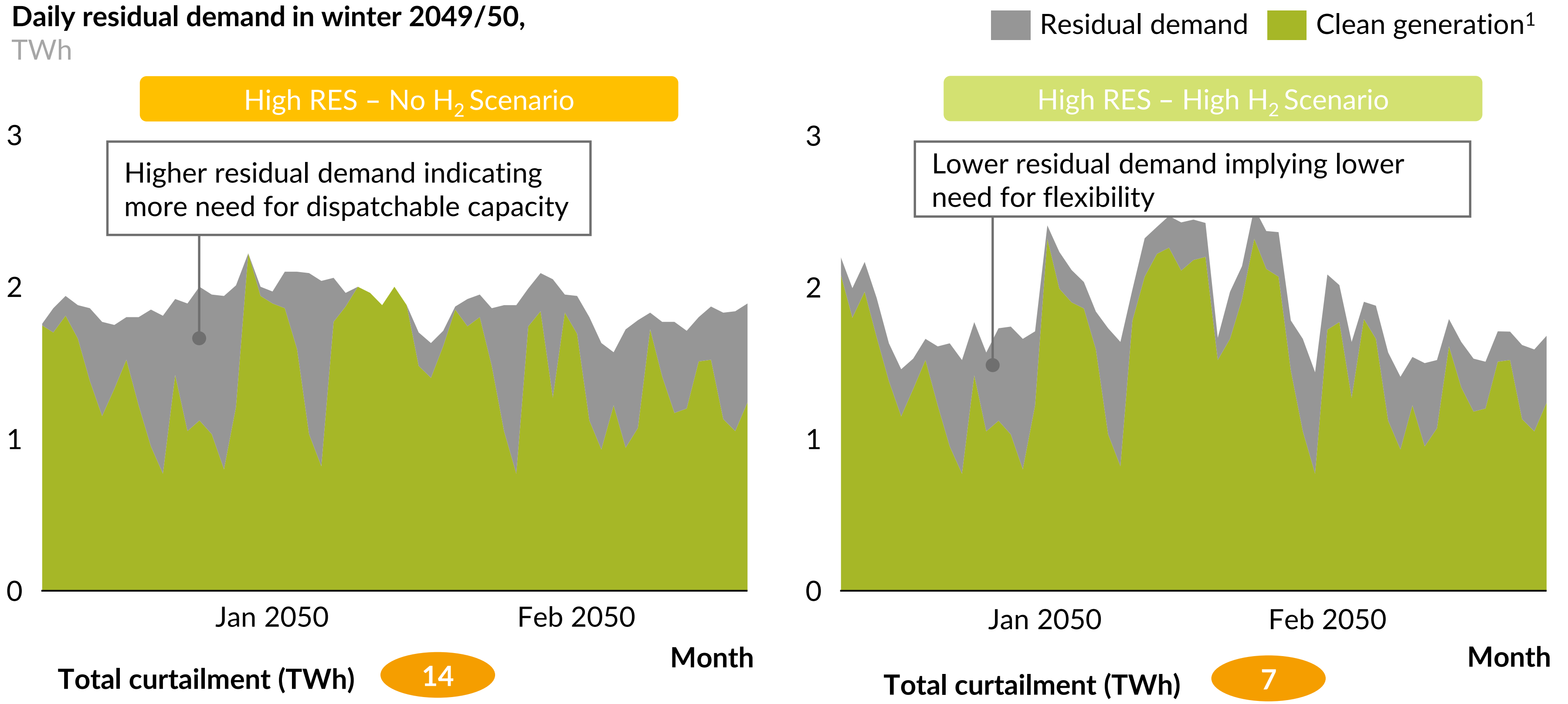
- Most of the value addition for the low-carbon power sector is expected to be driven by higher capture prices due to electrolyser demand
- For offshore wind the increase in capture prices will lead to lower economic curtailment during periods of very high wind
- For solar, the impact on capture price is very high largely due to the ability of H_2 to store excess renewable generation for use in winter

1. Most of the offshore wind generation delta comes from reduced curtailment in existing fleet rather than new capacity 2.Does not include value add from generation due to electrolyser demand

Source: Aurora Energy Research

High H_2 penetration will reduce the power sector requirement for flexibility during peak winter months

Daily residual demand in winter 2049/50,
TWh



- In a high H_2 demand scenario residual power demand during winter months is reduced due to: 1) lower seasonality of power demand (due to less electrification of heating), and 2) more RES capacity
- This results in a lower need for flexible generation capacity in the system to meet this residual demand
- Additionally, demand from electrolysers can help balance the grid during periods of very high wind

1. Clean generation includes generation form intermittent renewables, hydro, and nuclear. Residual demand is the difference between total demand (including EVs and electrolysers) and this clean generation

Source: Aurora Energy Research

H_2 turbines can generate flexible or baseload power, and could become cost-competitive with gas turbines

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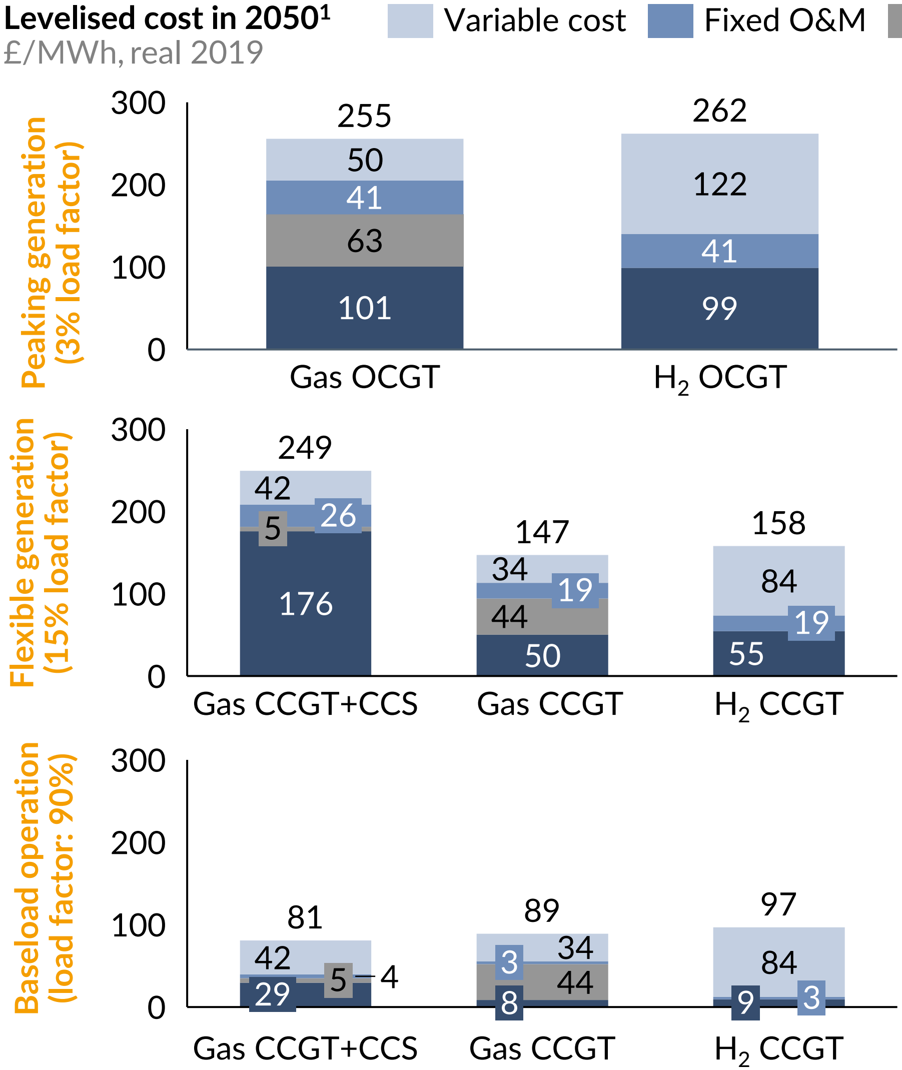
Levelised cost in 2050[1]
£/MWh, real 2019



- Even with very high RES penetration and widespread adoption of H_2, there will still be requirement for **c.195TWh** of generation from baseload and flexible power technologies in 2050, which can be provided by nuclear, CCGTs[1] (with CCS), OCGTs[2], gas recips, batteries and H_2 turbines
- In the 2040s when RES generation is high and demand for flexibility is reduced due to the H_2 market, expected load factors for these plants will be 10-20%
- The switch-over to H_2 could be incentivised through policy measures (like higher carbon pricing), with an expected **£160 million/year (by 2050) additional** investment required to incentivise H_2 over unabated CCGTs
- For baseload operation, gas CCGTs with CCS have an advantage due to higher running hours since their substantially higher Capex becomes a smaller component of levelised cost
- Given the residual emissions associated with both gas CCS and H_2 turbines (due to input blue H_2), the trade-off between costs and emissions should be an important consideration for policymakers

1. Combined Cycle Gas Turbines 2. Open Cycle Gas Turbines

Source: Aurora Energy Research

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Development of a H_2 supply chain will require intensive investment and policy development across sectors

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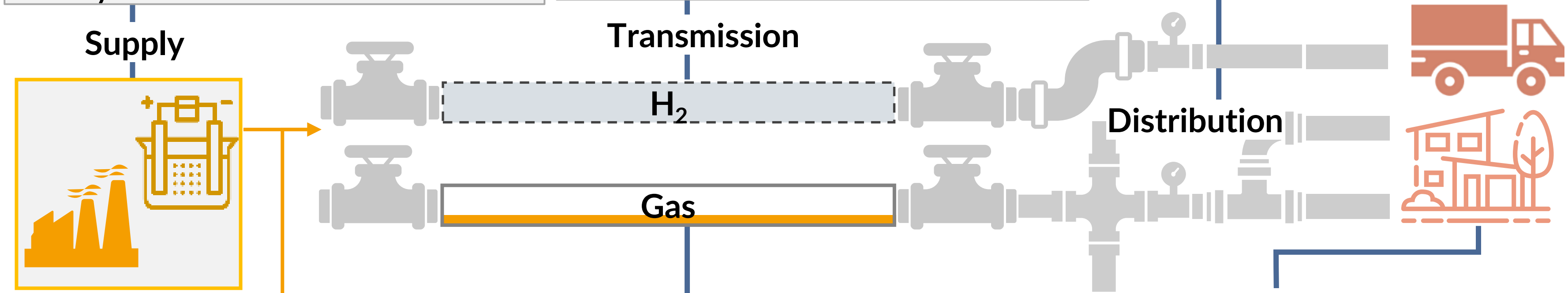
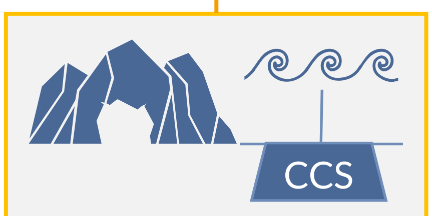
Expanding and financing H_2 supply quickly will be a challenge. We expect cumulative **investment in the supply side to surpass £50 bn**[1] between now and 2050. **Risk-hedging** policies could be crucial in reducing cost of capital of **heavily frontloaded investments.**

The feasibility of repurposing gas pipelines for H_2 transmission is uncertain. We considered the buildout of **new** dedicated transmission pipelines, requiring **over £200 M in yearly investments** throughout the 2030s.

With the IMRP[2] finishing in 2032, studies indicate **that the gas distribution grid could accommodate pure H_2 flows** to meet commercial and residential demand with few upgrading requirements[3].





Net Zero poses risk of some **stranded assets** for existing gas infrastructure. Additional risks arise from the operation of networks with **greatly reduced flows.**

Demand

CO_2 and H_2 Storage

Required CCS investment can reach **£1 bn annually by the late 2030s**, potentially reaching **£5 bn by 2050,** while deploying H_2 storage **could require tens of millions in yearly investments after 2030 and hundreds after 2040**.

- Strategic opportunities exist for **industrial clusters** and certain public applications to become **early adopters of H_2**
- Updating appliance and network safety and standardisation could **enable H_2 blending** in the short term[4], further spurring demand and supply
- **Pilot and demonstration projects and R&D** would be especially important in **tackling technical and financial uncertainties**

1. In our High H_2 scenarios. 2. Iron Mains Replacement Programme. 3. Imperial College London. 4. In a volume that is significant enough to spur supply. Current allowed levels of H_2 blending in GB's gas grid is 0.1% in volume terms.

Sources: CCC, Element Energy, Equinor, H21, National Grid, Aurora Energy Research

No pathway is decisively better in terms of system cost: uncertainties and strategy would drive policy decisions

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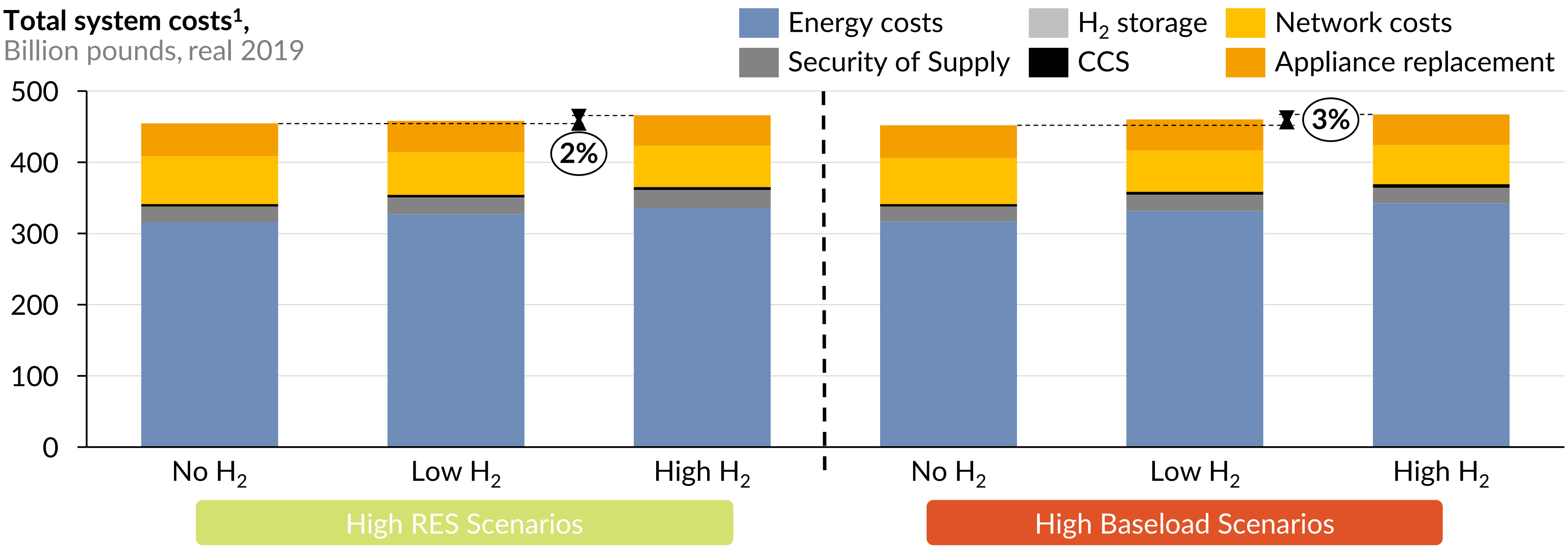

- Difference in system cost requirements between scenarios is relatively small. Minor changes in core assumptions such as gas and carbon prices, or acceleration in technology cost reductions, would easily change the cost ranking
- Generally, H_2 scenarios require additional investments on H_2 T&D[2] infrastructure and present higher energy costs. The latter is due to the higher overall energy requirement due to efficiency losses in the production of H_2 carrier and the lower efficiency of H_2 use in transport and heating when compared to electricity. However, these scenarios reduce subsidy spending, power network costs and capacity market spending
- With no evidently optimal pathway, the importance of second order benefits, such as knowledge and technology export, can play a decisive role in policy discussions and market design
- Energy and network components are by far the most influential on total network costs. This makes the planning and coordination of infrastructure critical in achieving cost-effective and reliable decarbonisation pathways

1. Net present value (NPV) of 2020-2050 expenses for each scenario, assuming a 10% discount rate. Costs for CCS and hydrogen networks are indicative only. 2. Transmission and Distribution

Source: Aurora Energy Research

Multiple existing and upcoming initiatives have been set to explore H_2 potential across the country

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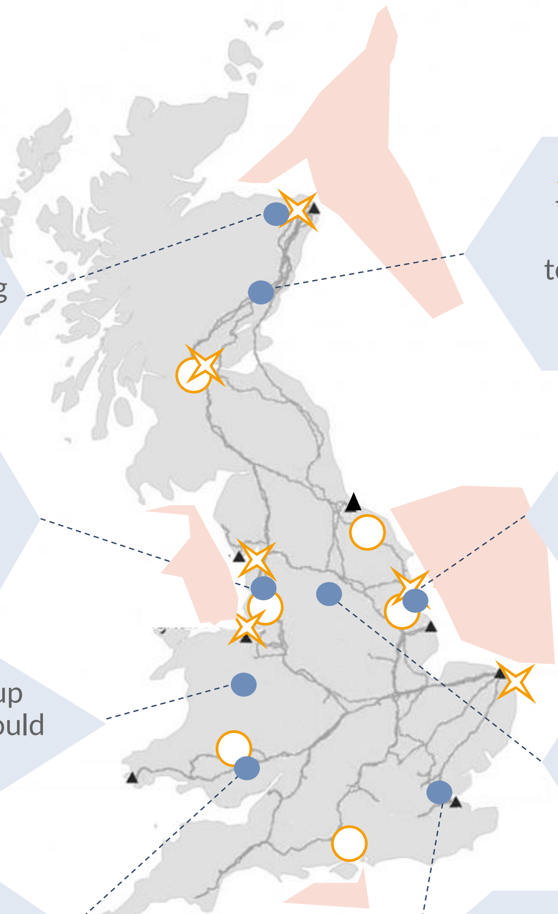
- High potential onshore CCS transport terminal[1]
- Industrial clusters
- Hydrogen projects
- Offshore carbon storage regions
- Gas transmission pipelines
- Gas terminal



The **Feasibility of H_2 in the NTS** project in St Fergus is seeking to determine the **capability of the gas transmission network to transport H_2**, including the development of a **pipeline case study** and draft report for offline trials

Strategic locations in GB combine the presence of **dense demand centres** with **H_2 and CO_2 storage** potential as well potentially **repurposable gas infrastructure**. Key projects like **HyNet** are exploring this potential

HyDeploy seeks to demonstrate the feasibility of up to **20% blending of H_2 in the gas network**, which could unlock one of the earliest sources of H_2 demand

The HyHy project in Cardiff is seeking to understand the financial and carbon-saving performance of **hybrid heating solutions** and **bulk hydrogen supply** to inform key policy decisions on heat decarbonisation

Aberdeen Vision is seeking to demonstrate the viability of **injecting up to 2% H_2 into the gas transmission system**, addressing key technical uncertainties and possibly unlocking the capacity to transport and export H_2 through the gas transmission network

Green Hydrogen for Humber will deploy **PEM electrolysers** at a GW scale to provide **green H_2 to a mix of industries**. Meanwhile, the **Humber-DP** project will explore **CCS and fuel switching** opportunities, seeking to **decarbonise the industrial cluster by 2030**

H21: Northern Gas Networks carried out detailed feasibility studies in the city of Leeds, finding that it is technically feasible to **convert the gas grid to H_2 with acceptable costs for consumers**

National Grid's **Project Cavendish** is exploring the feasibility of **producing, storing and importing H_2** at the Isle of Grain, in Kent

1. Hydrogen Supply Chain Evidence Base – Element Energy

We identified multiple low-regret options for policy that can anticipate challenges and tackle key uncertainties

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Supply Chain Segment	Low-regret option	Rationale
Supply	Identification of areas of high curtailment in the medium and long term	With increasing renewables, curtailment will inevitably increase, especially in RES clusters. **Identifying these areas** and **integrating these findings in planning efforts** can help spawn green H_2 clusters while also minimising financial disruption for RES assets
Transport and Storage	Increasing knowledge and deployment of CCS with focus on strategic locations	CCS has been shown as crucial in all studied scenarios. However, little advancements have been made nationally in this matter in the last years. Further **exploring the feasibility** of CCS in strategic sites **and promoting R&D** to address uncertainties are seen as advisable, low-regret measures
	Standardisation of networks and safety regulations	Even if H_2 is deployed for niche regions or applications, **standardisation** will still be required. Doing this with a global focus could also avoid potential increased technology costs caused by mismatches between UK and foreign standards
Demand	Advancing energy efficiency efforts across the country	Heat electrification is an important component in all scenarios. Given the age of the national housing stock and technical limitations of heat pumps, **energy efficiency will be necessary** regardless of the pathway
	Industry decarbonisation targets	The industry sector lacks clear targets or pathways for decarbonisation, while clusters are strategically equipped to kickstart both the H_2 and CCS sectors. **Establishing decarbonisation targets**, **promoting demonstration or R&D** projects and **enacting low-carbon product targets** can spur their development
	Promoting low-carbon H_2 demand in promising sectors	The fertiliser, refinery and industrial sectors, along with public transport and blending of H_2 in the gas grid could become early off-takers of low-carbon H_2 in the short term. **Promoting demand to shift towards low-carbon H_2** in these segments can help deploy infrastructure and mature the H_2 supply chain, with little impact or risk

Source: Aurora Energy Research

In the medium and long term, policy focus could shift to harmonising markets and accelerating cost reductions

Category	Policy implication	Rationale
Supply	Market design	Intra-day and long-term markets could serve as the industry's financial and operational backbone. Policy could anticipate these requirements by **establishing a roadmap** for defining these markets and their regulation
	H_2 Security of Supply	Regulation should **define criteria for security of supply** in the H_2 space, including consideration of RES, gas and H_2 storage assets, and imports. Reaching sufficient deployment will require additional sources of revenue, which could be supplied by the structuring of **capacity markets, ancillary services**, or a **strategic reserve**
	Technology support	Akin to RES, creating investable frameworks (**FiTs or CfDs**) that address the risk associated with H_2 technologies – both in the H_2 and power sectors – would help build the supply chain, **reduce cost of capital** and **accelerate cost reductions**
Transport and Storage	Enabling forward-looking investments in existing networks	Policy could ensure the regulation applicable to current network owners allows them to **invest in upgrades** that can significantly **minimise risk of stranded assets** and **reduce foreseeable costs** in view of a transition to H_2
	Defining ownership and remuneration of H_2 Networks	Decisions will need to be made between **expanding the regulated asset base of existing network owners** versus **introducing new, competitively-appointed owners** (e.g. **CATO regime)**
Demand	Technology readiness	If hydrogen use becomes widespread, mandating **technology readiness (H_2-ready boilers and houses)** can save millions of pounds to consumers in areas where electrification is not a viable or cost-effective option. **Firms will require early signals** to prepare the technology and adjust commercially and logistically
Market-wide	Carbon pricing	Carbon pricing is a key enabler that incentivises H_2 business models in both the supply and demand sides, as well as CCS deployment and decarbonisation in general. Our scenarios rely on **effective and sustained carbon pricing**, which we consider essential for materialising all of the proposed Net Zero scenarios

Source: Aurora Energy Research

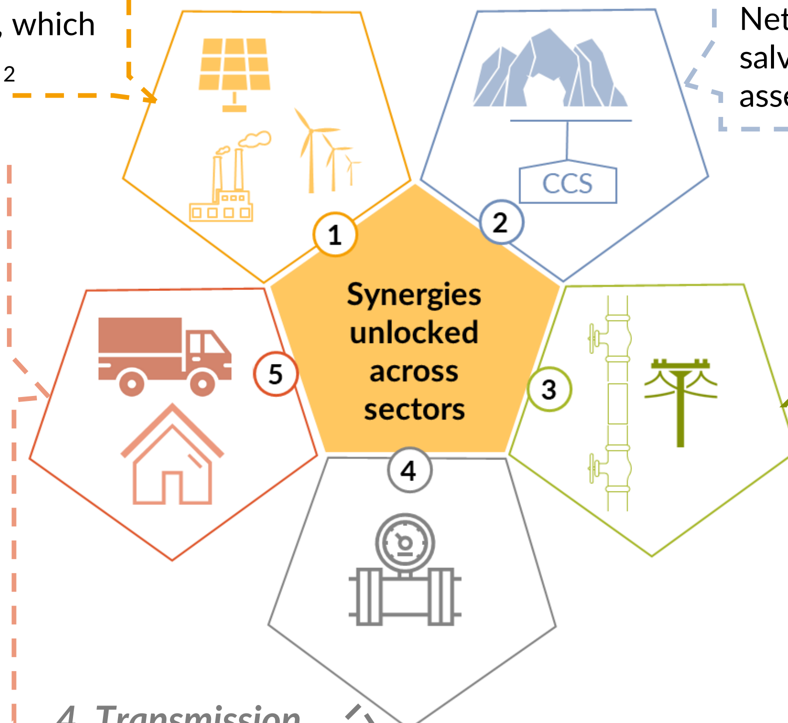
H_2 unlocks cross-sector synergies which, if harnessed, could greatly reduce system costs

1. Supply

H_2 can increase the low-carbon power value pool by reducing and shortening low price periods and minimising both economic and system curtailment, which could be used to produce green H_2

2. Storage

Depleted gas fields and their existing infrastructure could be leveraged on to push CCS deployment – necessary in all Net Zero pathways –while also salvaging remaining value of those assets



3. Distribution

In high electrification scenarios, gas networks can face great risk of stranded assets. Conversion of distribution networks to H_2 would make hydrogen pathways radically less disruptive and costly, while also revamping the value of gas networks

Deferral of power grid upgrade requirements would allow operators to optimise their investments while also potentially reducing costs and increasing value for ratepayers

4. Transmission

In the long term, ageing gas transmission assets could be converted to hydrogen either for transmission or to serve as linepack storage. Gas storage infrastructure could be used to serve blue H_2 production and to provide SoS

5. Demand

Hydrogen can complement electrification as a decarbonisation option, allowing regions to adopt the pathways that result most beneficial for them

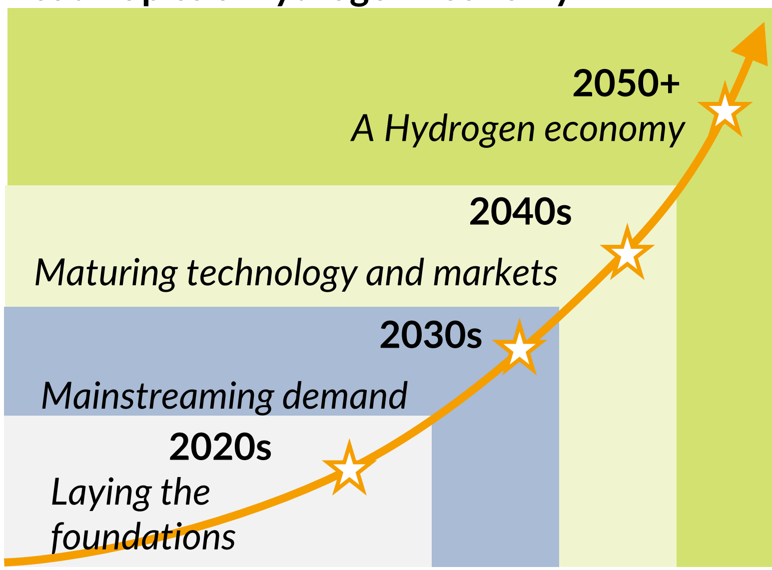
H_2 can reduce CfD spending, potentially optimising cost allocation by charging direct consumers

Additionally, potential optimisation of gas and power network sizing could decrease tariffs for users of both networks

Source: Aurora Energy Research

Unlocking the benefits of a H_2 economy will require early signals, systematic changes and continuous investments

Roadmap to a Hydrogen Economy

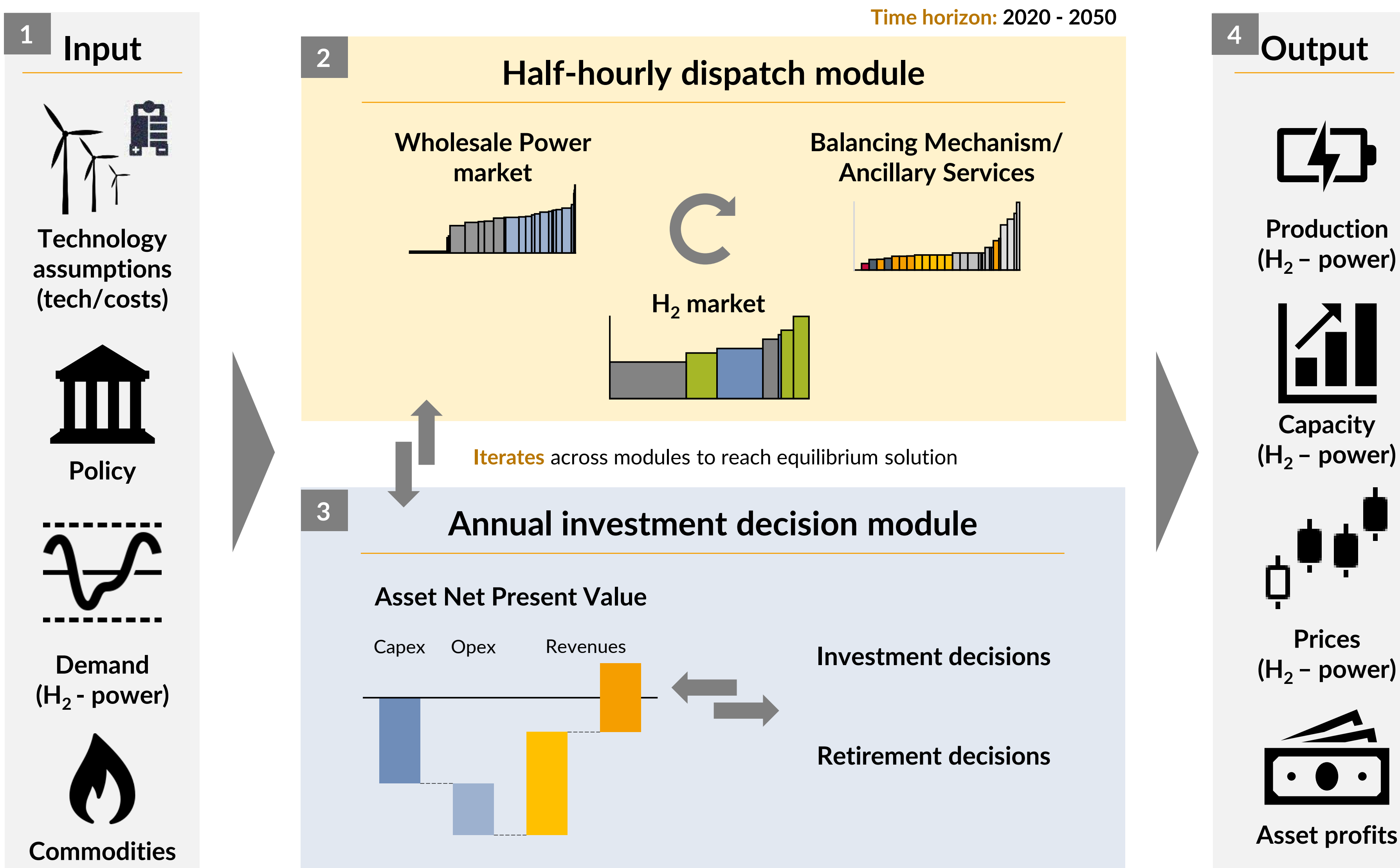


- Existing policies alone are not sufficient to meet the Net Zero target or enable the level of H_2 demand assumed in our scenarios
- Achieving the proposed pathways will require early market signals, structuring of bankable frameworks for key elements of the supply chain and strong policy support
- We have mapped the key milestones that would help materialise these pathways, achieving Net Zero and unlocking high levels of H_2 deployment

Period	Leap-of-faith assumptions
2020s	▪ Extensive rollout of **energy efficiency** to allow for effective heat electrification, required in all scenarios ▪ Net Zero-aligned **carbon pricing** enacted and sustained ▪ **Pathways and mandates for decarbonisation** defined for all major demand segments, especially industry, where the UK can gain an early leadership ▪ **Roll-out of pilot and demonstration projects**, especially around industrial clusters, catalyse significant CO_2 and H_2 infrastructure deployment and **standardisation**
2030s	▪ Industrial UK sector starts to leverage on competitive H_2 prices to lead **low-carbon industrial goods** markets ▪ Enabling of regional H_2 networks starts unlocking **rapid demand growth in heating and industries** with moderate growth in the **transport sector** ▪ Support enables **rapid supply growth**, mostly in regions with potential of H_2 uptake in the short term ▪ Early opportunities **spur infrastructure deployment** and help **the supply chain mature**
2040s	▪ UK established as a **leader exporter** of knowledge and technology in the global H_2 space ▪ High level of **maturity of H_2 markets** and services is achieved, including security of supply ▪ **Cost reduction** in electrolyser technologies enables **rapid penetration of green H_2**
Beyond 2050	▪ **Cross-sector synergies** effectively harnessed ▪ H_2 becomes mainstream and widely traded

Contents

We have developed a model to provide consistent outcomes across the various power and H_2 markets



Source: Aurora Energy Research

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