AURORA ENERGY RESEARCH

Decarbonising hydrogen in a net zero economy

27 September 2021

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Report context

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Aurora Energy Research has been commissioned by Urenco to investigate the benefits of the deployment of both RES and nuclear to support decarbonisation and reduce reliance on fossil fuels as a transitional fuel source in GB.

The scenarios presented in this report are not Aurora forecasts but exploratory scenarios to assess a wider range of technology mixes.

In addition to integrated modelling of power and hydrogen markets, this report also discusses potential risks to the transition and policy implications of modelled technology pathways.

Additional input has been provided by LucidCatalyst, the International Atomic Energy Agency (IAEA), and EDF.

Authored by:

AURORA ENERGY RESEARCH

Commissioned by:

urenco The Energy to Succeed

Additional inputs from:

LUCID CATALYST

IAEA

eDF

What's new?

The majority of studies on the future of the hydrogen sector in GB focus electrolytic H_2 from RES and fossil based H_2 with CCS. The potential for nuclear to participate in the H_2 economy is often not considered due to high costs of recent assets and lack of clear policy direction leading to planned projects being put on hold. This study investigates how policy support for new nuclear technologies and business models to provide low carbon electrolytic H_2 could reduce nuclear and system costs whilst reducing reliance on fossil fuels when deployed alongside RES on the path to net-zero.

Research questions

1. **Routes to decarbonise**
   Can total system costs and emissions be reduced by including nuclear in a net-zero strategy?
2. **The hydrogen economy**
   How could renewables and new nuclear technologies influence the hydrogen economy?
3. **The role of nuclear**
   Can new nuclear business models and technologies with co-located H_2 production provide flexibility to the grid, displace reliance on fossil fuels and improve nuclear economics?

Modelling approach

1. **Integrated in-house modelling simultaneously solves for supply mixes in power and hydrogen markets**
2. **Use of a capacity market with a high carbon price to incentivise economic entry of low carbon capacity**
3. **Modelling new nuclear technologies and business models in the power sector**
4. **Economic entry of hydrogen supply from nuclear**
5. **Discussion of the implications of each modelled scenario for policy and consumers in addition to the risks associated with achieving net-zero**

Source: Aurora Energy Research

Key insights

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1 **Deploying renewables and nuclear for power and hydrogen is required to ensure rapid decarbonisation and reduced reliance on fossil fuels**
Cumulative emissions from 2021-2050 can be reduced by 80 MtCO2e and gas usage in power and H_2 by 8k TWh_{th} in our core scenarios.

2 **Achieving H_2 volumes required for net-zero without fossil fuels will be challenging without support for electrolytic H_2 from RES and nuclear**
The high share of virtually baseload H_2 demand from transport and industry results in a high dependence on fossil based blue H_2, comprising over 35% of demand in 2050 in all scenarios that exclude a "Gigafactory" for nuclear derived H_2. Clear support for electrolytic H_2 is required to reduce costs relative to fossil based blue H_2.

3 **Including nuclear with co-located electrolysers alongside high RES is economically efficient, reducing total system spending by 6-9% (NPV from 2021 – 2050)**
Co-locating electrolysers with nuclear enables nuclear plants to provide additional flexibility to the power grid to match fluctuations in RES supply by diverting electricity output to or away from electrolysers for H_2 production.

4 **Novel business models for nuclear energy can provide cost competitive and scalable sources of zero carbon electricity and hydrogen**
There are opportunities for existing and new nuclear co-located with H_2 electrolysers to produce cost competitive electricity and H_2. In addition, a new generation of nuclear reactors (i.e. small modular reactors and Gen IV reactors) can potentially speed up decarbonisation and reduce use of fossil fuels. Utilising new high temperature nuclear as a source of heat can further increase efficiency of hydrogen production.

5 **Careful market design and policy support structures are required to get to net-zero**
Systems with large volumes of RES and nuclear but limited fossil fuels result in many hours of very low power prices. This leads to an increased need for either support payments or new market designs to bring forward low carbon supply. The continuation of direct support for RES and nuclear (i.e. via CfDs or RABs) and changes to the Capacity Market (CM) are key tools to ensure sufficient low carbon capacity is built. Nuclear can play a key role in decarbonising power and H_2 but clear policy intention is required to lower the financing cost of nuclear and deploy a pipeline of identical projects at low cost.

6 **Broader potential benefits of technology mixes should be considered**
Deploying RES alongside nuclear can facilitate low carbon systems and those with minimal reliance on fossil fuels are found to have the lowest costs. However, the ability of technologies to drive deeper decarbonisation should be considered such as the potential for nuclear gigafactories for H_2 production to decarbonise hard to abate sectors like aviation and shipping via H_2 directly or H_2 derived synthetic fuels.

Source: Aurora Energy Research

Hydrogen has the potential to decarbonise multiple sectors

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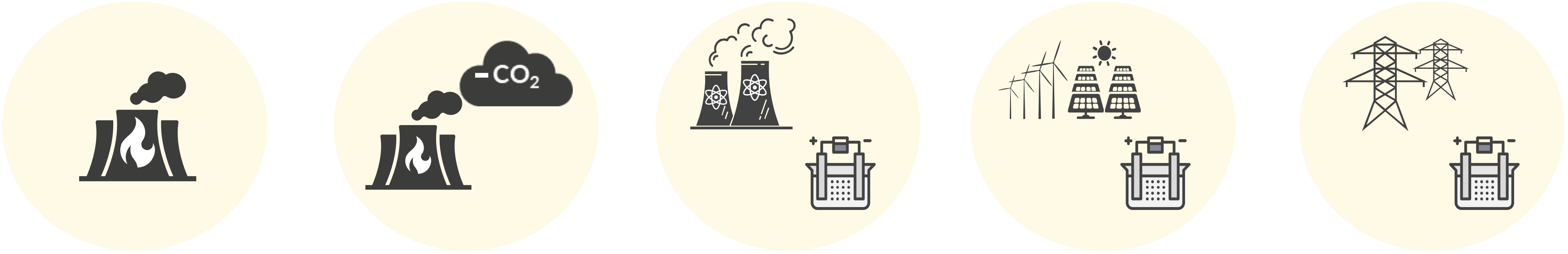
Sectors considered in report	Power	Heat	Road transport	Aviation	Shipping	Industry
Ease of abatement						
The challenge	Many low carbon technologies are available; the key challenge is coping with variable RES output without relying on fossil fuels.	The majority of UK homes are fitted with gas boilers, with many too inefficient to be compatible with electric heat pumps.	Costs of electric cars have plunged but uncertainties remain for road freight. H_2 fuel cells/or H_2 derived synfuels are an alternative but yet to be deployed at scale.	Orders for current models until the mid 2020s, combined with aircraft lifetimes of 20-30 years could lock-in reliance on fossil fuels for decades.	Electric vessels could decarbonise short-haul routes but sustainable alternative fuels (SAF) are needed for long-haul routes. Long vessel lifetimes require entry by 2030.	Many industrial processes (i.e. steel, cement, chemicals and synfuel manufacture) rely on fossil feedstock with complete overhaul of systems and processes required to decarbonise.
Low carbon solutions available	▪ H_2 combustion plants ▪ RES, Nuclear ▪ Gas-CCS ▪ Batteries, DSR	▪ H_2 boilers ▪ District heating (incl. nuclear waste heat)[1] ▪ Electricity (via heat pumps) ▪ Alternative thermal energy storage	▪ H_2 fuel cell vehicles ▪ Synfuels (via H_2) ▪ Electric vehicles	▪ H_2 ▪ Synfuels (via H_2)	▪ H_2 ▪ Synfuels (via H_2) ▪ Electricity (batteries)	▪ H_2 ▪ Synfuels (via H_2) ▪ Electricity (batteries)

1) District heating using waste heat from nuclear has not been considered in this report.

Source: Aurora Energy Research

The majority of hydrogen is currently derived from fossil fuels but can be produced by a range of low carbon methods



Standard nomenclature	Grey	Blue	Pink	Yellow[1]	Yellow
Nomenclature in report	**Grey**	**Blue**	**Green**	**Green**	**Yellow**
Conversion method	Steam reformation	Steam/autothermal reformation	Electrolysis	Electrolysis	Electrolysis
Primary energy source	Natural gas	Natural gas	Nuclear electricity and waste heat	Zero carbon grid electricity from RES and nuclear	Non-zero carbon grid electricity
Technologies modelled in report	Steam methane reformation (SMR)	Steam methane reformation with CCS (SMR+CCS) Autothermal reformation with CCS (ATR+CCS)	High temperature solid oxide electrolysis (SOE)	Alkaline electrolyte membrane (ALK) Polymer electrolyte membrane (PEM)	Alkaline electrolyte membrane (ALK) Polymer electrolyte membrane (PEM)
Emissions intensity, $kgCO_2/kgH_2$	8 – 12	0.6 - 1	0	0	0 - 9

1) Note that the current European Commission definition of green H_2 differs to that used in this report. The EU states that H_2 can only be considered green if created using electricity from new, H_2 production dedicated RES assets that do not provide electricity to the grid 2) No "yellow" electrolysis is seen in the core scenarios and electrolysers only produce when power prices are low.

Sources: Aurora Energy Research, IEA, CE Delft, NREL, NETL, EC JRC-IE

A range of scenarios have been modelled to investigate the impacts of differing levels of nuclear advancement on achieving net-zero

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Modelled GB market scenarios

#L Low H_2 demand #H High H_2 demand

Increasing nuclear ambition →

1. No new nuclear	2. Existing nuclear techs	3. New nuclear techs	4. Strong nuclear strategy

Core scenarios[1]

Core scenarios assume all technologies to compete for economic entry from 2030, with emissions reductions driven by carbon prices and restrictions on unabated thermal in the capacity market.

1L	2L	3L	4L
1H	2H	3H	4H

Results included in executive summary

Sensitivities[2]

Weather year sensitivities: Redispatch of 2040 only against 10 additional historic weather year profiles using the power and hydrogen market supply mix under the High H_2 demand scenarios.

Hydrogen storage sensitivities: Full scenario sensitivities testing 3x hydrogen storage infrastructure capacities.

Continued RES support sensitivities: Full scenario sensitivities using the same methodology but more closely aligned with policy intention. This is captured via higher levels of assumed offshore wind deployment. All other assumptions held equal.

1H: RES 3H: RES

Results included in executive summary

The scenarios that follow are exploratory scenarios to investigate the role of nuclear and H_2 in reaching net-zero and are not forecasts.

1) Core scenario modelling results are explored in detail in Section V; 2) Sensitivity analysis is presented in Section VI.

Source: Aurora Energy Research

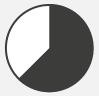
Two hydrogen demand scenarios reflecting differing levels of ambition are modelled in this report

Overview of Aurora's GB H_2 demand scenarios – scrutinised by over 18 market participants

	Low Hydrogen	High Hydrogen
Transport	Low penetration of FCEVs for private transport with moderate use of Hydrogen for in freight and public transport, where use of natural gas prevails. **18 TWh H2 in 2050**	Moderate presence of H_2 in private transport, with higher uptake in public transport and freight. Adoption of H_2 for maritime and rail transport. **162 TWh H_2 in 2050**
Heating	H_2 serves certain areas in the country with advantageous conditions, but use is not widespread. **110 TWh H2 in 2050**	Gas networks are converted to hydrogen with 14 million H_2 boilers present in 2050. **230 TWh in 2050**
Industry	H_2 use for high-grade heat applications along with CCS, electricity serving with low-grade heat requirements. Use as feedstock remains. **82 TWh by 2050**	H_2 used for both high and low-grade heat applications, as well as for industrial feedstock. **114 TWh by 2050**

Source: Aurora Energy Research

Other transport segments were considered only in our High H_2 scenario, but likelihood of uptake is still uncertain

	GB outlook for H_2 Adoption	Likelihood	GB High H_2 Scenario Assumption[3]
Railway	▪ Most promising options for rail decarbonisation include electrification and fuel switching to biofuels or H_2. ▪ There are concerns on supply limitations for biofuels and, in some areas, cost and infrastructure disruption could make electrification prohibitive, making a case for H_2 adoption.		**29 TWh by 2050** Equivalent to a third of all trains in the UK switching fuel use to H_2
Aviation	▪ Prospective measures include increasing efficiency, reducing allowed cargo and using alternative fuels. ▪ Even with all these measures, the sector will likely face disruption or high abatement needs in order to reach Net Zero. ▪ Although small demonstration projects seek to prove feasibility, H_2 uptake in the sector is highly uncertain.		**No demand** was assumed for this sector in the high H_2 scenario, however higher H_2 demand scenarios could see adoption in aviation
Shipping	▪ International Maritime Organisation has enacted a mandate to cut the sector's CO_2 emissions by 50% (relative to 2008 levels) by 2050. ▪ Organisations have stated that without the use of alternative fuels this is likely to be missed. ▪ Despite technical and financial challenges, potential for H_2 uptake in the sector is considered high, either through direct use or as ammonia.[1]		**11 TWh by 2050** Equivalent to the forecasted fuel demand for the sector[2]

1) ICCT; 2) BEIS' forecast extrapolated to 2050; 3) None of these segments were considered in our Low H_2 scenarios.

Sources: Aurora Energy Research, ICCT

Final energy demand across scenarios is held constant, with deviations in system size driven by electrification and electrolysers

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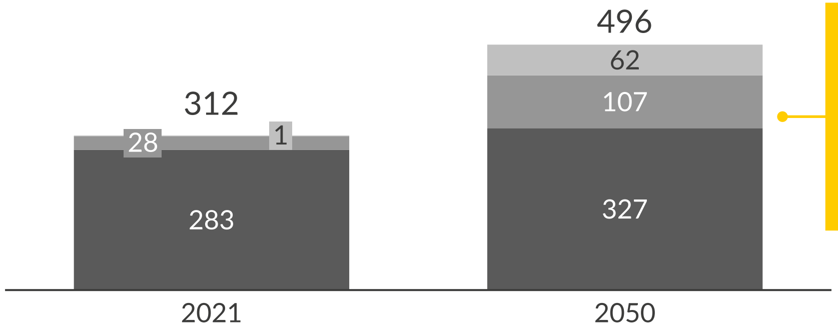
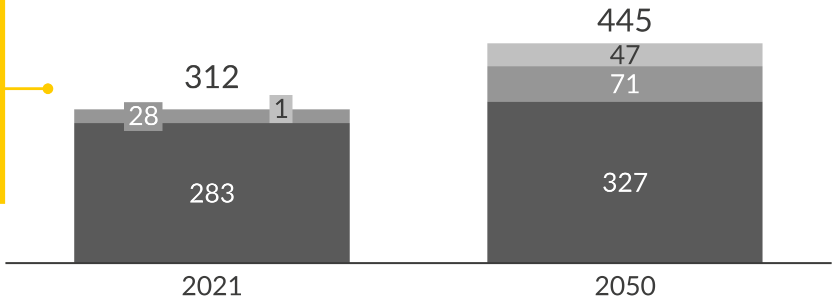
Low H_2 demand	High H_2 demand

GB annual power demand by sector[1]

TWh electricity



Additional power demand from electrolysers is excluded as this is a model output but **total system demand increases 68-103%** from 2021 to 2050 across the core scenarios



Electric Vehicles | Electric Heating | Base power demand[2]

GB annual hydrogen demand by Sector

TWh H_2

Industry | Transport | Heat

1) Excludes power demand from electrolysers for H_2 production as this is a model output. Total power demand therefore varies in each market scenario.

Source: Aurora Energy Research

Adopting a strong nuclear strategy could reduce power system reliance on fossil fuels to just 3% of generation

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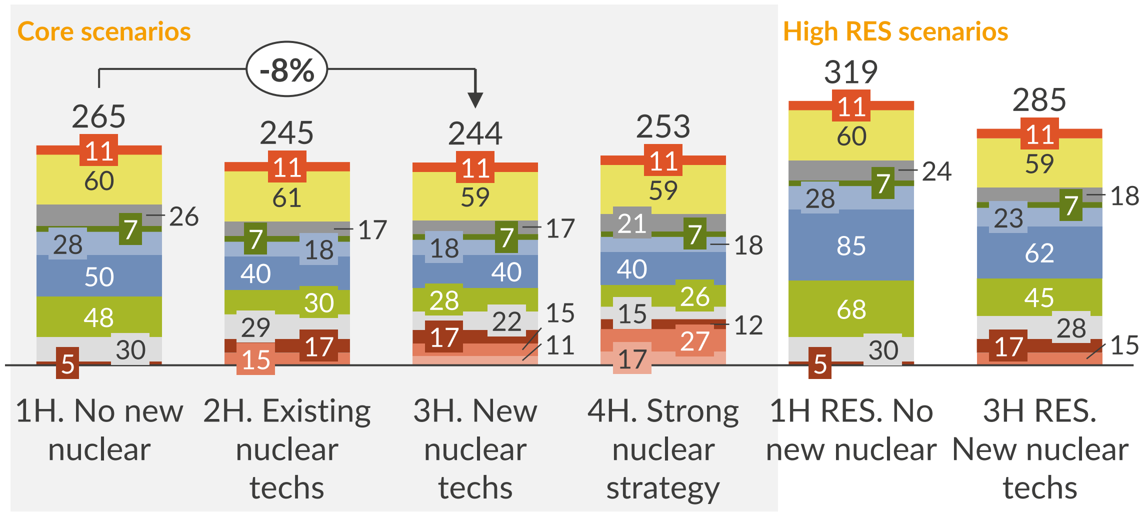
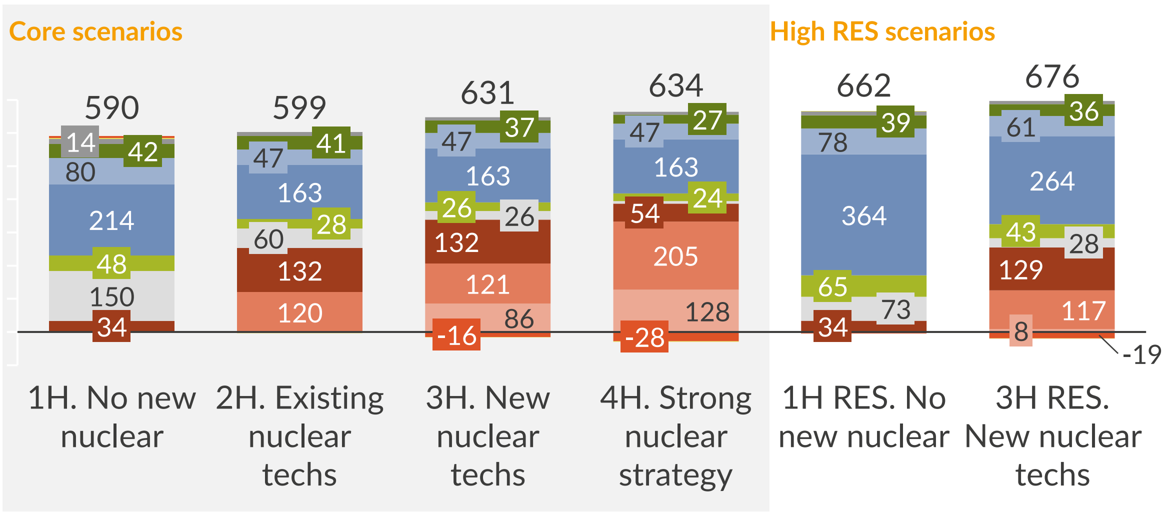
GB installed capacity in 2050
GW



GB electricity production and net imports in 2050
TWh



- The four core scenarios show an increasing prevalence of nuclear power, with most of the demand in 4H met by nuclear sources by 2050 facilitated by low nuclear costs. The bulk of this generation comes from small modular and Gen IV reactors, which are expected to come online from the 2030s onwards. 4H sees less economic deployment of large nuclear reactors as they are displaced by small and Gen IV reactors which see lower costs in this scenario.
- Higher levels of cheap electricity from RES and nuclear lead to greater overall electricity demand, due to increased demand for electrolytic H_2 which benefits from low electricity prices.
- The 1H RES and 3H RES sensitivities assume more support for renewables than their core scenario counterparts. This leads to a RES-dominated supply mix and lower levels of nuclear buildout. It also creates a larger system in terms of installed capacity, due to the lower load factors of RES relative to nuclear.

Interconnectors | Unabated thermal[2] | Onshore wind | Solar PV | Large nuclear | Gen IV with electrolyser
Low carbon flex[1] | Other RES[3] | Offshore wind | Gas CCS | Small Modular Reactor

1) Low carbon flex includes DSR, battery storage, hydrogen peakers, hydrogen CCGT, pumped storage 2) Other RES includes biomass, BECCS, EfW and marine; 3) Unabated thermal includes CCGTs, gas peaking, embedded CHP.

Source: Aurora Energy Research

Low nuclear costs and economic entry of a hydrogen Gigafactory enable reliance on fossil H_2 to drop to 6% by 2050

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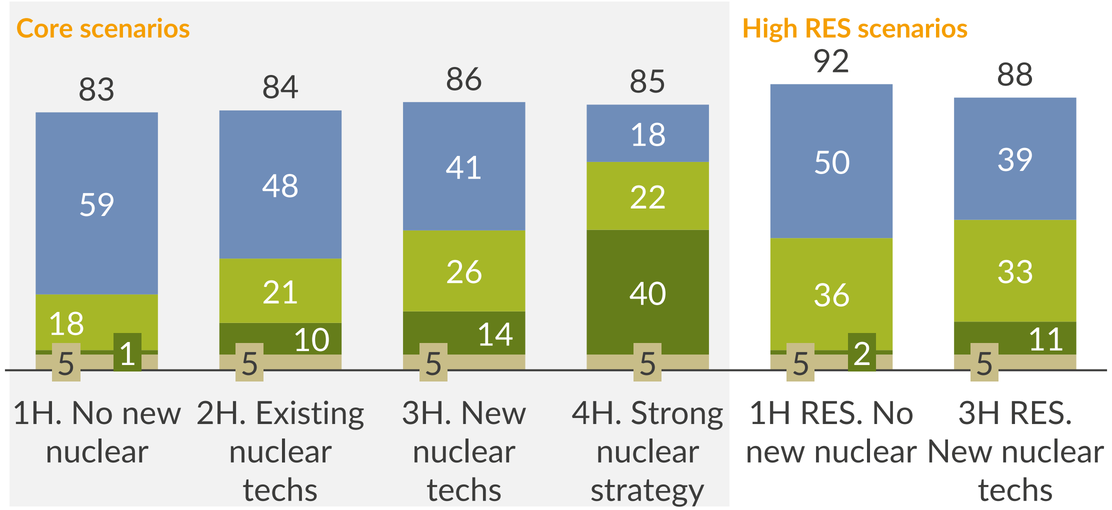
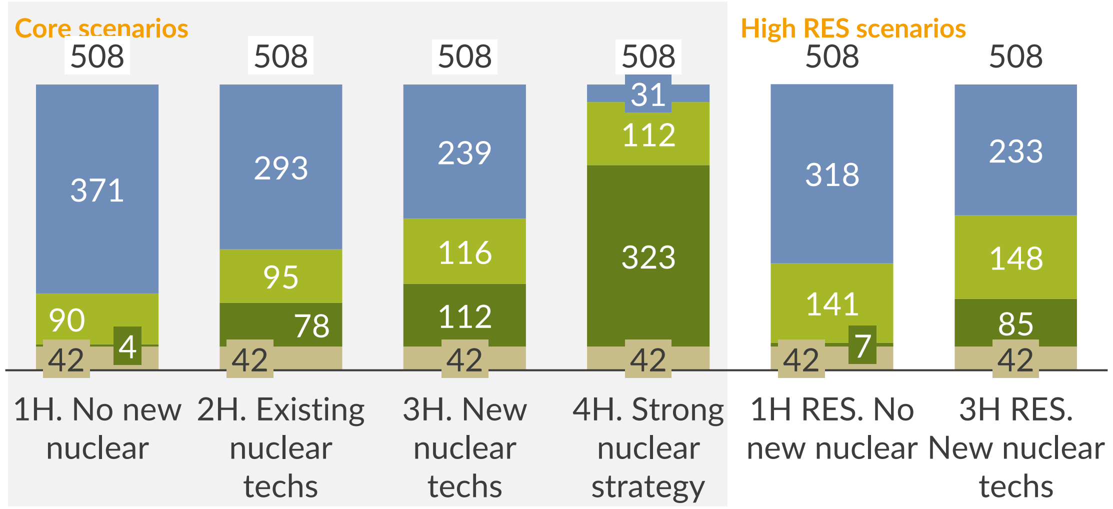
GB installed capacity in 2050

GW H_2



GB gross H_2 production in 2050

TWh H_2



- All scenarios with the exception of 4H have a high reliance on blue H_2 made from fossil gas with CCS. This is responsible for 73% of supply in 2050 in 1H and remains a significant source of H_2 in 2H and 3H. Variability in RES output, combined with low levels of excess RES lead to unfavourable economics for non-nuclear derived green H_2 relative to fossil based blue H_2.
- Indeed, in 1H RES and 3H RES, the greater levels of intermittent, cheap renewable generation create more periods of low power prices, enabling more grid connected electrolysers to enter profitably.
- Scenario 4H outlines that strong support for a nuclear construction pipeline could establish a nuclear gigafactory consisting of many small nuclear reactors dedicated to H_2 production via SOEs. This enables almost all 2050 H_2 demand to be met via zero-carbon electrolysis and reduces reliance on fossil fuels for H_2 production to just 6%.
- The “negative carbon emissions” associated with BECCS are expected to be highly valuable and attributed to hard to abate sectors. This capacity is therefore assumed in model as it is likely to be driven by policy or valuable carbon credits.

BECCS | Green: nuclear derived | Green: grid connected | Blue | Grey

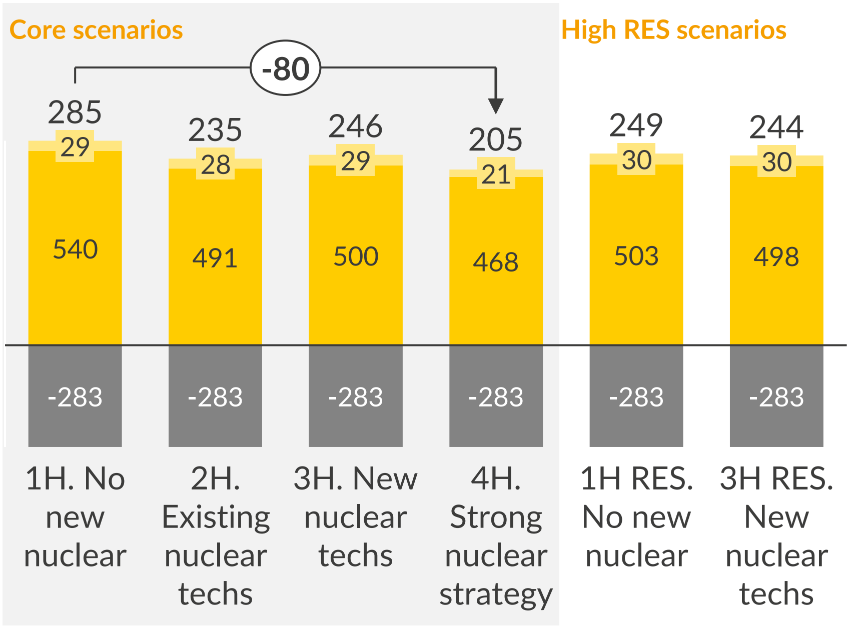
1) Majority of PEM electrolyser capacity and generation shown here correspond to re-fuelling stations providing pure H_2 for hydrogen –powered vehicles. These are treated separately and do not contribute to market dynamics shown in the following slides.

Source: Aurora Energy Research

Systems with higher levels of nuclear deployment lead to lower emissions from the power and hydrogen sectors

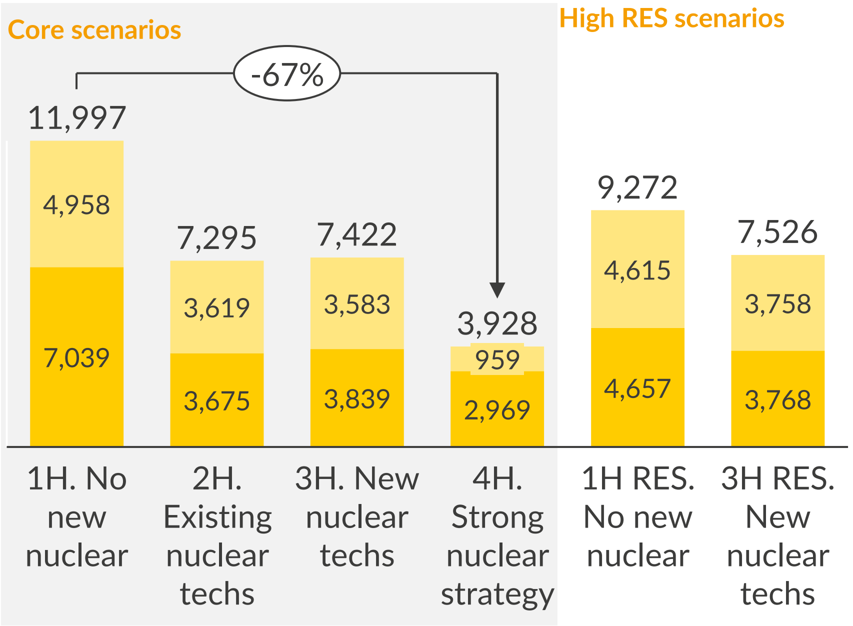
GB cumulative emissions from electricity and H_2 production (2021-50)

$MtCO_2$



GB cumulative natural gas usage from electricity and H_2 production (2021-50)

TWhth HHV



GB emissions from electricity and H_2 production in 2050 excluding BECCs

$MtCO_2$

8.6	5.5	4.4	3.0	6.5	4.5

GB natural gas usage from electricity and H_2 production in 2050

TWhth HHV

883	584	437	128	647	433

Power production | Hydrogen production | BECCs[1]

Power sector | Hydrogen sector

- Support for a pipeline of nuclear projects leading to low nuclear costs can lead to:
  - 80 $MtCO_2e$ avoided emissions from 2021-2050
  - 67% reduction in fossil gas usage from 2021-2050.
- 1H, 1H RES and 3H RES have the highest fossil fuel use due to the variability in RES output requiring flexible gas plants to ramp up and down to meet demand.
- Comparing 1H and 3H to their high RES counterparts highlights that while supporting renewables buildout can help reduce fuel use and emissions, the benefits of doing so are less stark in a high nuclear system (3H) as emissions are already very low.

1) Potential to cancel out up to 36 $MtCO_2$ annually by considering negative emissions from sustainable biomass paired with CCS.

Source: Aurora Energy Research

Net-zero pathways that adopt RES and nuclear in power and hydrogen markets can reduce total system spending by 6-9% (NPV)

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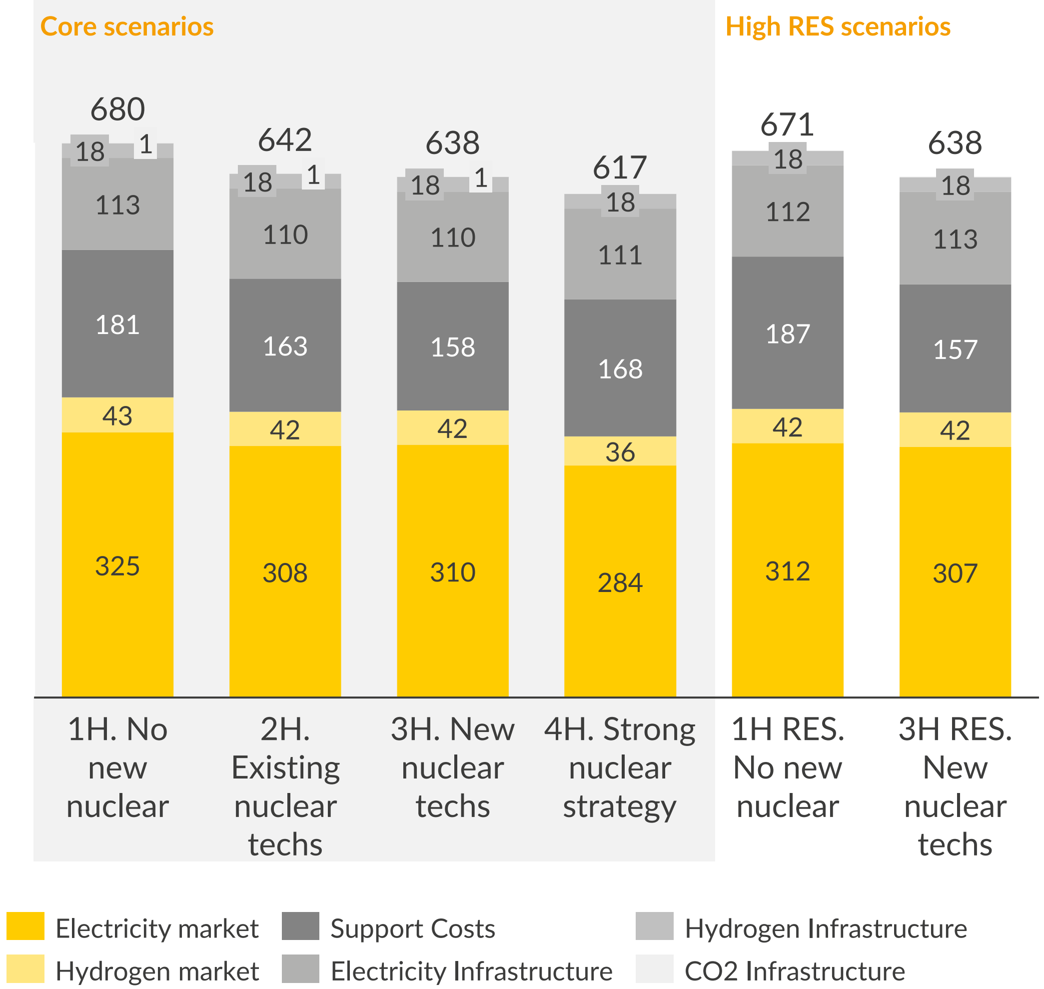
GB NPV total system spend from 2021 - 2050[1]

£bn



- **Electricity market spending** is the key driver of total system spend across scenarios and is directly linked to the supply mix. Scenarios with a high share of RES and nuclear dampen electricity prices, whereas scenarios that rely on more expensive fossil based sources for baseload and flexibility see higher electricity prices.
- **Hydrogen market spending** is similar across scenarios as prices are typically set by blue H_2 and strongly correlated with gas prices. Lower costs in 4H are driven by nuclear derived electrolytic H_2 meeting demand in summer.
- **Support costs** are strongly linked to electricity market prices as low wholesale market revenues lead to higher top-ups for existing contracts (CfDs) and higher CM payments for new capacity to break even. The need for higher support costs in 4H due to low electricity prices is counteracted by lower costs for nuclear and a smaller system overall.
- **Infrastructure costs** are similar across all core scenarios as systems are of a similar size and H_2 and CO_2 costs are volumetric. H_2 and CO_2 costs could vary much more depending on proximity of supply to demand.

1) Costs are discounted using a rate of 5%.

Source: Aurora Energy Research

A series of least regret options can be pursued to minimise risks to the transition towards net-zero

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1 **Continued revenue support for low carbon technologies**
To incentivise deployment of low-carbon capacity despite low wholesale market revenues as a result of high penetrations of low marginal cost supply. A level playing field for all technologies is required.

2 **Limit participation of unabated thermal in the CM**
To prevent locking in reliance on new unabated thermal assets, that will remain online for 25 years, by only procuring low carbon alternatives.

3 **Studies on the role of green H_2 from RES and nuclear to displace fossil fuels**
Further investigations of H_2 only business models for RES and nuclear to create low cost H_2 without fossil fuels.

4 **Conduct in depth siting and feasibility studies for nuclear and RES deployment**
To ensure target deployment can be met.

5 **Assess infrastructure requirements of decarbonisation pathways**
To assess need, cost, development time and ecological impact for required infrastructure to be deployed in time for assets to online.

6 **Examine the role existing nuclear can play in green H_2 production**
Co-location of electrolysers with existing nuclear can unlock additional revenue streams whilst providing additional power system flexibility.

7 **Explore support for a construction pipeline of small modular reactors**
To enable deployment, costs reductions and assess feasibility of large scale deployment.

8 **Explore support options for nuclear business models for power + H_2**
To compare against other low carbon technologies.

9 **Further investigate the benefits of high temperature nuclear (Gen IV)**
High temperature reactors could unlock very high H_2 conversion efficiencies using waste heat, with potential for cost reductions.

10 **Development of clear business models for H_2 and CO_2 infrastructure**
To assess costs and incentivise investment.

Source: Aurora Energy Research

Glossary of terms

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Term	Description	Term	Description
UK-ETS	United Kingdom Emission Trading Scheme	CCGT	Combined Cycle Gas Turbine
gCO_2	Gram of carbon dioxide	CCS	Carbon capture and storage
GWe	Gigawatt Electricity	SOE	Solid oxide electrolyser
HHV	Higher Heating value	Blue H_2	H_2 derived from natural gas with CCS
kWhe	Kilowatt-hour Electricity	Green H_2	H_2 derived from electrolysers
Mt CO_2	Megatonne carbon dioxide	Hydrogen Gigafactory	Nuclear and electrolysers for dedicated H_2 production with no connection to the electricity grid
MWhe	Megawatt-hour Electricity	Low-marginal cost	Supply sources with low costs of producing an additional unit of output (i.e. RES and nuclear as they face low fuel costs)
TWhe	Terawatt-hour Electricity	Capture price	The production weighted average market price achieved
GW H2	Gigawatt Hydrogen	Merchant	Refers to assets that build without subsidies
kWh H2	Kilowatt-hour Hydrogen		
MWh H2	Megawatt-hour Hydrogen		
TWh H2	Terawatt-hour Hydrogen		

Source: Aurora Energy Research

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The UK is almost half way to net-zero but additional policies are required to meet current targets

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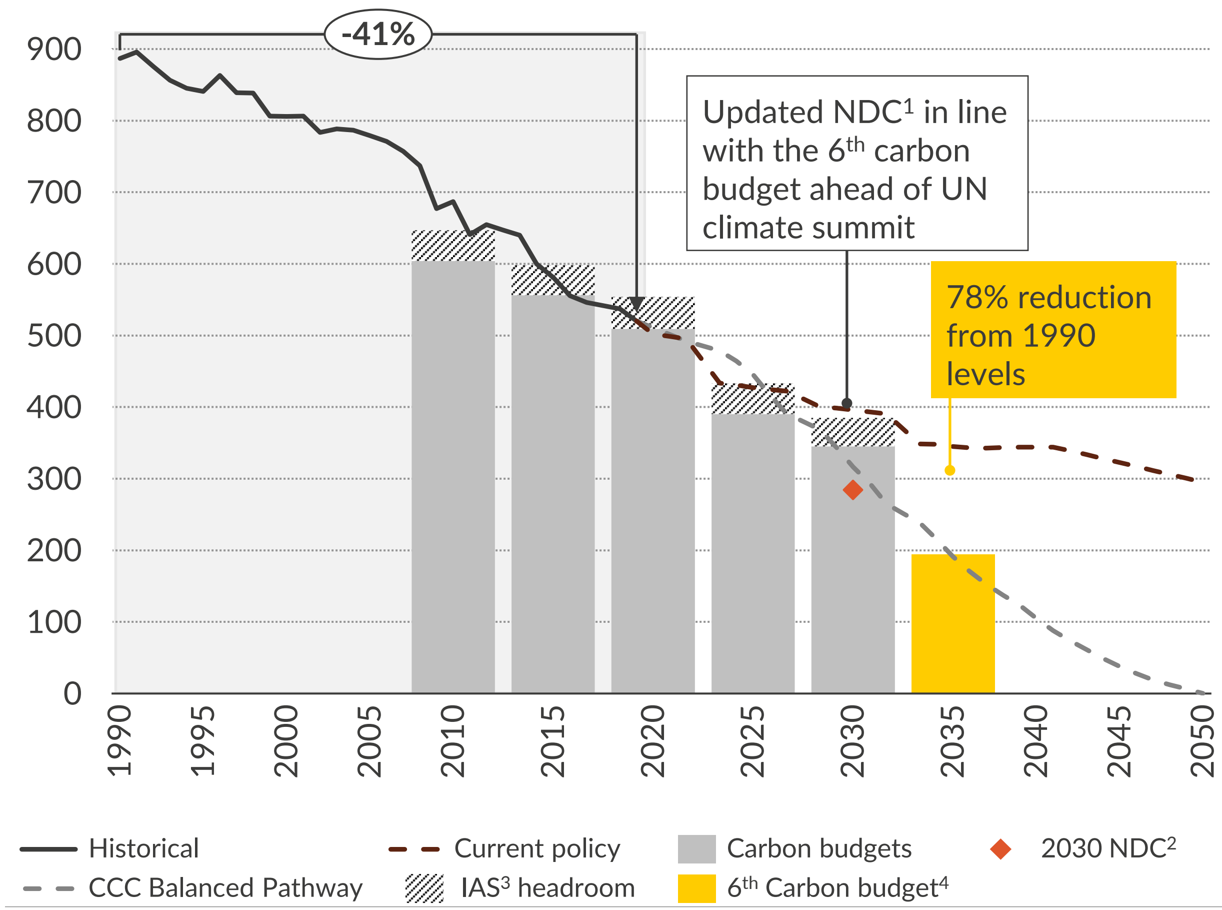
GB has been a world leader in reducing emissions, and the first country to introduce a legally binding target of net-zero emissions by 2050 however significant challenges must be overcome to reach net-zero emissions

Total UK Greenhouse Gas Emissions and carbon budgets

$MtCO_2e$



- The Climate Change act (2008) committed the UK to 80% emissions reductions below 1990 levels by 2050 through setting legally binding 5-year carbon budgets advised by the Committee on Climate Change (CCC).
- The UK has seen a 41% decline in emissions since 1990 and has beaten all of its carbon budgets to date.
- This has mainly been driven by decarbonisation in the power sector, initially linked to the switch from coal to gas, and later due to the introduction of the Carbon Price Support, and growth in renewables through subsidies (see next slide).
- Further abatement efforts across the economy are expected to be increasingly challenging, especially outside of the power sector.
- The previous 5 carbon budgets, which covers the period to 2032, were based on the old 80% target for 2050. The 6th carbon budget, published in December 2020, which covers the time period between 2033 – 2037, seeks to align the UK's trajectory with its recently legislated 2050 net zero target in June 2019.
- The CCC recommend a **78% reduction from 1990 levels** across greenhouse gas emissions by 2035 (including international aviation and shipping). This new target essentially brings forward the previous 80% emission reduction target for 2050 forward by 15 years.

1) Nationally Determined Contributions; 2) NDCs excludes international aviation and shipping as per UN convention; 3) International aviation and shipping; 4) CCC's 6th Carbon budget includes IAS emissions.

Sources: Aurora Energy Research, BEIS, CCC

Technologies for power sector decarbonisation are plentiful; hydrogen can participate in all sectors even when options are limited

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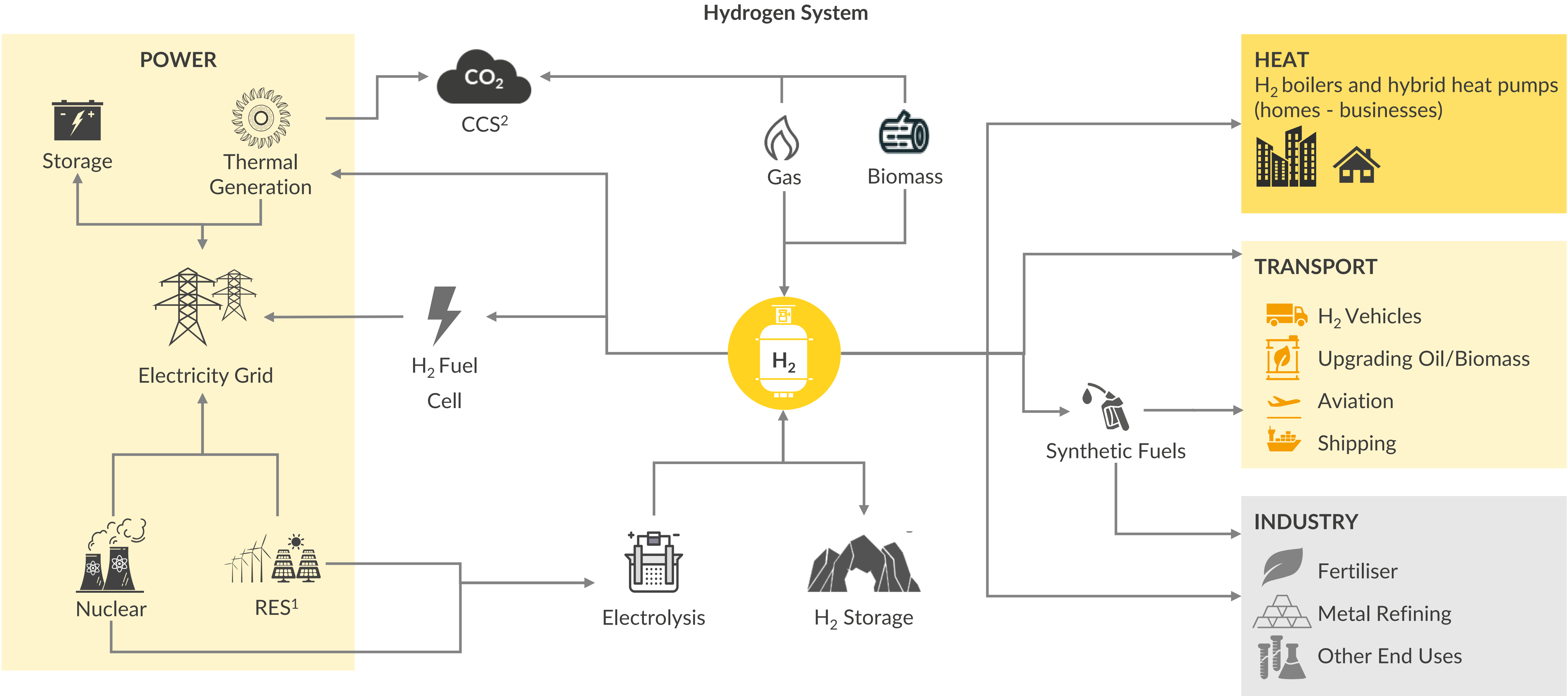
Sectors considered in report

	Power	Heat	Road transport	Aviation	Shipping	Industry
Ease of abatement	● (full)	◕ (three-quarters)	◑ (half)	◔ (quarter)	◔ (quarter)	◔ (quarter)
The challenge	Many low carbon technologies are available; the key challenge is coping with variable RES output without relying on fossil fuels.	The majority of UK homes are fitted with gas boilers, with many too inefficient to be compatible with electric heat pumps.	Costs of electric cars have plunged but uncertainties remain for road freight. H_2 fuel cells/or H_2 derived synfuels are an alternative but yet to be deployed at scale.	Orders for current models until the mid 2020s, combined with aircraft lifetimes of 20-30 years could lock-in reliance on fossil fuels for decades.	Electric vessels could decarbonise short-haul routes but sustainable alternative fuels (SAF) are needed for long-haul routes. Long vessel lifetimes require entry by 2030.	Many industrial processes (i.e. steel, cement, chemicals and synfuel manufacture) rely on fossil feedstock with complete overhaul of systems and processes required to decarbonise.
Low carbon solutions available	▪ RES, Nuclear ▪ Gas-CCS ▪ **H_2 combustion plants** ▪ Batteries, DSR	▪ Electricity (via heat pumps) ▪ District heating (incl. nuclear waste heat)[1] ▪ **H_2 boilers** ▪ Alternative thermal energy storage	▪ Electric vehicles ▪ **H_2 fuel cell vehicles** ▪ **Synfuels (via H_2)**	▪ **H_2** ▪ **Synfuels (via H_2)**	▪ Electricity (batteries) ▪ **H_2** ▪ **Synfuels (via H_2)**	▪ Electricity (batteries) ▪ **H_2** ▪ **Synfuels (via H_2)**

1) District heating using waste heat from nuclear has not been considered in this report.

Source: Aurora Energy Research

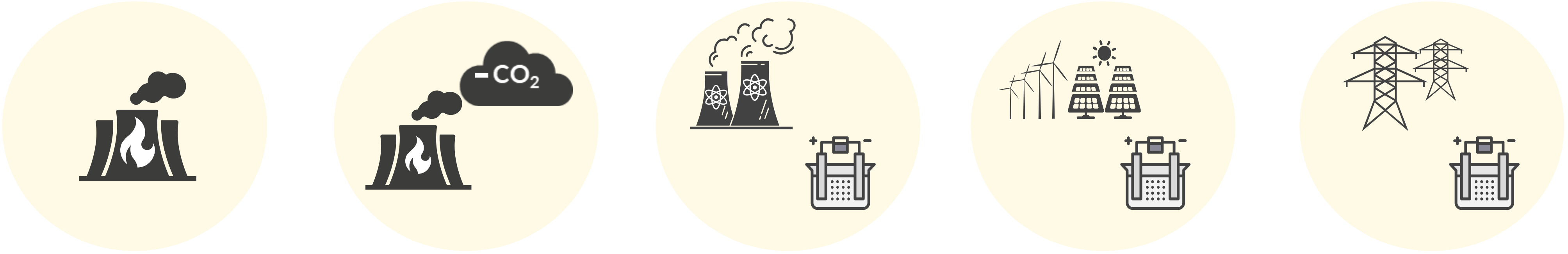
Hydrogen is emerging as a potential key player to decarbonise multiple hard to abate sectors



1) Renewable Energy Sources; 2) Carbon Capture and Storage.

Source: Aurora Energy Research

Hydrogen can be produced by a range of low carbon methods, however most H_2 today is currently derived from fossil fuels



Standard nomenclature	Grey	Blue	Pink	Yellow[1]	Yellow
Nomenclature in report	**Grey**	**Blue**	**Green**	**Green**	**Yellow**
Conversion method	Steam reformation	Steam/autothermal reformation	Electrolysis	Electrolysis	Electrolysis
Primary energy source	Natural gas	Natural gas	Nuclear electricity and waste heat	Zero carbon grid electricity from RES and nuclear	Non-zero carbon grid electricity
Technologies modelled in report	Steam methane reformation (SMR)	Steam methane reformation with CCS (SMR+CCS) Autothermal reformation with CCS (ATR+CCS)	High temperature solid oxide electrolysis (SOE)	Alkaline electrolyte membrane (ALK) Polymer electrolyte membrane (PEM)	Alkaline electrolyte membrane (ALK) Polymer electrolyte membrane (PEM)
Emissions intensity, $kgCO_2/kgH_2$	8 – 12	0.6 - 1	0	0	0 - 9

1) Note that the current European Commission definition of green H_2 differs to that used in this report. The EU states that H_2 can only be considered green if created using electricity from new, H_2 production dedicated RES assets that do not provide electricity to the grid 2) No "yellow" electrolysis is seen in the core scenarios and electrolysers only produce when power prices are low.

Sources: Aurora Energy Research, IEA, CE Delft, NREL, NETL, EC JRC-IE

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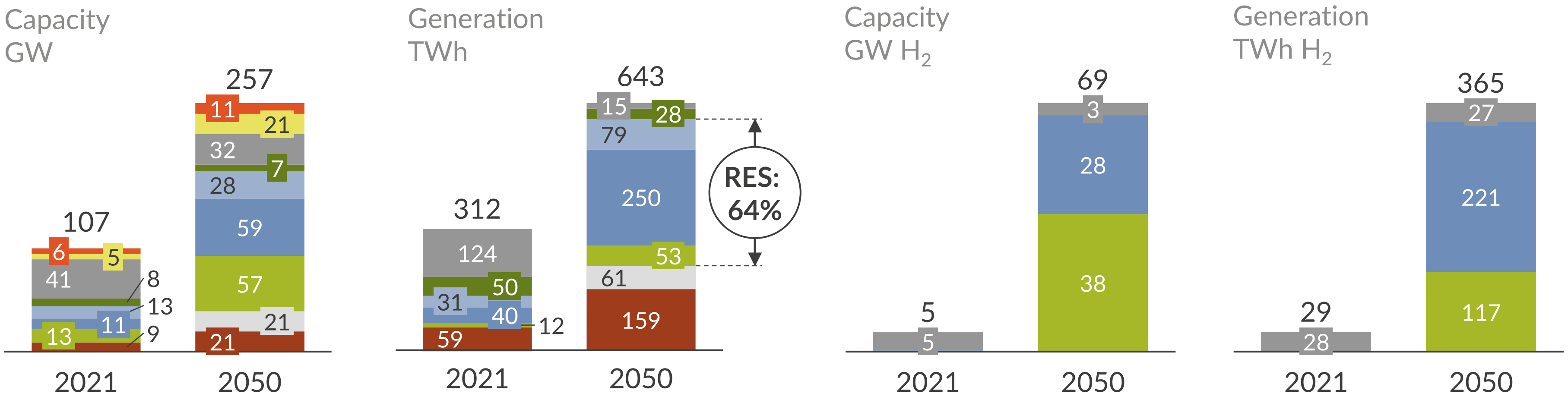
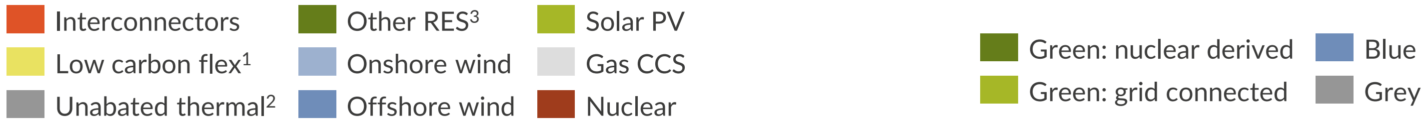
Aurora's in-house Net Zero view sees strong deployment of RES capacity, with wind making up >50% of generation in 2050

GB power Production in 2050 – Aurora Net Zero | **GB hydrogen Production in 2050 – Aurora Net Zero**



- Aurora forecasts demand to more than double by 2050 to meet rising electricity demand, driven by the decarbonisation of sectors including heat and transport via electrification and hydrogen via electrolysis. The core scenarios modelled in this report see a 68% - 103% increase in electricity demand.
- Power capacities are similarly required to increase due to the replacement of unabated thermal plants which run at high capacity factors of over 80% with RES, which run at comparatively lower load factors and require additional battery storage and peaking capacities.
- GB does not match the specific support for electrolytic H_2 seen in other European countries like Germany and 60% H_2 supply in 2050 is forecast to come from fossil based blue H_2.



1) Low carbon flex includes DSR, battery storage, hydrogen peakers, hydrogen CCGT, pumped storage 2) Other RES includes biomass, BECCS, EfW and marine; 3) Unabated thermal includes CCGTs, gas peaking, embedded CHP.
Source: Aurora Energy Research, BEIS Energy White Paper

- Our in-house Net Zero scenario reflects all recent government targets, including the Energy White Paper's 40GW of offshore wind and capture of 10 $MtCO_2$ via CCS by 2030.
- Installed power capacity increases by 150 GW across the horizon, driven by rapid growth of renewable and peaking capacity.
- Hydrogen capacity increases by almost 20x across the horizon, with electrolysers and ATR+CCS being key contributors to hydrogen production in the long-term.
- The scenarios modelled in this report do not represent Aurora's forecasts but instead explore the implications of high nuclear systems.

What's new?

The majority of studies on the future of the hydrogen sector in GB focus electrolytic H_2 from RES and fossil based H_2 with CCS. The potential for nuclear to participate in the H_2 economy is often not considered due to high costs of recent assets and lack of clear policy direction leading to planned projects being put on hold. This study investigates how policy support for new nuclear technologies and business models to provide low carbon electrolytic H_2 could reduce nuclear and system costs whilst reducing reliance on fossil fuels when deployed alongside RES on the path to net-zero.

Research questions

1. **Routes to decarbonise**
   Can total system costs and emissions be reduced by including nuclear in a net-zero strategy?

2. **The hydrogen economy**
   How could renewables and new nuclear technologies influence the hydrogen economy?

3. **The role of nuclear**
   Can new nuclear business models and technologies with co-located H_2 production provide flexibility to the grid, displace reliance on fossil fuels and improve nuclear economics?

Modelling approach

1. **Integrated in-house modelling simultaneously solves for supply mixes in power and hydrogen markets**
2. **Use of a capacity market with a high carbon price to incentivise economic entry of low carbon capacity**
3. **Modelling new nuclear technologies and business models in the power sector**
4. **Economic entry of hydrogen supply from nuclear**
5. **Discussion of the implications of each modelled scenario for policy and consumers in addition to the risks associated with achieving net-zero**

Source: Aurora Energy Research

This study utilises our integrated modelling suite to capture market interactions and impacts of deploying RES and nuclear

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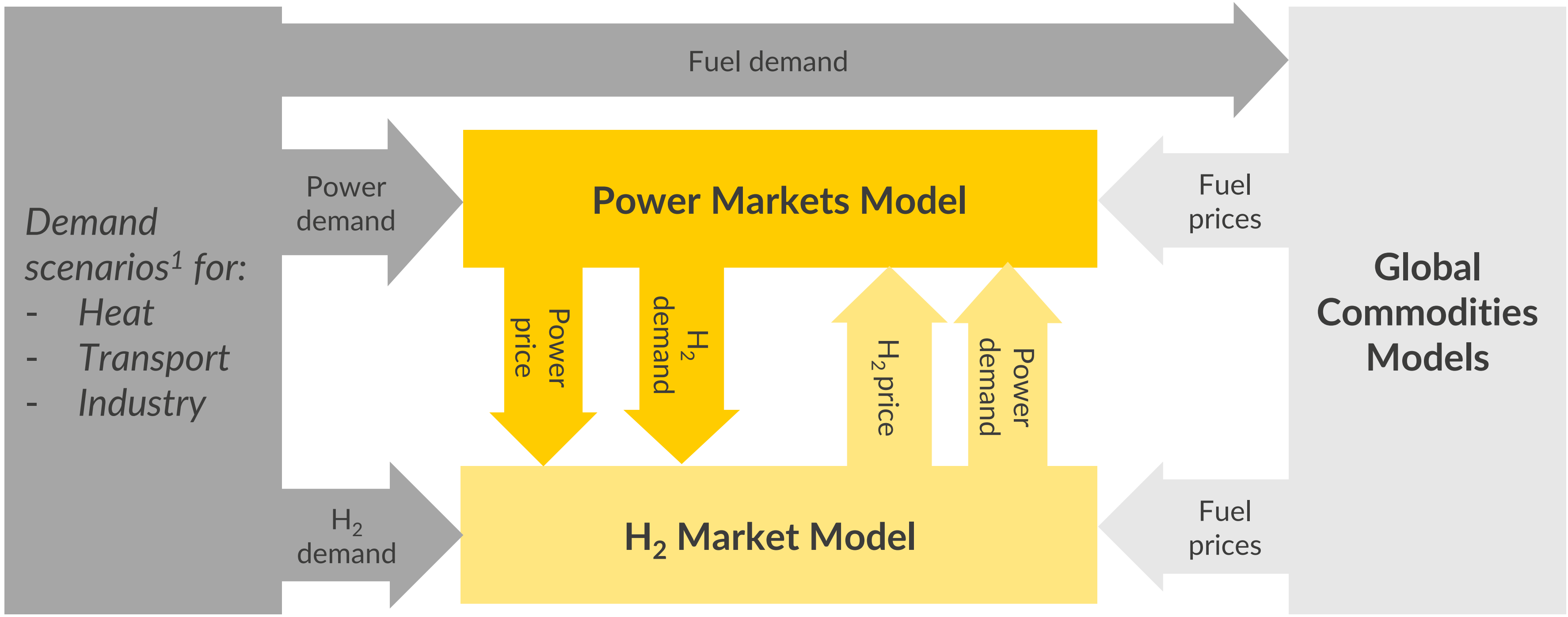
1 Integrated in-house modelling and economic entry of capacity in power and hydrogen markets

Overview of Aurora's modelling suite



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.

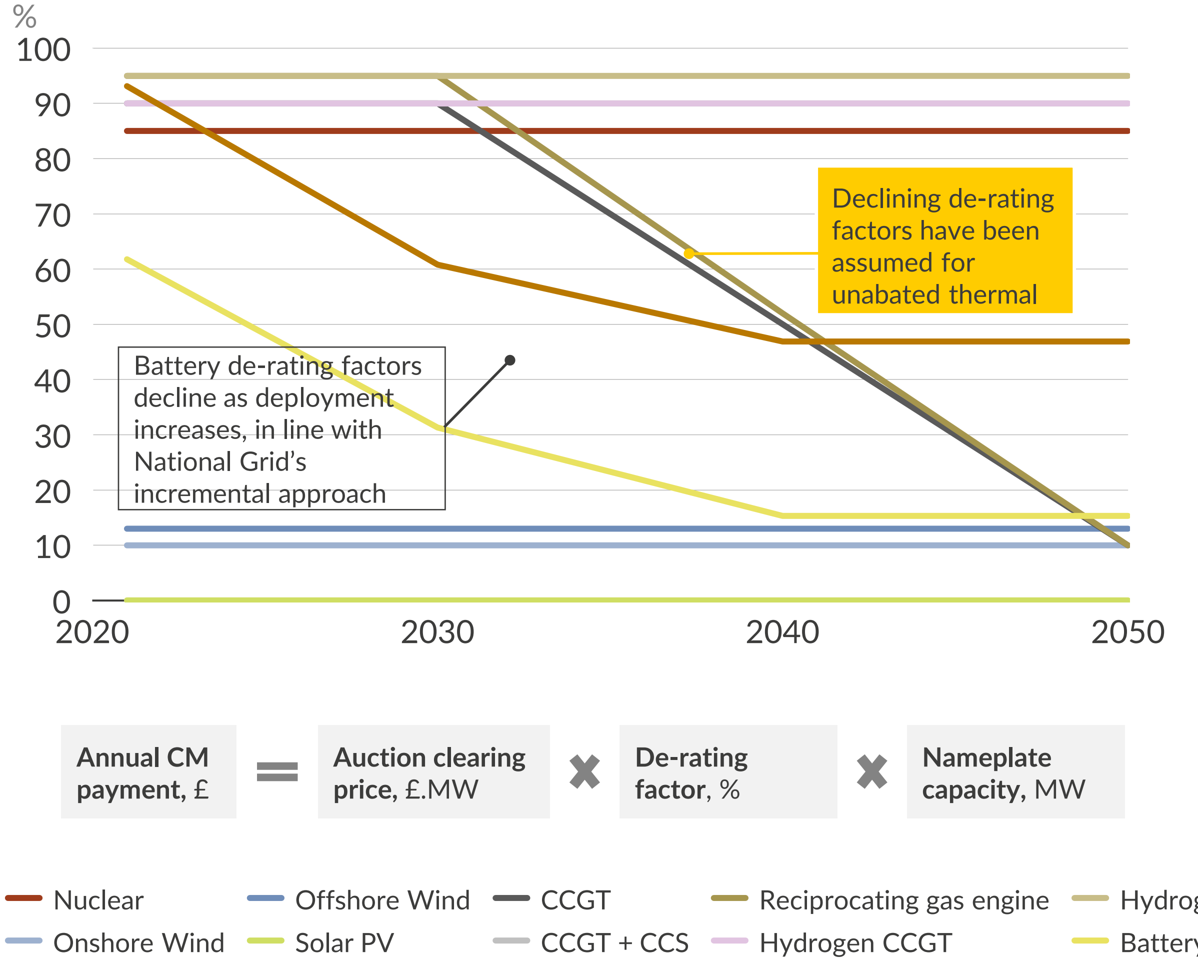
By integrating H_2 and power market modelling, Aurora's approach captures the interactions of power and H_2.

Source: Aurora Energy Research

A revised Capacity Market is used to deploy low carbon capacity but has limited effectiveness in fully merchant low marginal cost systems

2 Use of a capacity market to incentivise economic entry of low carbon capacity

Capacity market de-rating factor (i.e. contribution to security of supply)



Annual CM payment, £ = **Auction clearing price, £.MW** × **De-rating factor, %** × **Nameplate capacity, MW**

- The Capacity Market (CM) awards contracts, paid to existing (1yr) and new-build (15yr, 1yr) assets on a £/kW basis in a pay-as-clear auction, to ensure there is sufficient capacity to meet demand.
- De-rating factor are applied to each technology to reflect their contribution to security of supply and influences the size of the payment received and the volume of capacity procured each year.
- Typically, the CM payment covers any shortfall in forecast revenue from wholesale and balancing markets, and ancillary services required to keep existing capacity online or enable entry of new capacity.
- In this modelling exercise, all capacity entering post-2030 in the core market scenarios is assumed to enter economically on a merchant basis (i.e. without direct subsidy support) based on returns available in model and the use of the CM has been expanded to procure low-carbon capacity by assuming declining de-rating factors for unabated thermal assets.
- As the CM is the only tool providing contracted revenues to top-up any shortfalls in wholesale and balancing markets, this modelling approach favours the build of firm dispatchable capacity to meet supply targets (i.e. nuclear, gas-CCS) over RES that contributes less to security of supply.
- Merchant RES build-out in systems with high shares of low-marginal cost supply and a low carbon CM will inherently be low.

Note that the current administrative CM price cap of £75/kW has been removed for this exercise.

Source: Aurora Energy Research

Economic entry of RES and nuclear under a range of business models have been considered in this report

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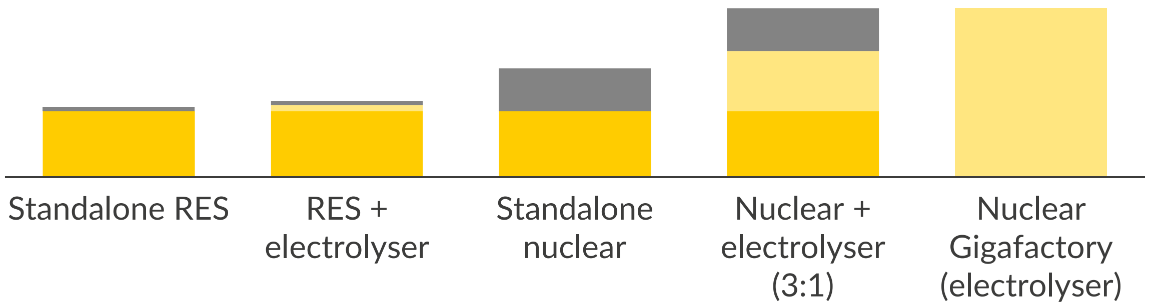
3 Modelling new nuclear technologies and business models in the power sector

Revenue streams for new capacity (illustrative)

£/kW



- Most RES capacity in GB has been deployed via direct support i.e. CfDs[1], however merchant business models, especially with PPA[2] contracts are increasing.
- Dedicated RES for H_2 co-located with electrolysers do not deploy in this modelling without very high RES deployment but mechanisms could be introduced to facilitate these business models.
- New nuclear in GB has recently been supported with a CfD but other options are being explored (i.e. RAB model).
- The majority of new nuclear in this modelling builds with a co-located electrolyser for H_2 as this enables nuclear to secure higher value for power output in H_2 markets when electricity prices are low.
- Colocation of RES or nuclear with electrolysers could reduce market risk and therefore discount rates, however this has not been modelled in this report.

Wholesale electricity | Wholesale hydrogen | Capacity market

Overview of modelled nuclear business models

	Unit size (MW_e)	Electrolyser pairing	H_2 conversion efficiency (% HHV)[3]	Description
Existing nuclear: large scale (gen III)	c.1500	PEM/ Alkaline	75%	Hinkley Point C and Sizewell B are assumed to install onsite electrolysers in 2030.
Large scale (gen III)	c.1500	Solid oxide	107%	Same underlying technology but smaller unit sizes facilitate siting closer to demand centres.
Small scale (gen III)	<300	Solid oxide	107%	
Large/small scale (gen IV)	c.1500 /<300	Solid oxide	114%	High temp. reactors allow greater efficiency of electrolysis using high grade heat.
Gigafactory (gen IV)	Min. 1000	Solid oxide	114%	Dedicated H_2 production facility with nuclear & electrolysers near H_2 demand sources.

1) Contract for Difference 2) Power Purchase Agreement (PPA) 3) MWh electric to MWh H_2 conversion, values greater than 100% achieved for solid oxide electrolysers due to the added energy input from heat.

Source: Aurora Energy Research

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8 core market scenarios explore 4 alternative nuclear supply pathways under two H_2 demand outlooks

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Modelled GB market scenarios

#L Low H_2 demand #H High H_2 demand

Increasing nuclear ambition →

	1. No new nuclear	2. Existing nuclear techs	3. New nuclear techs	4. Strong nuclear strategy
Core scenarios[1]	**Core scenarios** assume all technologies to compete for economic entry from 2030, with emissions reductions driven by carbon prices and restrictions on unabated thermal in the capacity market.			
	1L	2L	3L	4L
			Results from these high H_2 demand scenarios are shown as standard unless specified	
	1H	2H	3H	4H
Sensitivities[2]	**Weather year sensitivities:** Redispatch of 2040 only against 10 additional historic weather year profiles using the power and hydrogen market supply mix under the High H_2 demand scenarios.			
	Hydrogen storage sensitivities: Full scenario sensitivities testing 3x hydrogen storage infrastructure capacities.			
	Continued RES support sensitivities: Full scenario sensitivities using the same methodology but more closely aligned with policy intention. This is captured via higher levels of assumed offshore wind deployment. All other assumptions held equal.			
	1H: RES		3H: RES	

The scenarios that follow are exploratory scenarios to investigate the role of nuclear and H_2 in reaching net-zero and are not forecasts.

1) Core scenario modelling results are explored in detail in Section V; 2) Sensitivity analysis is presented in Section VI.

Source: Aurora Energy Research

Overview of core market scenario assumptions

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Key assumptions	1. No new nuclear	2. Existing nuclear techs	3. New nuclear techs	4. Strong nuclear strategy
Electricity demand[1]	**2021:** 312 TWh rising to **2050:** 445 TWh (High H_2), 496 TWh (Low H_2)			
H_2 demand	**2021:** 28 TWh H_2 rising to **2050:** 508 TWh H_2 (High H_2), 210 TWh H_2 (Low H_2)			
H_2 storage	**2050:** 26 TWh H_2 (High H_2), 18 TWh H_2 (Low H_2), Includes salt caverns and pipelines			
Commodities	**Gas:** Base case, **Carbon price:** Base case			
Nuclear business models	Hinkley Point C and Sizewell B are co-located with PEM electrolysers			
		▪ LWSMR co-located with SOE electrolysers ▪ New large nuclear co-located with SOE electrolysers		
			▪ Gen IV co-located with SOE electrolysers ▪ Gigafactory of gen IV reactors and SOE electrolysers exclusively for H_2 production	
Nuclear costs	Base			Low
Policy support	**Capacity Market:** All technologies are allowed to participate with de-rating factors reflecting contribution to security of supply. Unabated thermal can only secure 1yr contracts post-2030 and their de-rating factors decline from 90% in 2030 to 10% by 2050. **Other:** Existing subsidies applied, and a further 9.3 GW offshore wind supported by CfDs to reach 40GW deployment by 2030. Unabated CCGTs are not allowed to build post-2030.			
Build decisions	Economic entry of capacity assuming 5% discount rates for low carbon technologies (incl. nuclear, RES, gas-CCS, all H_2 production technologies, hydrogen CCGTs and hydrogen OCGTs) and 11% for other technologies.			

Note that the high H_2 demand scenarios are shown as default in the main body of the report unless specified. Please see Appendix for detailed assumptions.

1) Excluding demand from electrolysers for H_2.

Source: Aurora Energy Research

Two internally consistent hydrogen demand scenarios are modelled, with implications for power demand

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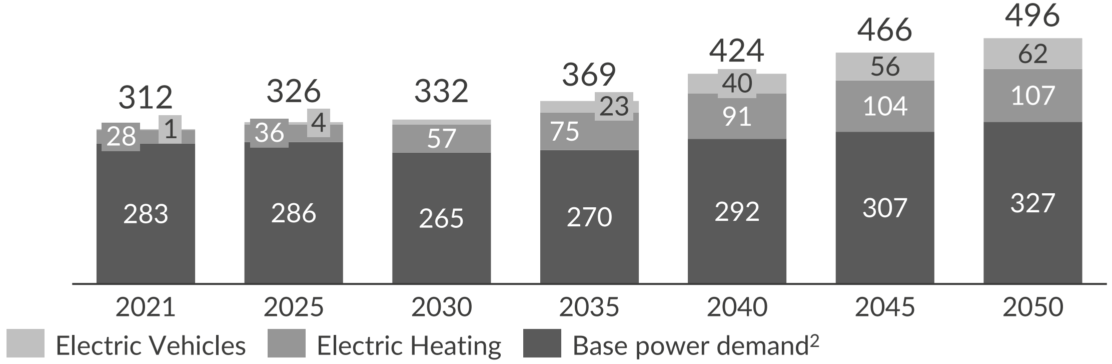
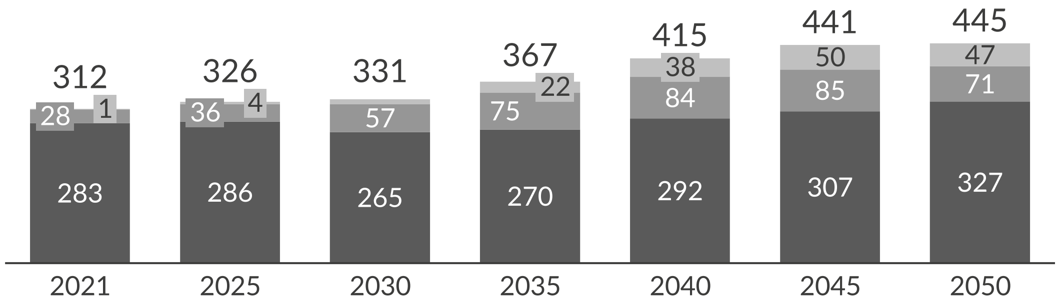
Low H_2 demand | High H_2 demand

GB annual power demand by sector[1]

TWh electricity

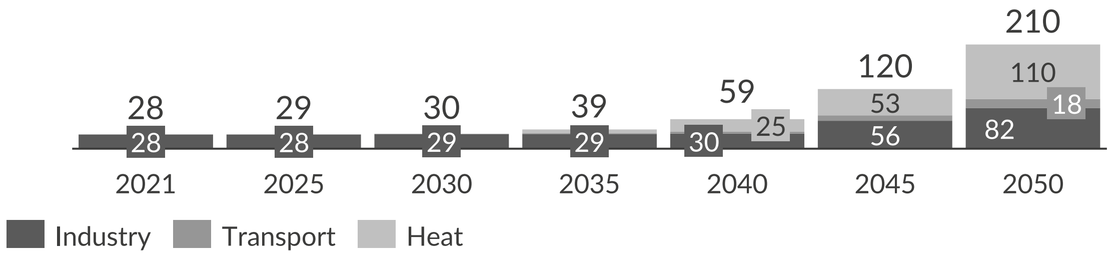
Additional power demand from electrolysers is excluded as this is a model output but **total system demand increases 68-103%** from 2021 to 2050 across the core scenarios

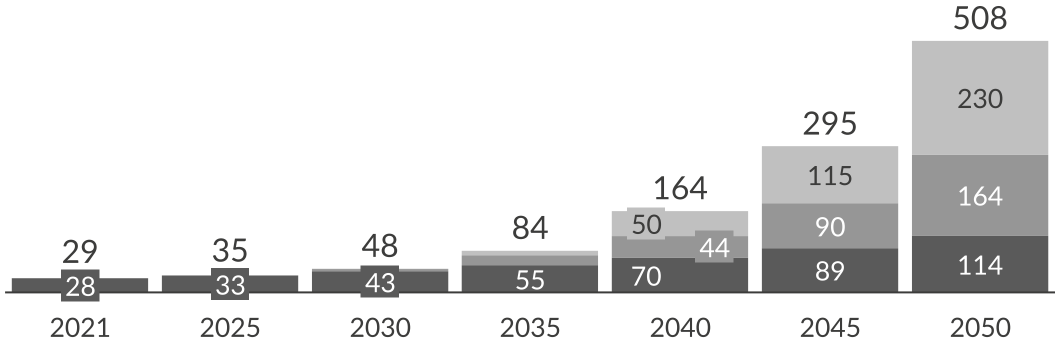




GB annual hydrogen demand by Sector

TWh H_2





1) Excludes power demand from electrolysers for H_2 production as this is a model output. Total power demand therefore varies in each market scenario.

Source: Aurora Energy Research

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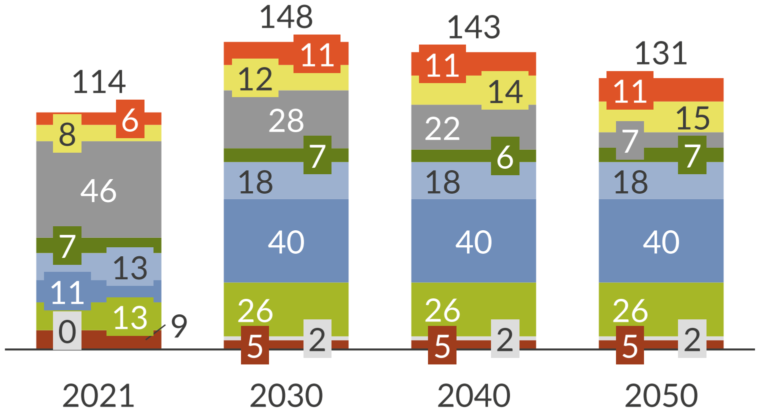
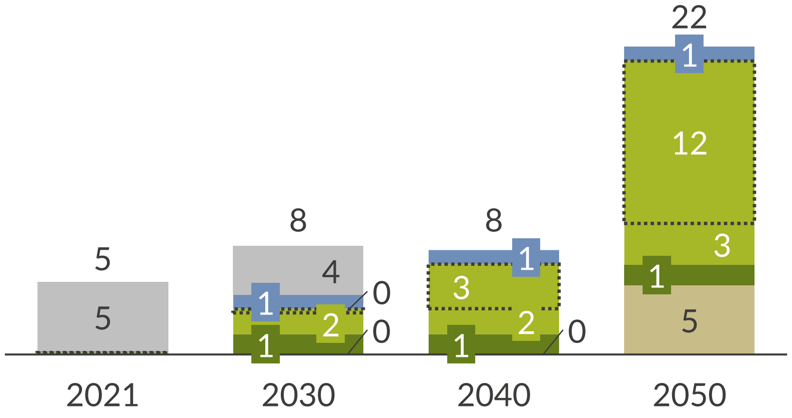
Assumed capacity deployment in the power and H_2 is consistent across scenarios; all other capacity decisions are solved in model

GB assumed power capacity timelines across all scenarios[1]
GW



- **RES** – assumed capacity is constant from 2030 in all scenarios
- **Nuclear** – existing capacity retires by 2030 except Sizewell B (2055). Hinkley Point C (HPC) enters from 2028.
- **Thermal** - Existing thermal assets may retire if insufficient revenues are secured in model. Coal assets must retire by 2024.
- **BECCS** – capacity is assumed to enter to secure "negative emissions".

GB assumed hydrogen capacity timeline across all scenarios[1]
GW



- Current H_2 supply is sourced from SMRs.
- 50% of H_2 transport demand is met by PEM electrolysers at fuel cell charging stations that do not interact with the market.
- Known blue H_2 pilot plants are assumed for entry by 2030
- H_2 storage in the form of pipelines and salt caverns is assumed.
- BECCS for H_2 production is also assumed to secure "negative emissions".

Interconnectors | Other RES[4] | Solar PV | Additional capacity assumed in high H_2 scenario | Green: grid connected
Low carbon flex[2] | Onshore wind | Gas CCS | Grey | Green: nuclear derived
Unabated thermal[3] | Offshore wind | Large nuclear | Blue | BECCS

1) Capacity can retire if uneconomic so assumed capacity, particularly thermal may be lower in the model outputs; 2) Low carbon flex includes DSR, battery storage, hydrogen peakers, hydrogen CCGT, pumped storage 3) Other RES includes biomass, BECCS, EfW and marine; 4) Unabated thermal includes CCGTs, gas peaking, embedded CHP.

Source: Aurora Energy Research

The majority of capacity until 2030 in both the power and hydrogen markets is assumed as a model input.

This assumption reflects:

- currently installed capacity
- known additions including contracted capacity, and
- some forecast additions reflecting current policy (i.e. 40GW offshore wind deployment by 2030).

Any additional capacity required to meet demand is built within model based on profitability of individual plants under each scenario.

All assumed capacity is incorporated in total system cost calculations.

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High nuclear scenarios lead to higher power demand than low H_2 scenarios, driven by increased demand from electrolytic H_2

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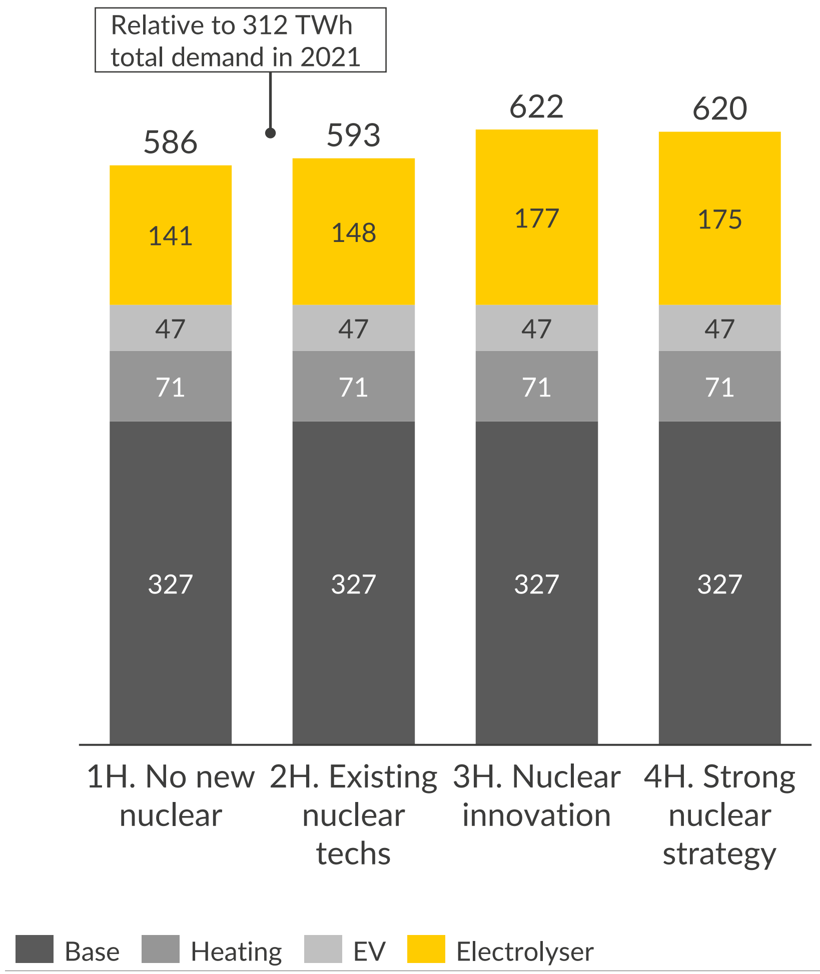
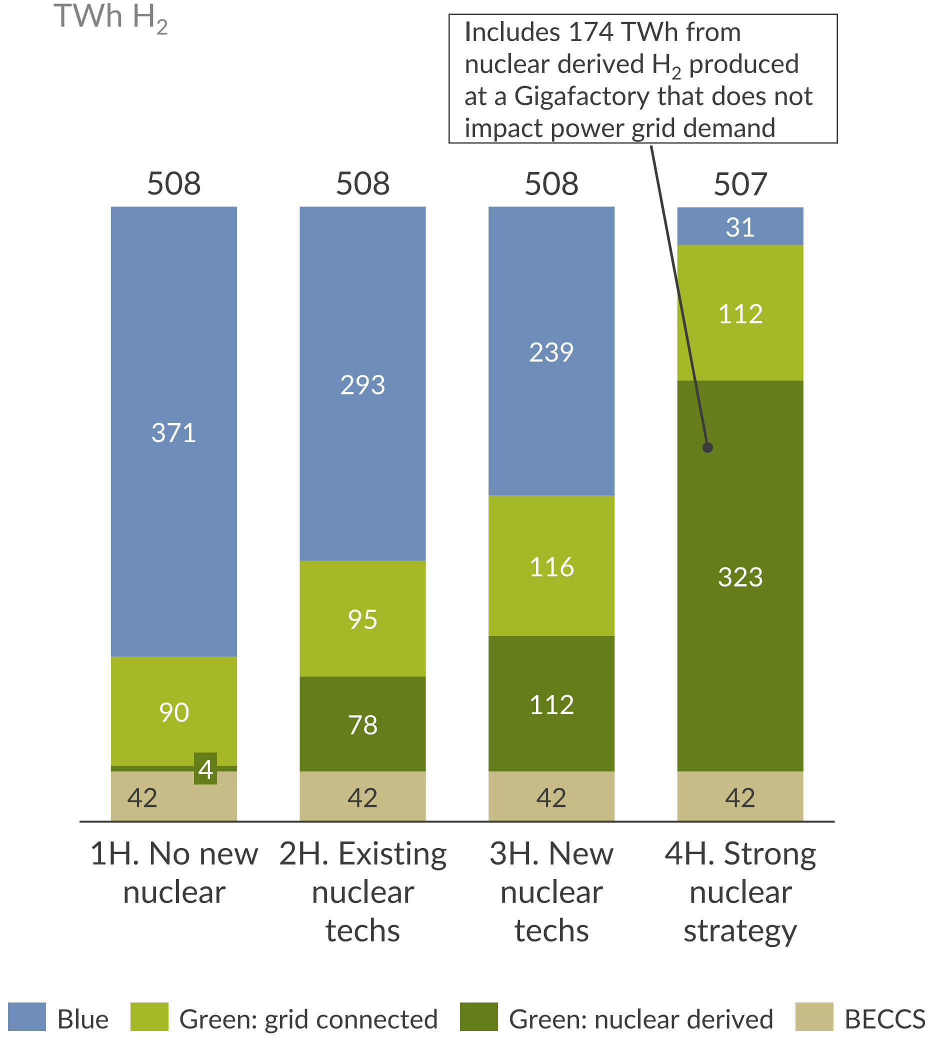
GB 2050 Power Demand
TWh



GB gross H_2 production in 2050
TWh H_2



- High nuclear penetration not only enables stable production of H_2 from collocated electrolysers, it also increases hydrogen production via standalone electrolysers by providing cheap power to the grid at high load factors.
- Despite resulting in higher energy demand, high levels of nuclear open up pathways to Net Zero with lower systems costs and emissions.

Source: Aurora Energy Research

Systems with higher levels of nuclear deployment lead to lower emissions from the power and hydrogen sectors

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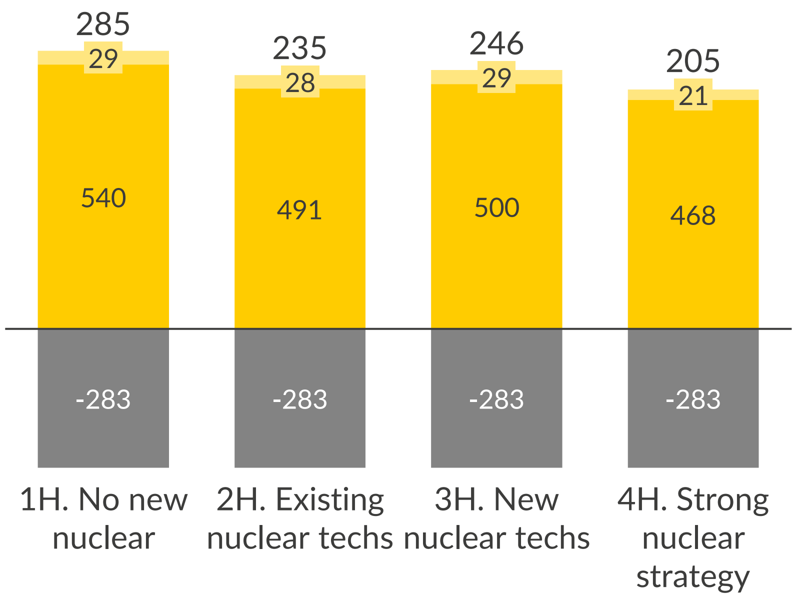
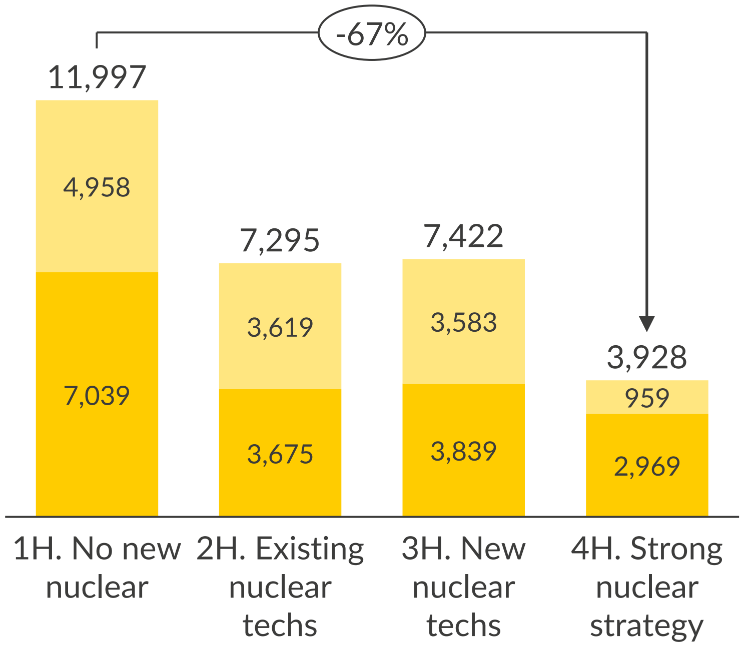
GB cumulative power and H_2 emissions from 2021-50
MtCO$_2$



GB cumulative power and H_2 gas usage from 2021-50
TWhth HHV



GB power and H_2 sector emissions in 2050 excluding BECCs
MtCO$_2$

8.6 | 5.5 | 4.4 | 3.0

GB total power and H_2 gas usage in 2050
TWhth HHV

883 | 584 | 437 | 128

Power production | Hydrogen production | BECCs

Power sector | Hydrogen sector

- Scenario 4H achieves net zero with the lowest emissions and fuel use.
- 1H has the highest fuel use due to high RES intermittency.
- Potential to cancel out up to 36 MtCO$_2$ annually by considering negative emissions from sustainable biomass paired with CCS.
- Fossil fuel usage is reduced dramatically as nuclear is added to the mix, with 4H having one third the reliance on gas of scenario 1H.

Source: Aurora Energy Research

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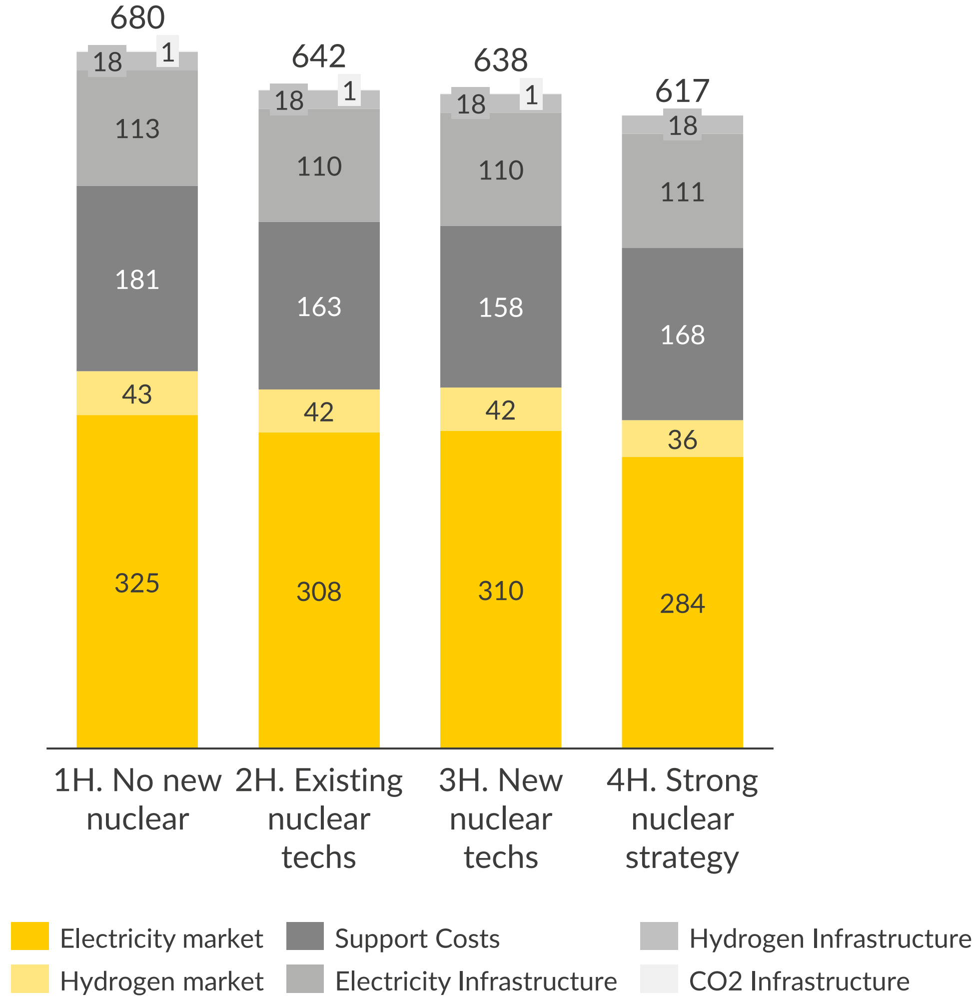
Electricity prices are the single biggest driver of deltas in system costs and outweigh deltas in infrastructure and support costs

GB NPV total system spend from 2021 – 2050[1]

£bn



Key drivers

- **Electricity market spending** is the key driver of total system spend across scenarios and is directly linked to the supply mix. Scenarios with a high share of RES and nuclear dampen electricity prices, whereas scenarios that rely on more expensive fossil based sources for baseload and flexibility see higher electricity prices.
- **Hydrogen market spending** is similar across scenarios as prices are typically set by blue H_2 and strongly correlated with gas prices. Lower costs in 4H are driven by nuclear derived electrolytic H_2 meeting demand in summer.
- **Support costs** are strongly linked to electricity market prices as low wholesale market revenues lead to higher top-ups for existing contracts (CfDs) and higher CM payments for new capacity to break even. The need for higher support costs in 4H due to low electricity prices is counteracted by lower costs for nuclear and a smaller system overall.
- **Infrastructure costs** are similar across all core scenarios as systems are of a similar size and H_2 and CO_2 costs are volumetric. H_2 and CO_2 costs could vary much more depending on proximity of supply to demand.

Overview of cost items[2]

- **Electricity market:** wholesale and balancing market price multiplied by volume.
- **Hydrogen market:** hydrogen market price multiplied by volume.
- **Support costs:** Capacity Market (CM), existing schemes (i.e. CfD) and any top-ups required for assumed capacity to break even.
- **Electricity network:** investment required to maintain and expand the transmission and distribution grids as new capacity is added.
- **H_2 and CO_2 infrastructure:** the capital investment required to transport and store the H_2 and captured CO_2 respectively from power and H_2 generation only.

1) Costs are discounted using a rate of 5% 2) See appendix for further details on methodology.

Source: Aurora Energy Research

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Deploying RES alongside nuclear could reduce power system reliance on fossil fuels to just 3% of supply in the strong nuclear strategy case

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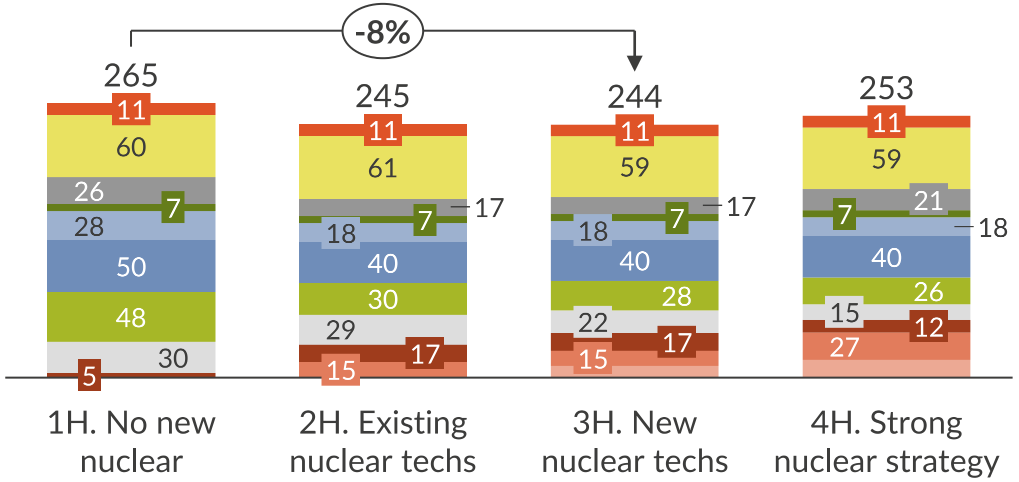
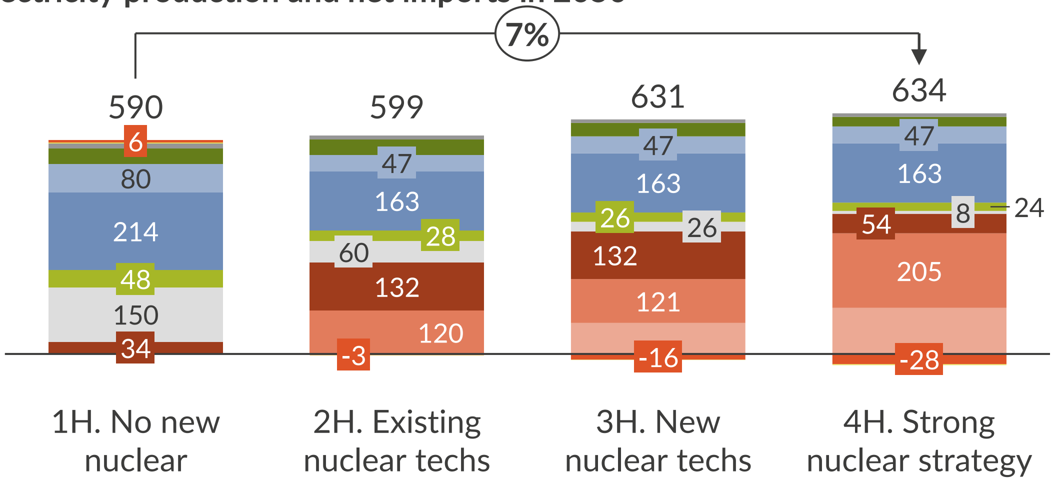
GB installed capacity in 2050
GW



GB electricity production and net imports in 2050
TWh



- 1H with no new nuclear sees just 66% supply met by RES and nuclear and relies on fossil fuels for 28% of supply. Enabling new nuclear to co-locate with electrolysers for H_2 production could drastically reduce reliance on fossil fuels. By comparison, 3H enables 90% generation to be met by nuclear (53%) and RES (37%) and just 6% provided by fossil fuels. Low nuclear costs assumed in 4H enable 95% generation to be met via nuclear and RES with just 3% from fossil fuels.
- The low nuclear costs in 4H enable small modular and gen IV reactors to be cost competitive with large reactors, displacing 5 GW large reactors and 18 GW small and gen IV reactors.
- Limited RES build out is observed in all new nuclear scenarios due to low capture prices and higher returns for dispatchable capacity.
- Enabling substantial nuclear deployment can reduce overall system size by 8% in 3H relative to 1H as less overall capacity is required to meet demand. This is offset slightly in 4H where the increased levels of low marginal cost generation facilitate greater utilisation of electrolysers for H_2 and a resulting 6% increase in power demand, resulting in a larger system size. This has implications on land use and network costs.

Interconnectors | Unabated thermal[2] | Onshore wind | Solar PV | Large nuclear | Gen IV with electrolyser
Low carbon flex[1] | Other RES[3] | Offshore wind | Gas CCS | Small Modular Reactor

1) Low carbon flex includes DSR, battery storage, hydrogen peakers, hydrogen CCGT, pumped storage 2) Other RES includes biomass, BECCS, EfW and marine; 3) Unabated thermal includes CCGTs, gas peaking, embedded CHP.

Source: Aurora Energy Research

Three key factors determine power prices, with high penetration of RES and nuclear leading to lower prices

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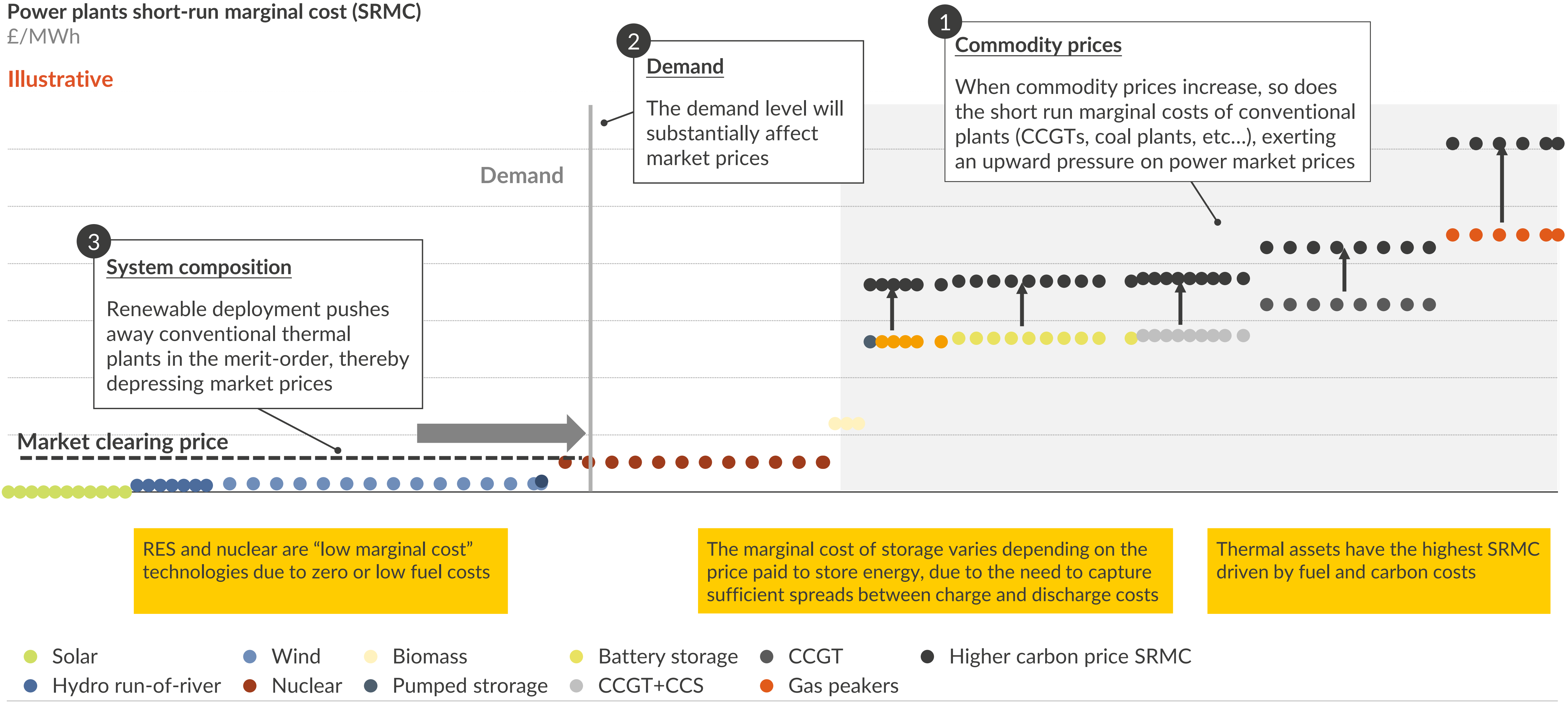

Higher levels of nuclear generation lead to a greater frequency of low price periods

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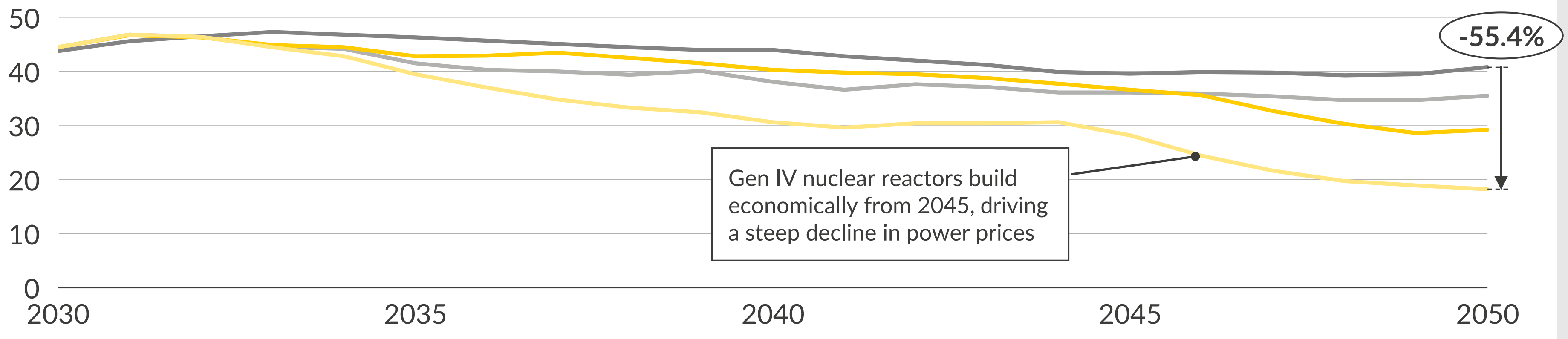
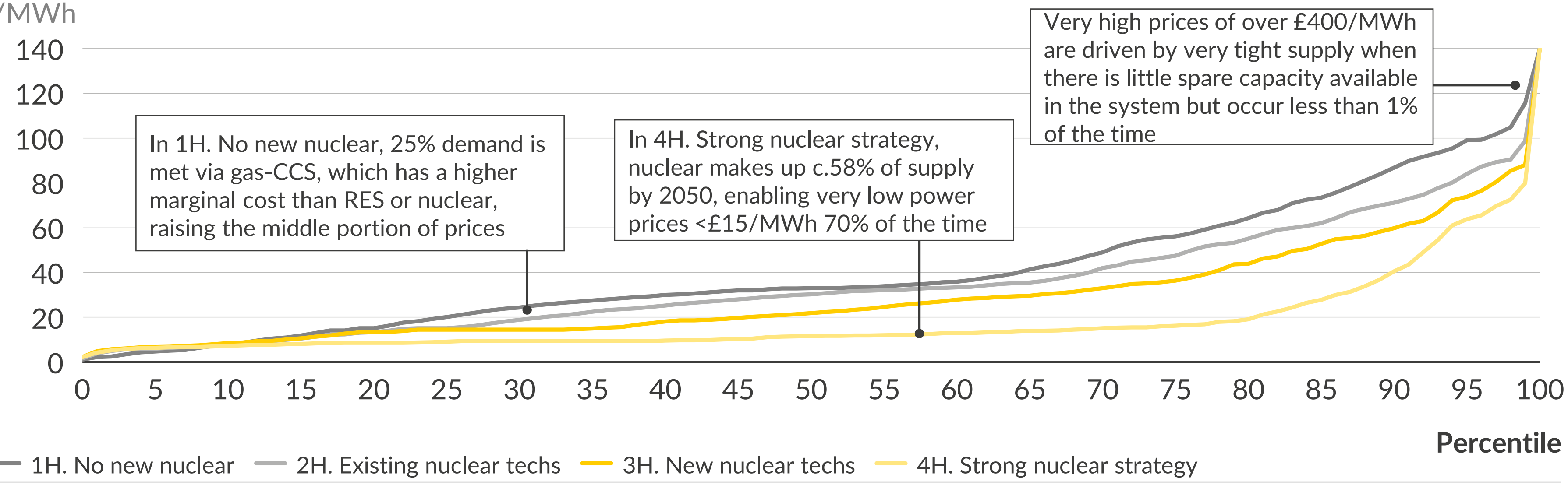
GB wholesale electricity price

£/MWh (real 2019)



GB power price distribution curve (PDC) in 2045

£/MWh



- The low marginal cost of nuclear generation keeps it almost always in merit.
- Large volumes of nuclear generation push more expensive thermal generation out of merit, allowing a cheaper technology to set the price.
- This leads to the wholesale baseload price in 2050 in Scenario 4H to be half of that in Scenario 1H.
- Scenario 4H sees prices below £20/MWh for more than half the settlement periods in 2045.
- None of the scenarios see negative prices by 2045 due to the lack of remaining RES assets with high subsidy payments or thermal that doesn't ramp down in face of low prices.

Source: Aurora Energy Research

Nuclear can meet baseload requirements, reducing the reliance on fossil fuelled gas-CCS by 3 TWh in one sample winter week alone

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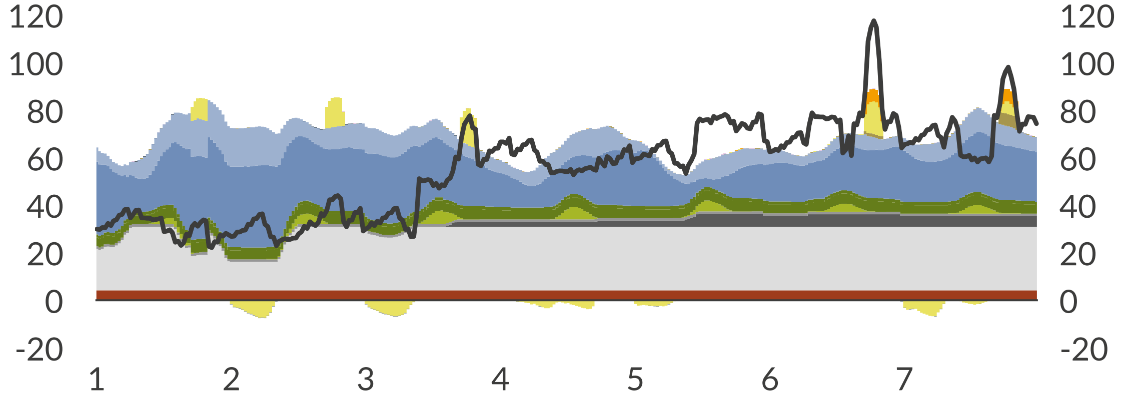
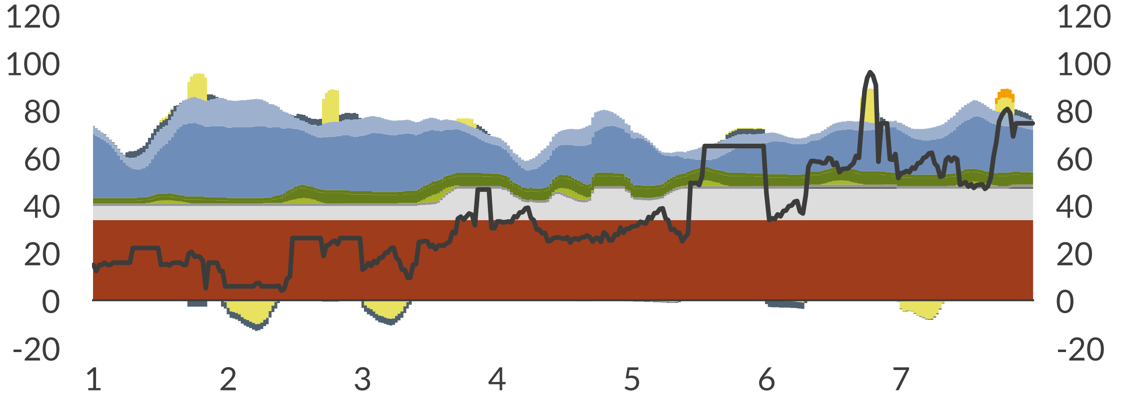
GB power supply sample winter week in 2045: 1H – No new nuclear
GW

GB power price
£/MWh



GB power supply sample winter week in 2045: 4H – Strong Nuclear Strategy
GW

GB power price
£/MWh



- During the winter solar generation in GB is minimal, so wind is the dominant source of renewable power generation, but it is not dispatchable.
- The sample winter week which sees a high price point corresponding to system tightness/ strain due to somewhat low instantaneous wind output during a period of high demand.
- Due to large amounts of cheap baseload low carbon generation, Scenario 4H is able to cope with system stress without gas peakers, keeping prices and emissions lower than in 1H. The contribution of nuclear to system resilience will be explored further in future weather sensitivity analysis.
- The many nuclear plants in 4H displace gas ccs as the dominant baseload supply, and are a more reliable source of clean power, as they are less likely to be pushed out of merit due to their low marginal cost.

Hydrogen CCGT | Battery storage | Pumped storage | Offshore wind | Solar | Gas CCGT | Nuclear
DSR | Peaking[1] | Onshore wind | Other RES[2] | Other thermal[3] | Gas CCS | EM Price

1) Peaking includes gas recips, OCGTs 2) Other RES includes biomass, BECCS, EfW and marine; 3) Other thermal includes embedded CHP.

Source: Aurora Energy Research

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Low nuclear costs and economic entry of a hydrogen Gigafactory enable reliance on fossil H_2 to drop to 6% by 2050

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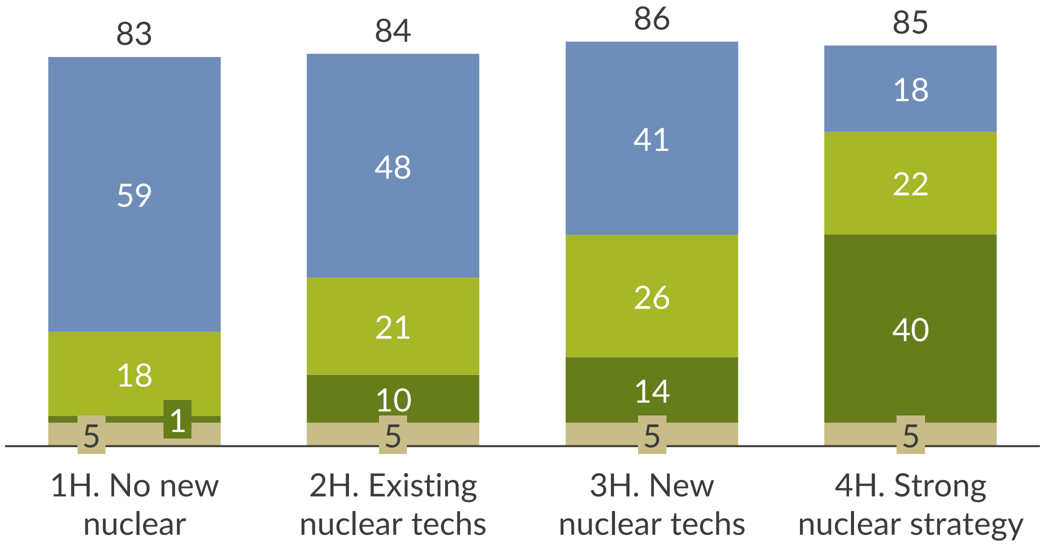
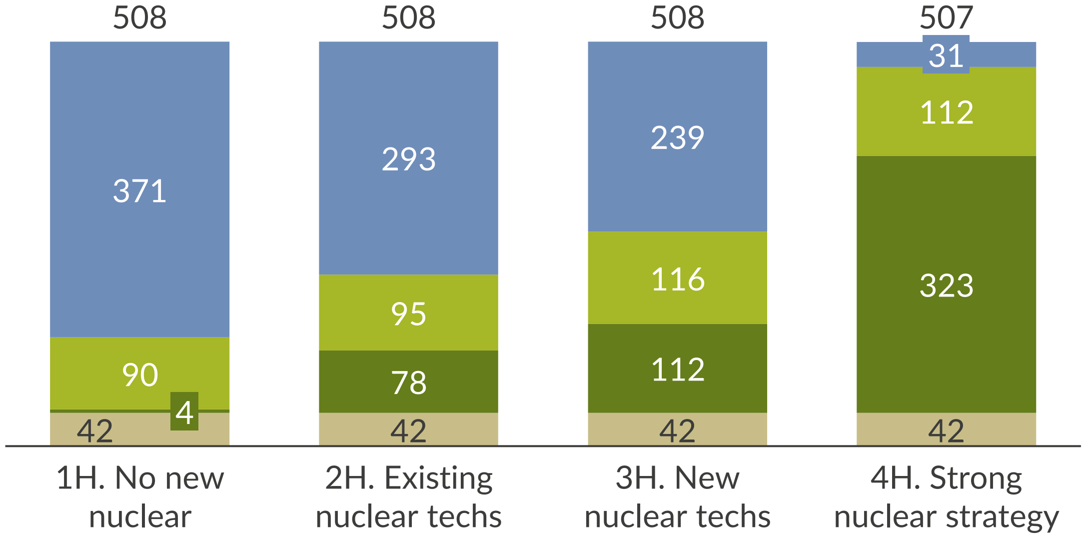
GB installed capacity in 2050
GW H_2



GB gross H_2 production in 2050
TWh H_2



- All scenarios with the exception of 4H have a high reliance on blue H_2 made from fossil gas with CCS. This is responsible for 73% of supply in 2050 in 1H and remains a significant source of H_2 in 2H and 3H. Variability in RES output, combined with low levels of excess RES lead to unfavourable economics for non-nuclear derived green H_2 relative to fossil based blue H_2.
- In contrast, strong support for a nuclear pipeline could enable the construction of a nuclear gigafactory consisting of many small nuclear reactors dedicated to H_2 production via SOEs can reduce reliance on fossil fuels for H_2 production to just 6% by 2050.
- The “negative carbon emissions” associated with BECCS are expected to be highly valuable and attributed to hard to abate sectors. This capacity is therefore assumed in model as it is likely to be driven by policy or valuable carbon credits.

Blue | Green: grid connected | Green: nuclear derived | BECCS

1) Majority of PEM electrolyser capacity and generation shown here correspond to re-fuelling stations providing pure H_2 for hydrogen –powered vehicles. These are treated separately and do not contribute to market dynamics shown in the following slides.

Source: Aurora Energy Research

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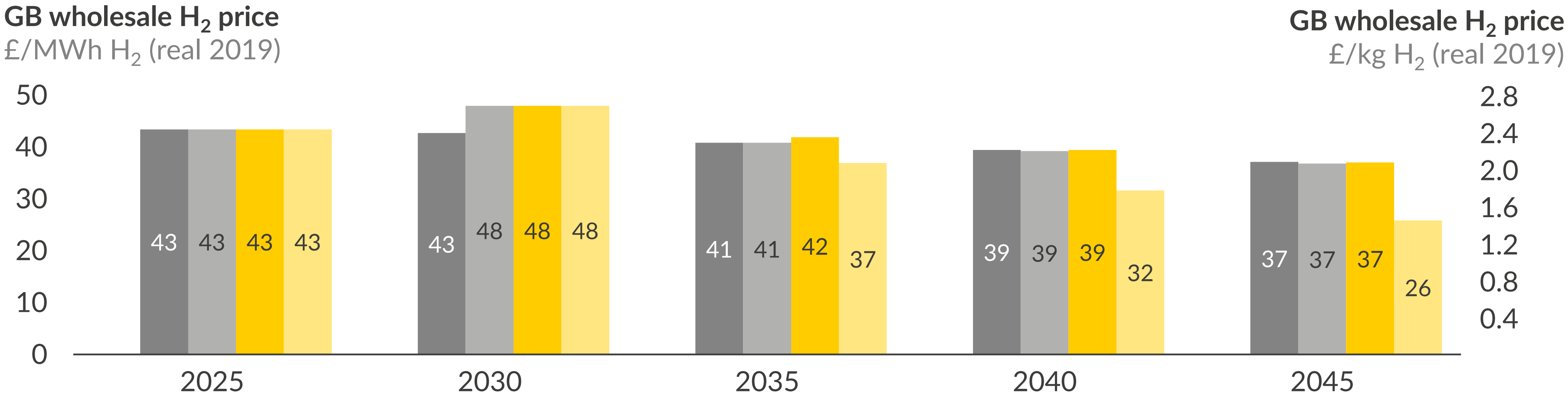
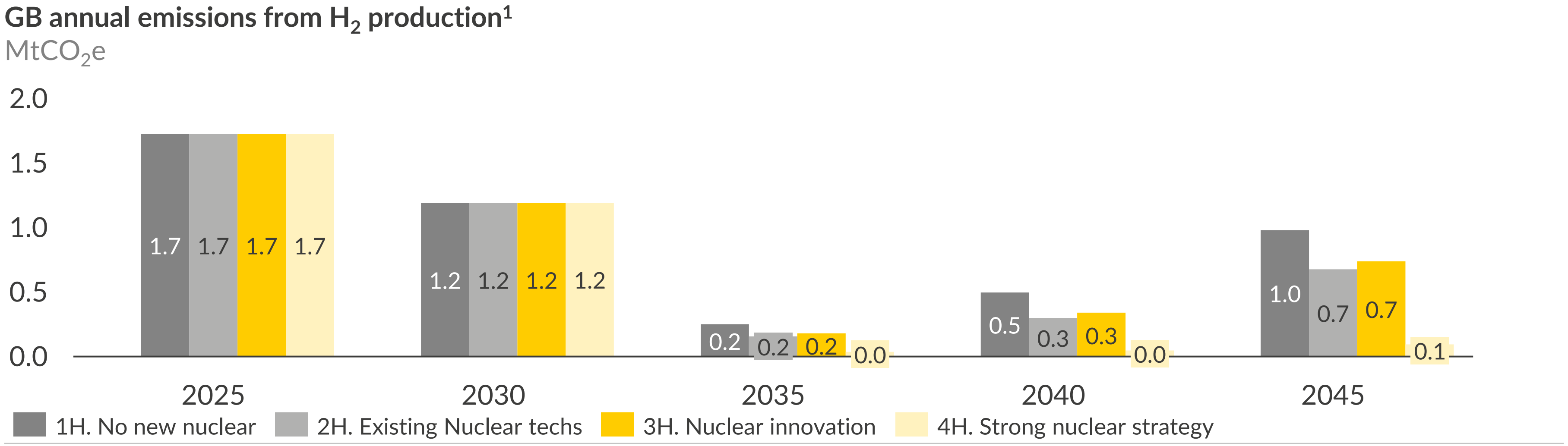
High levels of nuclear H_2 deployment facilitate cheaper and lower carbon intensity H_2





The availability of large volumes of low cost nuclear derived enable H_2 price reductions of c.1/3 due to the low costs of input heat and electricity relative to:

- Fossil gas for blue H_2 production
- Grid electricity prices for green/yellow H_2, particularly in winter.

The low marginal cost of nuclear derived H_2 displaces blue and yellow H_2 from the supply mix, enabling the rapid growth in H_2 demand being met with fewer cumulative emissions.

Emissions rise in all scenarios in the 2040s due to substantial increases in forecasted hydrogen demand and residual emissions from blue hydrogen, with the notable exception of 4H.

Source: Aurora Energy Research

Nuclear H_2 has the potential to meet demand at low prices throughout the summer, with marginal blue H_2 used in winter

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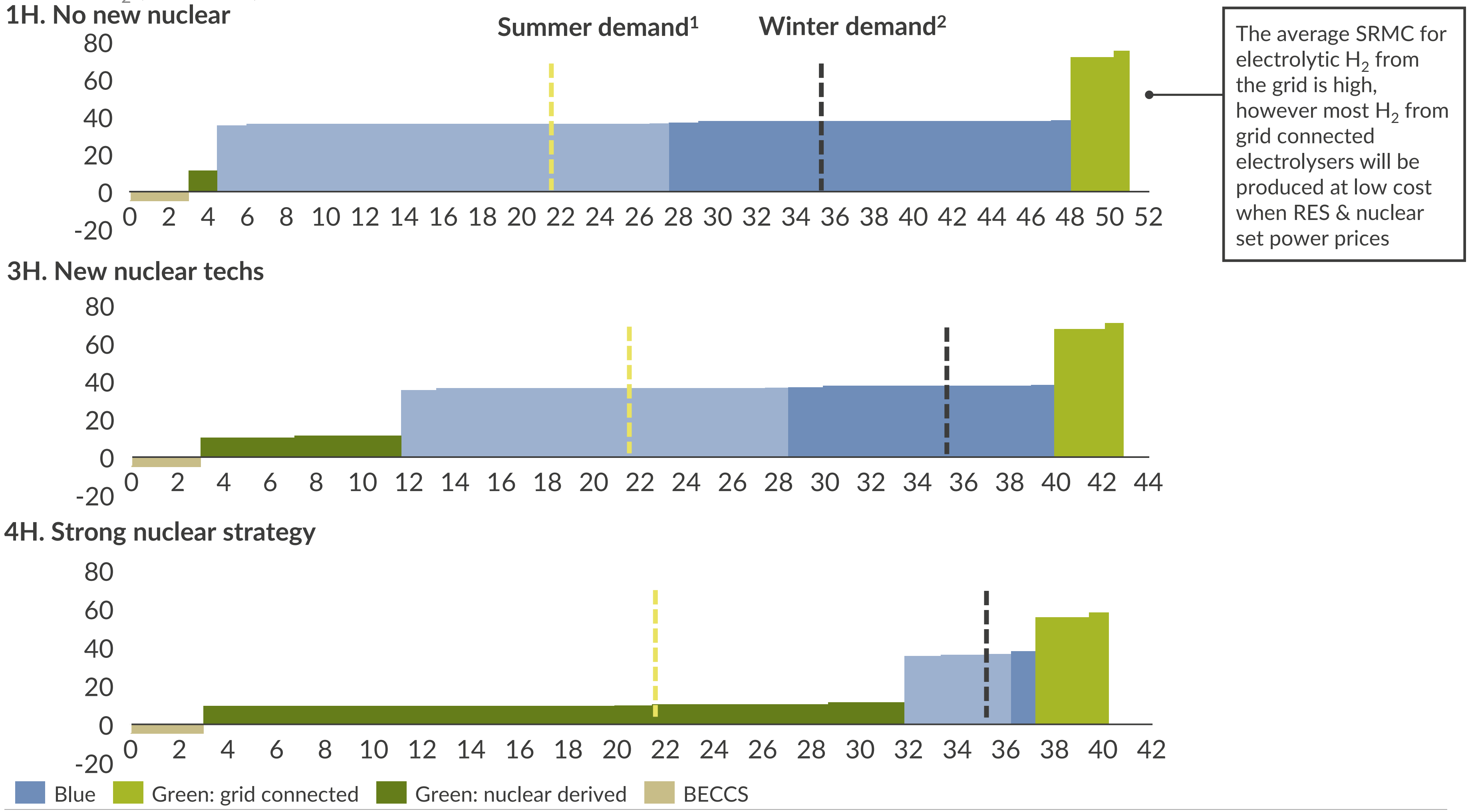
GB average merit order of H_2 supply in 2045
£/MWh H_2 (real 2019)



- In 1H the supply stack in 2045 is dominated by blue hydrogen. This sets the price around the £40/MWh H_2 in both summer and winter.
- As more nuclear comes onto the system the blue hydrogen production technologies are shifted up the merit order.
- In 4H, nuclear derived H_2 sets the very low prices in summer with blue H_2 setting prices in winter.
- Storage is not included in the merit order as it does not capture how and when storage would decide to discharge, with other factors like opportunity costs and recovering the cost of charging requiring consideration.

1) Average hydrogen demand from April to September 2045; 2) Average hydrogen demand from January to March and October to December 2045.

Source: Aurora Energy Research

H_2 storage consistently discharges in winter when demand is high and charges in summer months when demand and prices are low

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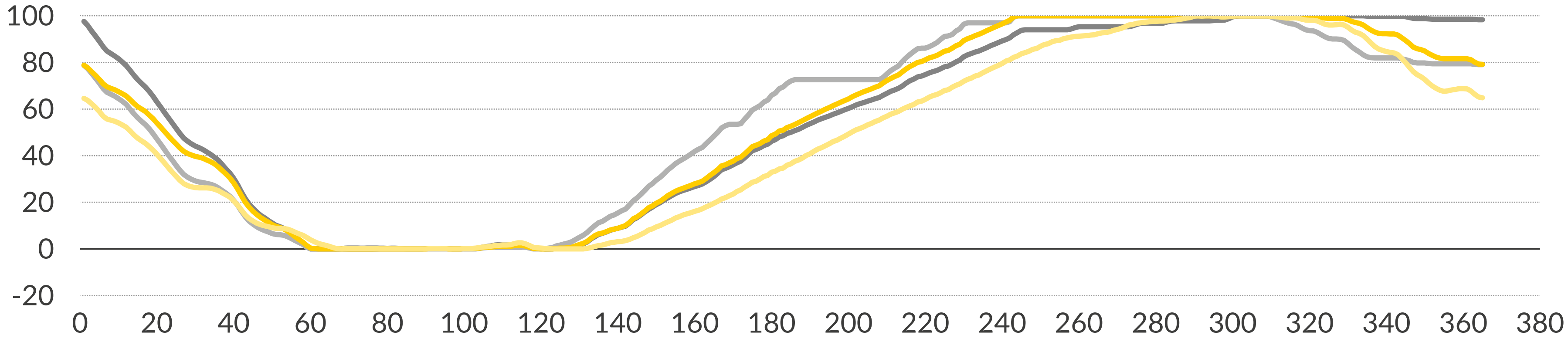
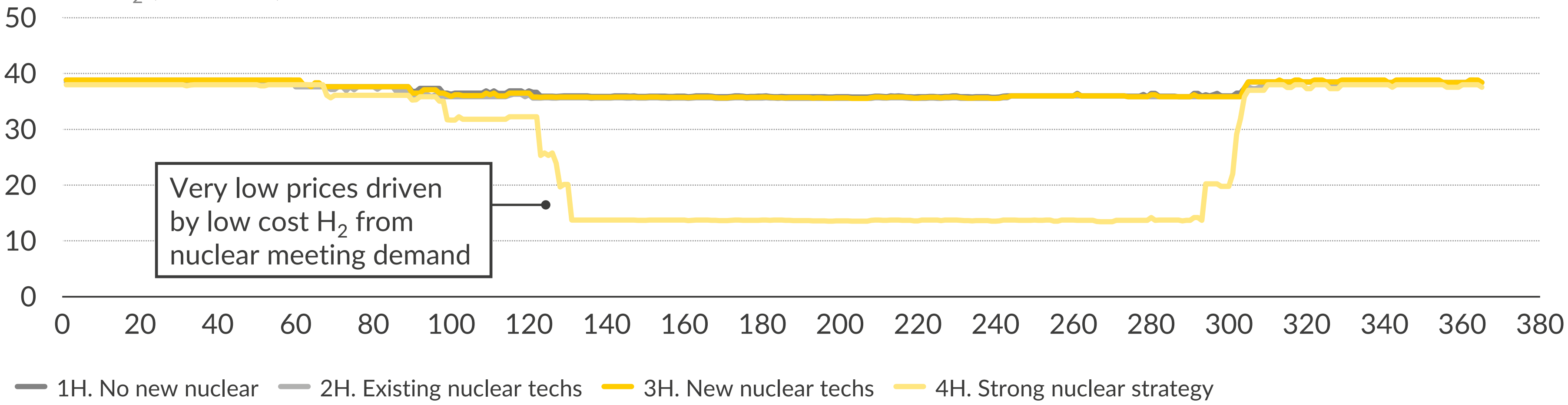
GB salt cavern H_2 storage state of charge in 2045

%



GB H_2 price in 2045

£/MWh H_2 (real 2019)



- Seasonality in H_2 storage levels is driven by selling H_2 to meet high winter demand for heating, followed by stockpiling during summer months, when hydrogen demand is lower.
- Storage utilisation is similar across all scenarios.
- In scenarios 1-3, blue hydrogen technologies set the price throughout the year.
- The very high penetration of nuclear derived H_2 in 4,H enabled by hydrogen gigafactories, allows all demand in summer months to be met by nuclear derived H_2, resulting in very low prices of c.£14/MWh H_2.

Source: Aurora Energy Research

The majority of demand is met by blue H_2, with most dynamic use of storage in 4L where the share of green H_2 is greatest

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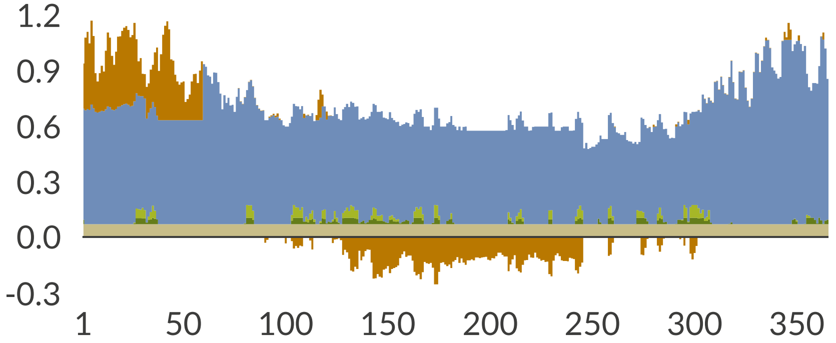
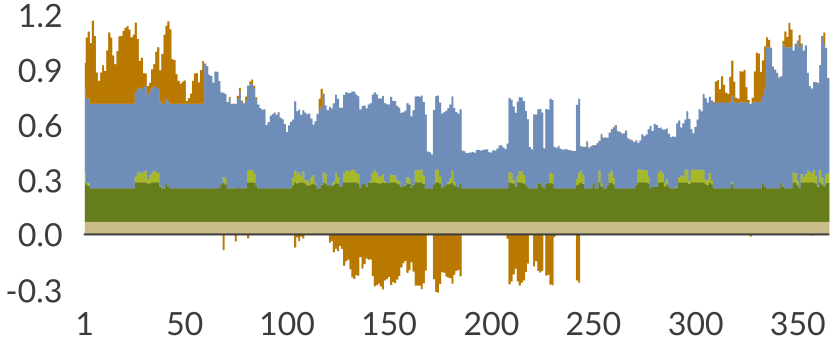
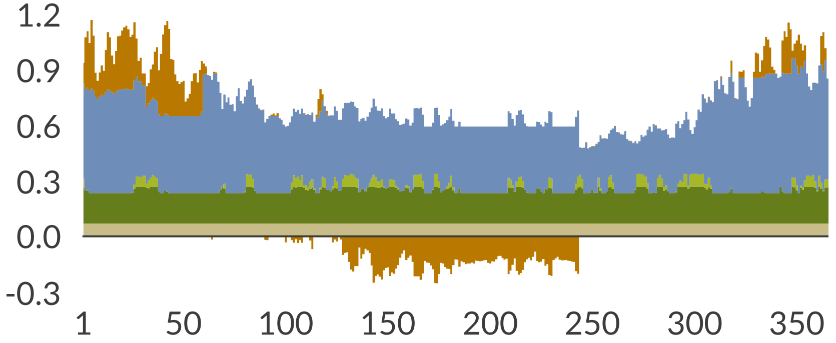
GB daily H_2 production in 2045: 1H. No new nuclear
TWh H_2



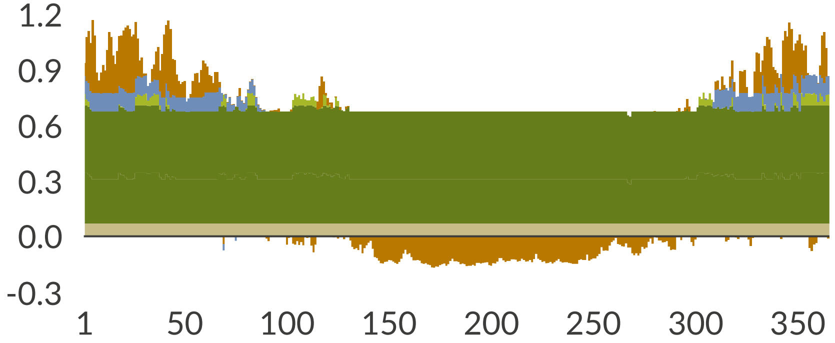
GB daily H_2 production in 2045: 2H. Existing nuclear techs
TWh H_2



GB daily H_2 production in 2045: 3H. New nuclear techs
TWh H_2



GB daily H_2 production in 2045: 4H. Strong nuclear strategy
TWh H_2



Blue | Green: grid connected | Green: nuclear derived | BECCS | Storage

- Fossil based blue H_2 plays an important role in achieving the volume of H_2 required in all scenarios bar 4H, ramping up in the winter to meet peak heating demand along with storage
- Nuclear derived electrolytic H_2 is a cheaper alternative that is able to displace blue H_2, providing a stable supply of Hydrogen throughout the year.
- This is most evident in scenario 4H, due to the deployment of nuclear H_2 gigafactories.
- RES and grid derived electrolytic H_2 are not able to consistently meet fluctuating H_2 demand throughout the year when competing with blue H_2.

Source: Aurora Energy Research

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Policy objectives and investment requirements must be met in order to deploy low carbon supply and limit risks to the transition

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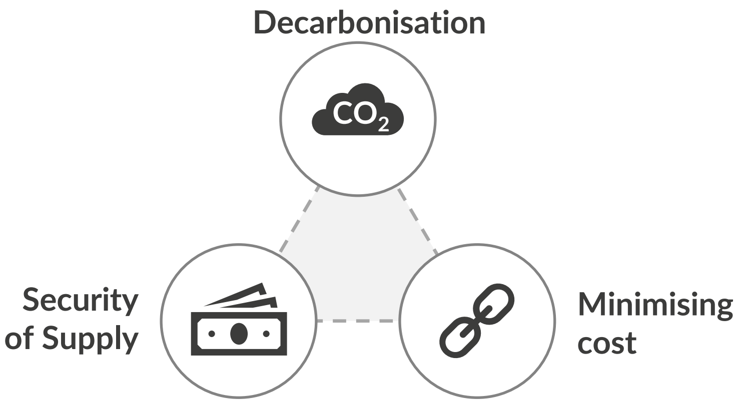
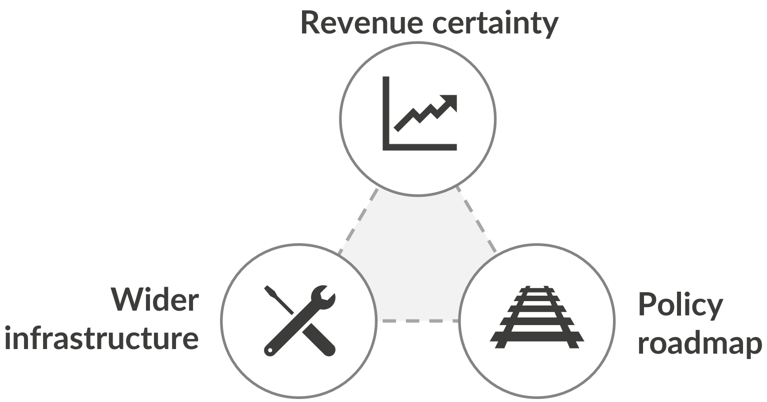
Government objectives



Investment requirements



1. **Decarbonisation**: Mitigate climate change and decrease emissions via policies that increase low carbon supply i.e. rising carbon prices that increase revenues for low carbon techs, direct support for low carbon techs, wider facilitation of low carbon systems.
2. **Security of Supply**: Objective to deliver energy security by ensuring adequate power capacity is available during peak times from a variety of technologies. The Capacity Market was created as the primary mechanism to achieve this.
3. **Minimising cost**: Objective to minimise cost to consumers through efficient markets and low-carbon support measures, household energy efficiency, and encouraging competition among suppliers.
4. **Revenue certainty**: Meet required returns via markets designed to support low carbon techs and additional value streams with long term contracts (i.e. CM, ancillary services, CfD) to account for market shortfalls. This reduces investor risk and therefore financing costs.
5. **Policy roadmap**: Required for clarity on future market developments, planning approval, development of a project pipeline and supply chains.
6. **Wider infrastructure**: High level planning for system infrastructure to ensure requisite infrastructure is in place in time for assets to be deployed.

Source: Aurora Energy Research

An assessment of risks in not achieving net-zero must be undertaken

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Policy & market design

- Low marginal cost systems yield low revenues and low carbon techs won't deploy without support under current market design.
- This led to low RES deployment in the core scenarios however introducing additional supported RES did not increase system costs.
- Unclear policy increases uncertainty, investor risk and the likelihood of projects not being delivered due to insufficient project pipelines.
- Inefficient market design may lead to suboptimal supply mixes being locked in for decades due to asset lifetimes.

System resilience & emissions

- Capacity is needed to meet demand during prolonged periods of low RES output.
- Without direct limitations on emissions intensive technologies.
- Climate change leads to increasingly unpredictable weather, potentially exacerbating risk of unexpected high emissions and fossil fuel use in high RES systems.
- Weather year sensitivities, using 10 years of historic weather data, found that systems with low nuclear penetration were more likely to see higher fossil fuel usage than high nuclear scenarios due to the reliance on fossil fuels for flexibility.

Infrastructure requirements

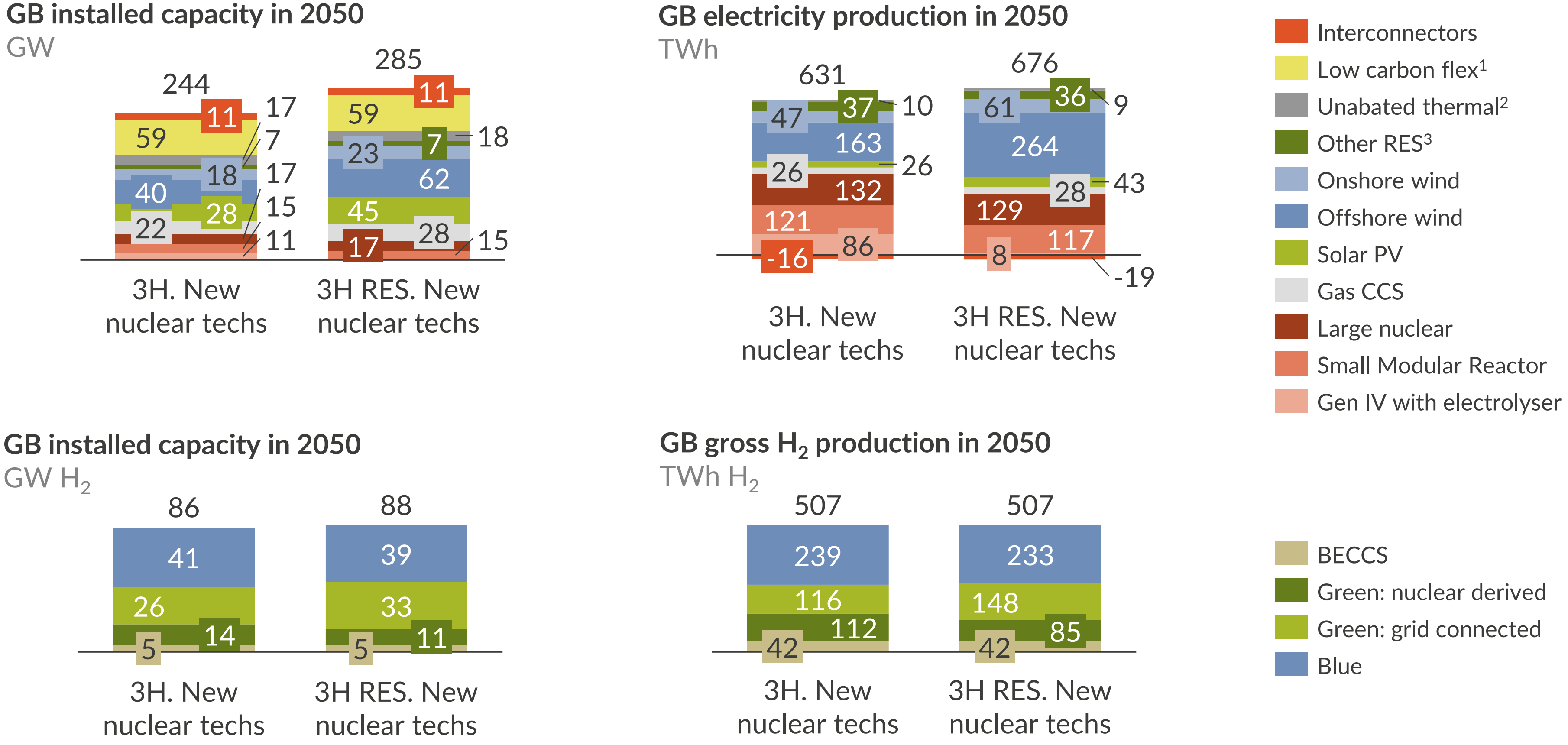
- Insufficient assessment of the requirements for very large systems at an early stage may result in unforeseen limits on deployment of low carbon techs in future.
- The H_2 and CO_2 transport and storage infrastructure is dependent on demand, with short haul transport of pure H_2 for transport and industry vs a large pipeline network for H_2 use in heating with decisions on infrastructure pathways required well in advance of deployable need.
- Infrastructure must be built before new supply can be connected, however large infrastructure projects often take a long time to deploy and are subject to cost and time overruns.

Costs

- An uncoordinated approach to decarbonisation may limit the scale of cost reductions or even increase project costs.
- Although technology cost declines have historically been underestimated, costs associated with deploying very high levels of low carbon tech may rise due to limited resource and site availability.
- The full infrastructure costs of decarbonisation pathways should be assessed to determine lowest cost pathways to net-zero and prevent unexpectedly high infrastructure investment costs in future when alternative options are limited.

Source: Aurora Energy Research

High RES net-zero systems in line with government ambition can be achieved at no additional cost with direct support for RES capacity



	3H. New nuclear techs	3H RES. New nuclear techs
NPV System costs 2021-50, £bn	638	638
H_2 and Power sector emissions 2050, $MtCO_2$	4.4	4.5

- To reflect government ambition for high RES systems, 3H RES assumes additional subsidised RES deployment beyond 2030. All other assumptions are equal to 3H.
- Despite resulting in a larger system capacity, 3H RES still reaches net-zero with similar system costs relative to 3H.
- This is driven by the very high share of low marginal cost supply on the system remaining relatively consistent between scenarios as electricity prices are the biggest driver for differences in total system costs.
- The large amounts of offshore wind generation on the system improve the economics of alkaline electrolysers in 3H RES reducing the total share of blue hydrogen.

1) Low carbon flex includes DSR, battery storage, hydrogen peakers, hydrogen CCGT, pumped storage 2) Other RES includes biomass, BECCS, EfW and marine; 3) Unabated thermal includes CCGTs, gas peaking, embedded CHP.
Source: Aurora Energy Research

High nuclear scenarios are more resilient to higher than expected emissions and fossil fuel usage under different weather patterns

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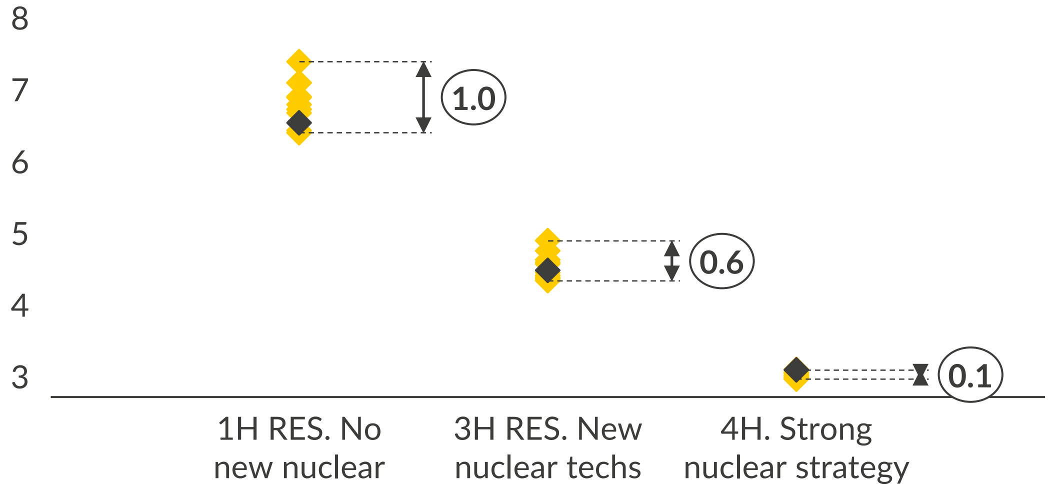
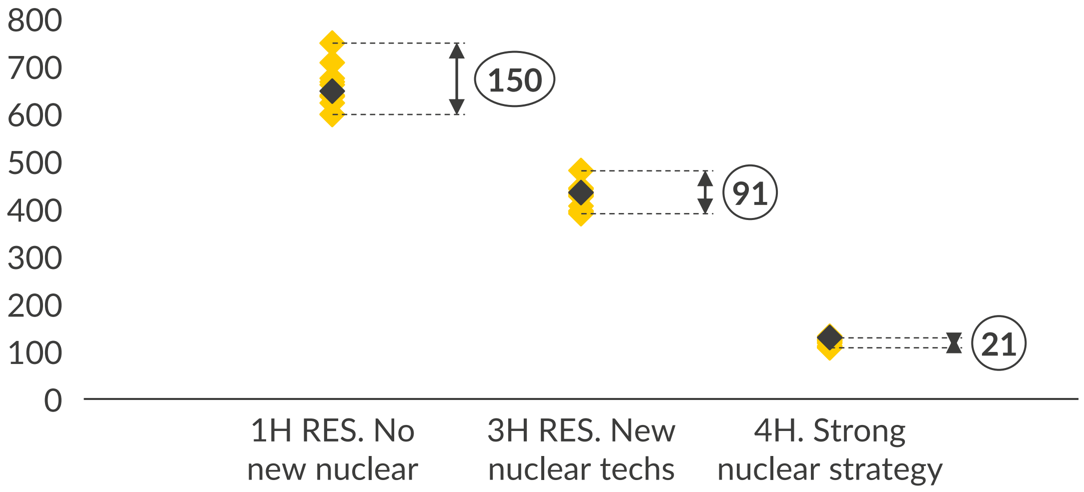
GB power and hydrogen market emissions 2050 (2006-2016 weather patterns)[1]

$MtCO_2e$



GB power and hydrogen market natural gas use in 2050 (2006-2016 weather patterns)

TWh_{th} HHV



- The core scenarios modelled in this report use historic weather patterns from 2013 to inform the profiles of RES generation and demand in the model and single year sensitivities using GB weather patterns from 2006- 2016 were applied to test resilience to emissions and fuel use.
- Variations in fuel use and emissions are lowest in 4H, where a high penetration of nuclear capacity co-located with electrolysers provides flexibility to the system to meet changing RES output. The variation is higher in the high RES scenarios, 1H RES and 3H RES, due to greater reliance on fossil fuels via gas-CCS or gas peaking plants to provide flexibility.
- Whilst the variations are modest, at <1 $MtCO_2e$, using historic weather patterns does not simulate the effects of extreme weather events such as wind droughts that are more likely in future as a result of climate change.
- A supply mix that combines RES and nuclear with limited reliance on fossil fuels for flexibility is key to minimising the risk of unexpected emissions on the path to net-zero.

◆ Sensitivity ◆ Original

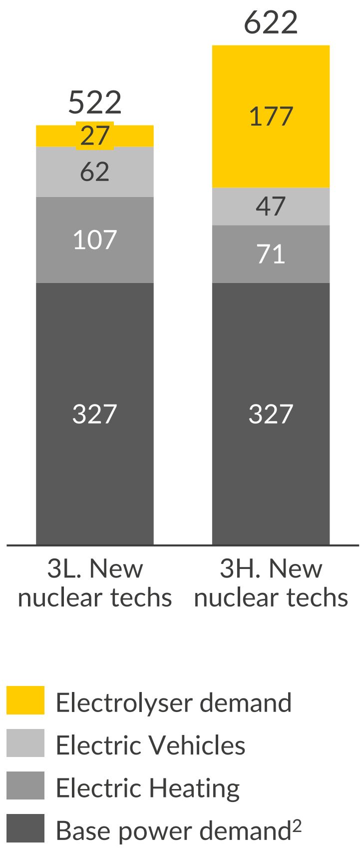
1) Note negative emissions from BECCS are not included.

Source: Aurora Energy Research

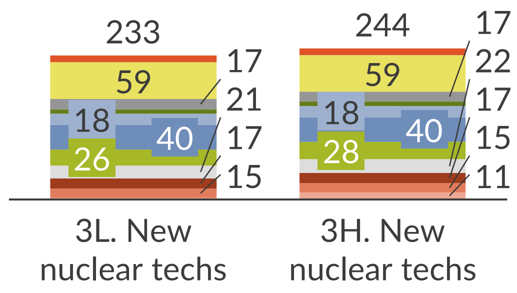
A high H_2 strategy leads to increased system size and therefore greater system costs due to electricity to H_2 conversion losses

The high H_2 demand scenarios assume the same degree of decarbonisation as low H_2 but with less electrification. Increased power demand in high H_2 scenarios is slightly counterintuitive but highlights the need for greater deployment of power and H_2 supplies and infrastructure.

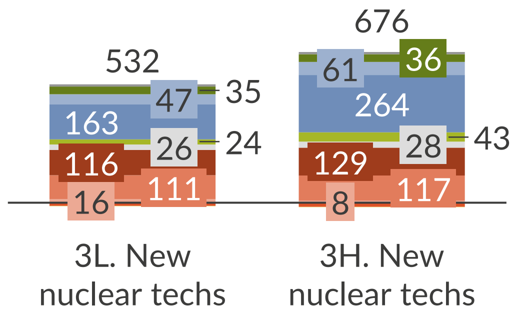
GB power demand in 2050
TWh



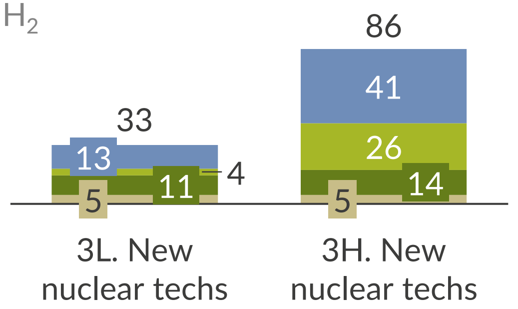
GB installed capacity in 2050
GW



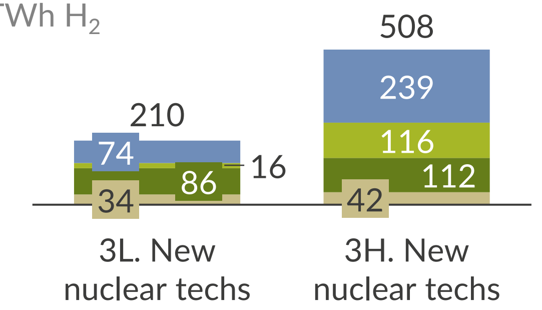
GB electricity production and net imports in 2050
TWh



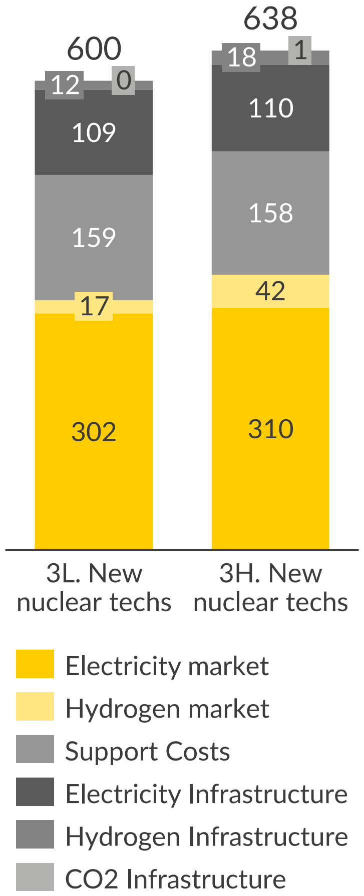
GB installed capacity in 2050
GW H_2



GB gross H_2 production in 2050
TWh H_2



GB NPV system spend (2021-2050)
£bn



1) Low carbon flex includes DSR, battery storage, hydrogen peakers, hydrogen CCGT, pumped storage 2) Other RES includes biomass, BECCS, EfW and marine; 3) Unabated thermal includes CCGTs, gas peaking, embedded CHP.

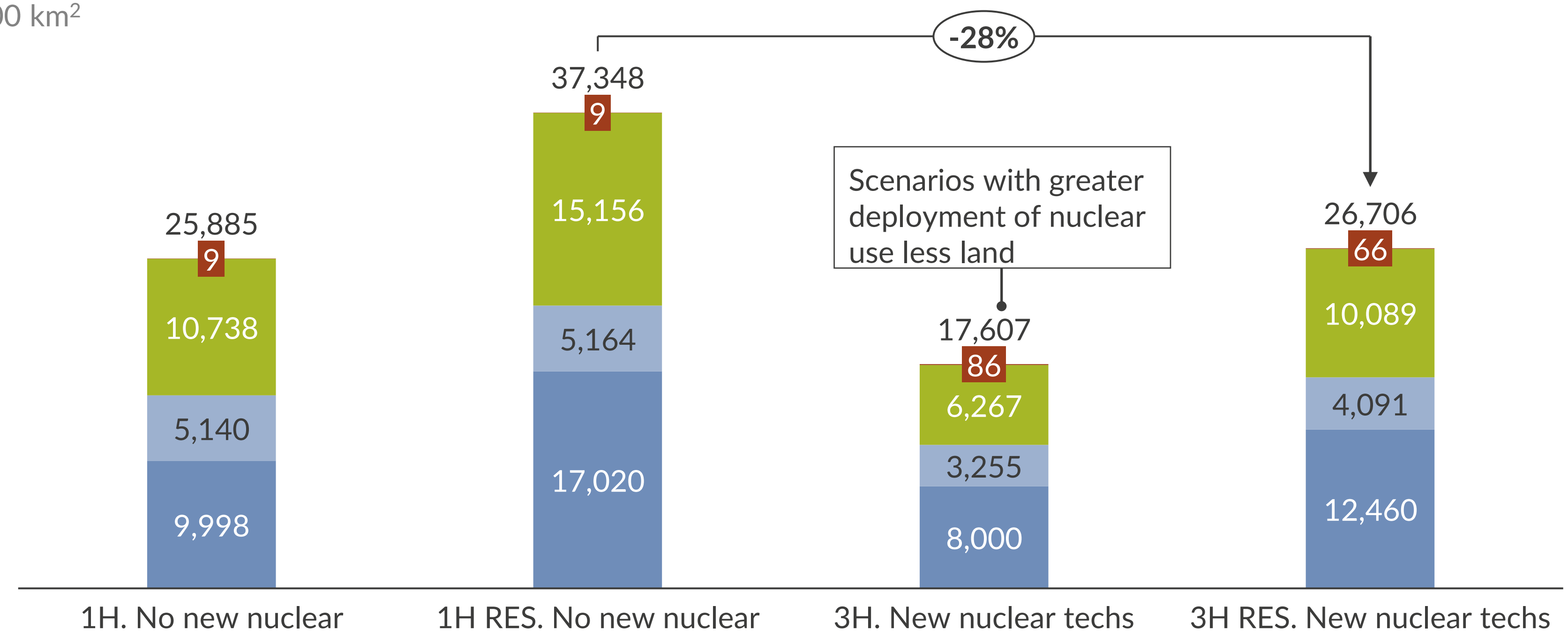
Source: Aurora Energy Research

Full feasibility assessments on the land use of different supply mixes are needed to assess ecological, environmental and deployment program risks

Power density of each technology
MW/km²

4.5 | 5 | 5.5 | 500

Area covered by technology in 2050[1]
'000 km²



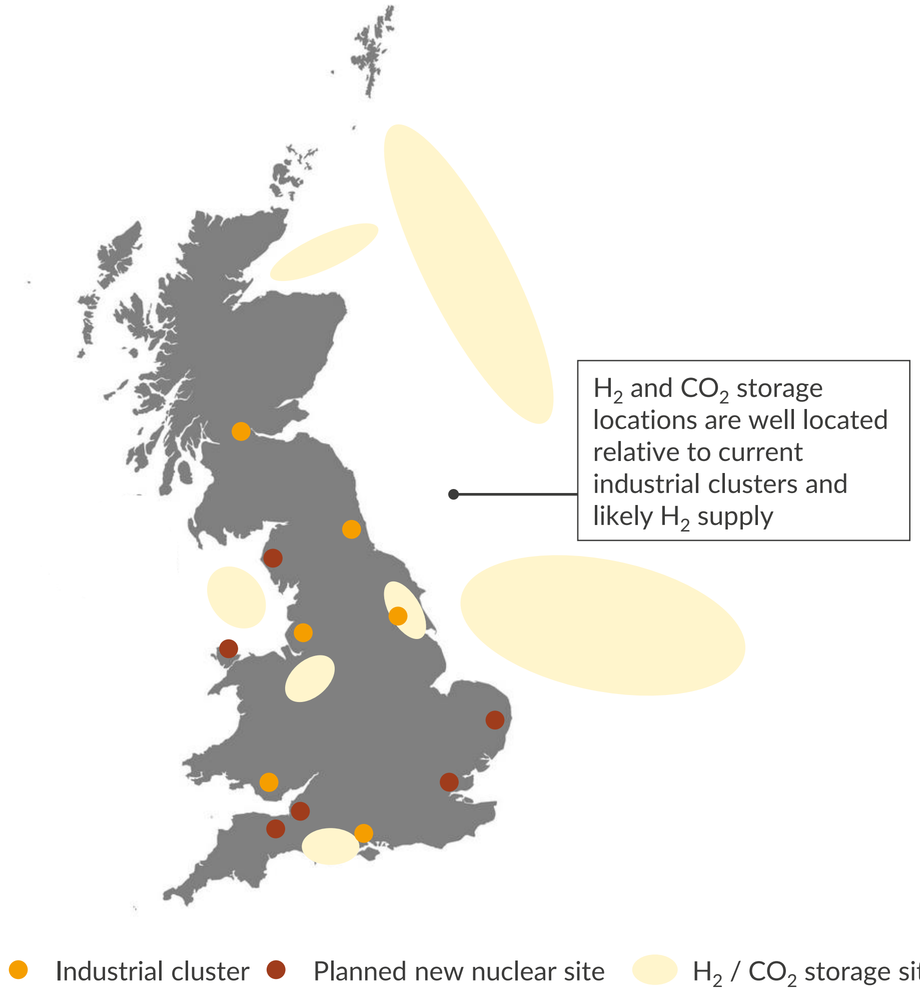
	1H. No new nuclear	1H RES. No new nuclear	3H. New nuclear techs	3H RES. New nuclear techs
GB land area covered (excluding offshore wind) %	7	9	4	6
GB total installed power capacity GW	265	319	244	285

Offshore wind | Onshore wind | Solar PV | Nuclear

Source: Aurora Energy Research, World Bank, , NREL, WindEurope, CCC, LucidCatalyst

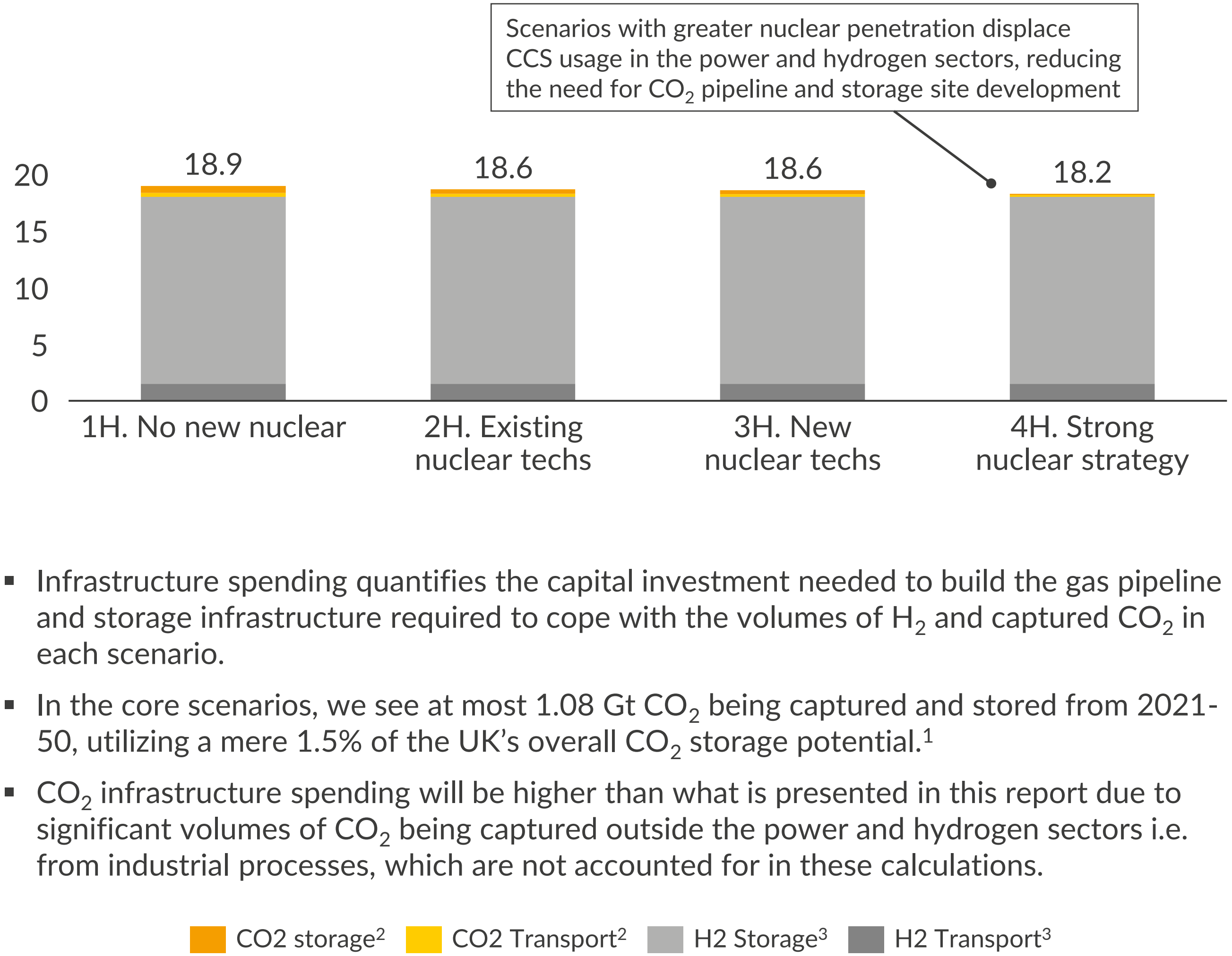
Hydrogen storage will take up ~90% of infrastructure investment in scenarios with high levels of hydrogen demand

Map of GB



NPV GB H_2 and CO_2 infrastructure spending

£bn



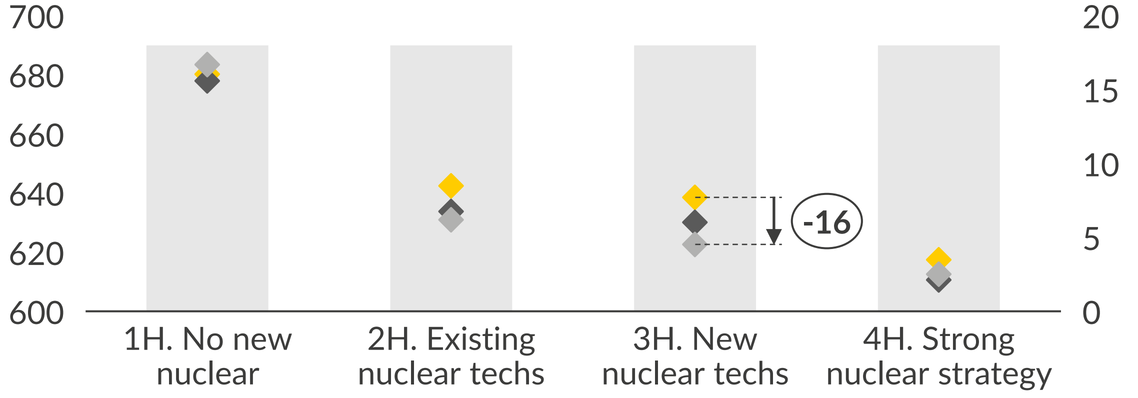
- Infrastructure spending quantifies the capital investment needed to build the gas pipeline and storage infrastructure required to cope with the volumes of H_2 and captured CO_2 in each scenario.
- In the core scenarios, we see at most 1.08 Gt CO_2 being captured and stored from 2021-50, utilizing a mere 1.5% of the UK's overall CO_2 storage potential.[1]
- CO_2 infrastructure spending will be higher than what is presented in this report due to significant volumes of CO_2 being captured outside the power and hydrogen sectors i.e. from industrial processes, which are not accounted for in these calculations.

1) This assumes an emission intensity of 7kg/MWh of biomass combusted. Supply chain emissions not included. 2) Costs for CO_2 transport include onshore and offshore pipelines from key industrial centres to offshore storage sites, most of which are saline aquifers 3) Costs for H_2 transport include transmission pipelines and repurposed natural gas distribution networks, while H_2 storage refers to long-term salt cavern storage.

Source: Aurora Energy Research, IEA, Pale Blue Dot, EU ZEP, CO2 Stored, AEA, H21, Element Energy

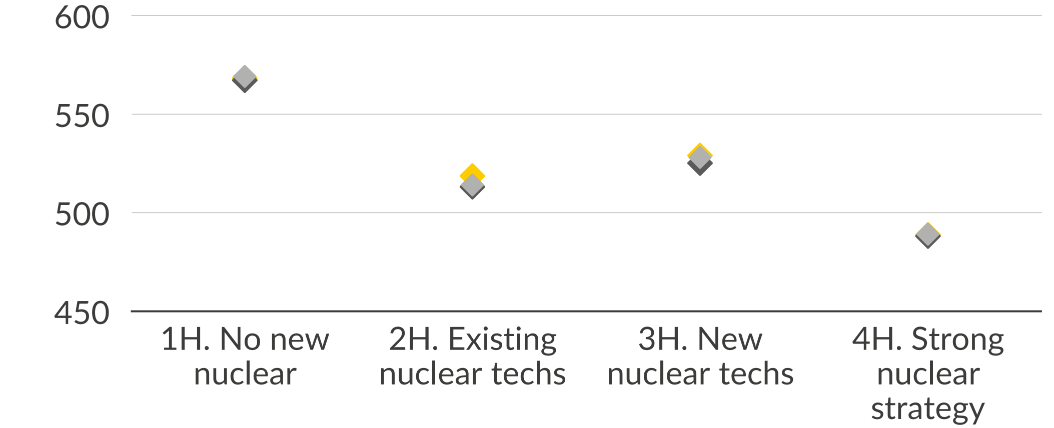
NPV savings of up to £16bn with minimal changes to emissions could be realised by lowering reliance on hydrogen storage

GB NPV total system spending[1] £bn | **GB NPV H_2 spend[1]** £bn

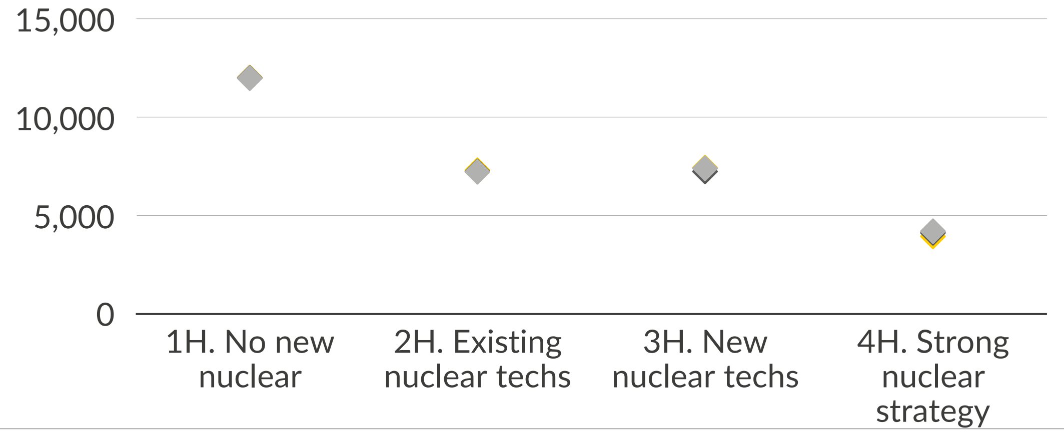


- System costs can be reduced on net by lowering the hydrogen storage capacity on the system.
- Scenario 3H demonstrates NPV savings of £16bn when lowering the 2050 hydrogen storage capacity from 26TWh to 10TWh. This is driven by a combination of reduced hydrogen infrastructure spend, support costs and electricity infrastructure spend.
- In a system with little power and hydrogen production from nuclear (1H), savings from reduced storage are not realised.
- Reducing the levels of hydrogen storage has limited risks in terms of increasing unabated emissions and reliance on fossil fuels.

GB cumulative emissions from power and hydrogen production, 2021-50
Mt CO_2



GB cumulative natural gas use for power and hydrogen production, 2021-50
TWhth HHV



H2 infrastructure | 26TWh H_2 storage | 18 TWh H_2 storage | 10 TWh H_2 storage

1) Using 5% discount rates on spending from 2021 – 2050.

Source: Aurora Energy Research

Technology costs could fall slower or faster than expected but historic reductions have largely been achieved by clear policy

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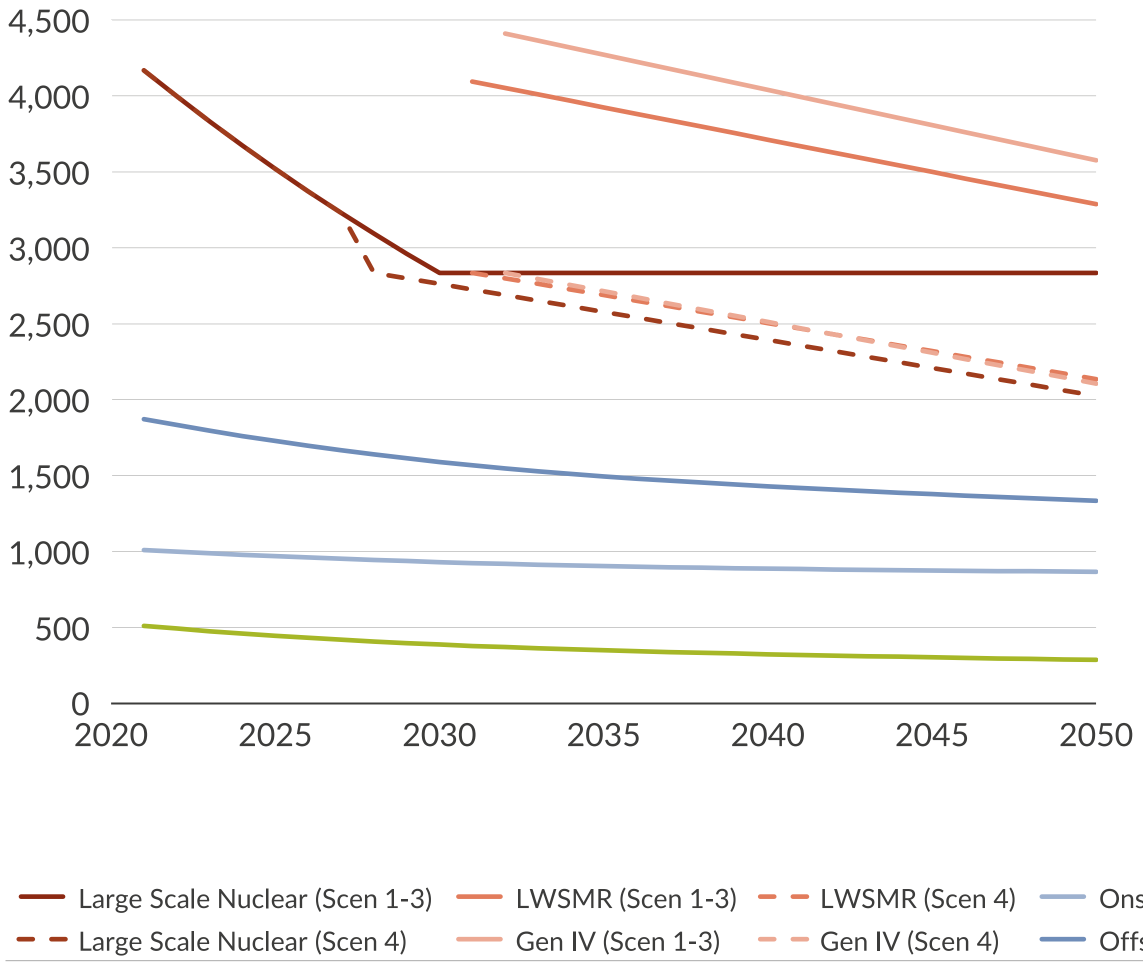
GB CAPEX
£/kW



- Technology cost reductions are assumed for RES, and new nuclear technologies, however these forecasts are uncertain and could increase due to:
  - **Lower than expected learning rates** although these have historically been underestimated
  - **Deploying capacity on worse sites** as capacity will first be deployed on sites with the lowest costs and therefore highest returns
  - **Tight supply chains and high demand** for key materials due to high levels of global demand and the pace of delivery required to reach net-zero.
- The most recent new build nuclear plant in GB, Hinkley Point C, has faced high costs driven by a number of factors including being a first of a kind (FOAK) plant and commencement of construction before completion of the plant design. Support for a pipeline of nuclear projects, particularly small reactors less exposed to delays and cost overruns, could lead to decreased costs for nuclear plants.
- If the low costs for nuclear in the *4H. Strong nuclear strategy* scenarios are not realised, system spending could increase by £21bn (NPV 2021-2050), when comparing against *3H. New nuclear techs*.

Source: Aurora Energy Research

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New policies for low carbon solutions beyond recently announced ambitious policies are needed to reach net-zero

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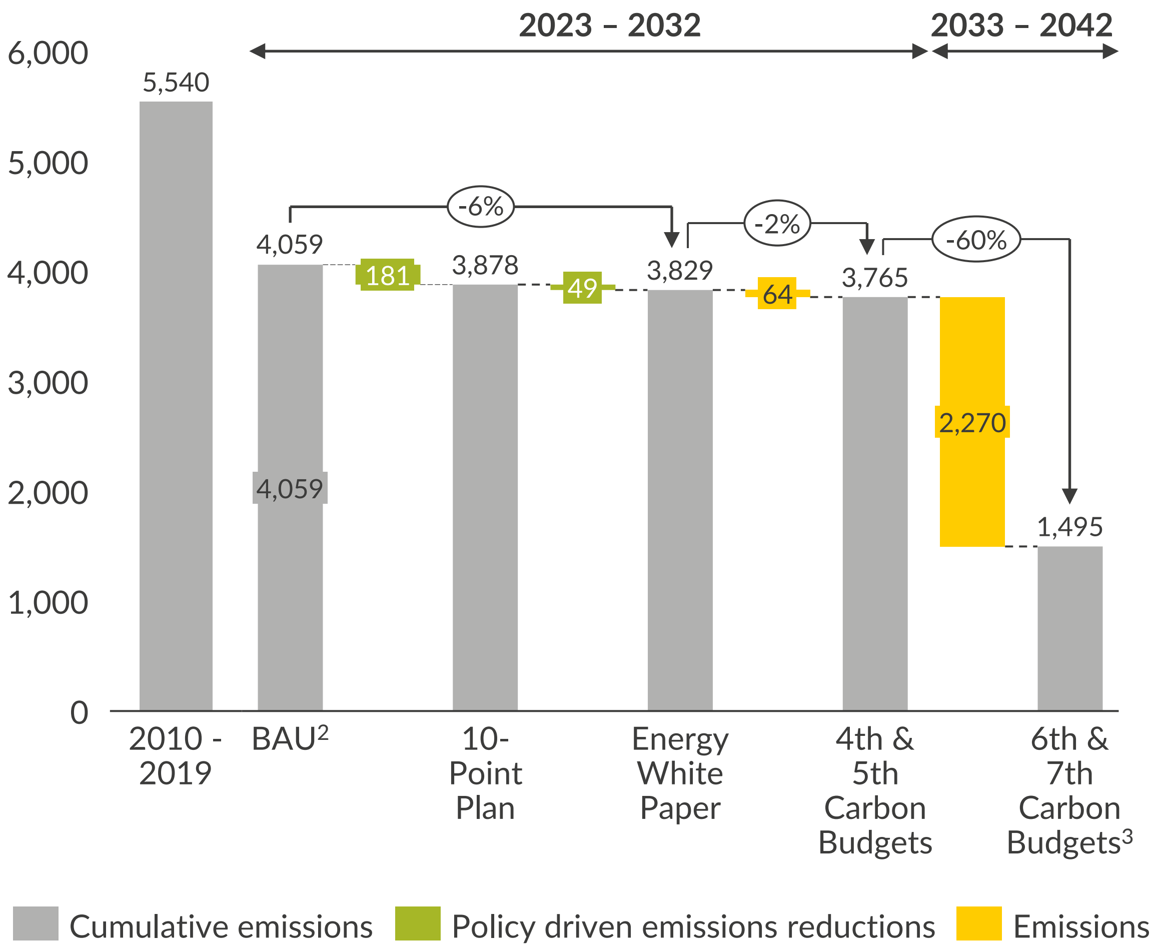
GB estimated reduction in annual GHG emissions from quantifiable policies announced in the 10-Point Plan and Energy White Paper (EWP)[1]
$MtCO_2e$



- GB has been a world leader in reducing emissions, and the first country to introduce a legally binding target of net-zero emissions by 2050.
- The 10-Point Plan, published in 2020, includes targets for:
  - **Energy:** 40 GW offshore wind by 2030
  - **Transport:** Ban on combustion engines from 2030 and hybrid vehicles from 2035
  - **Hydrogen:** 5 GW 'low-carbon' H2 production capacity by 2030
  - **CCS:** Removal of 10 MtCO2e per year by 2030
  - **Buildings:** 600k heat pumps installed annually from 2028
  - **Nature:** 30k hectares of trees planted each year.
- Combined with the Energy White Paper, these initiatives are expected to deliver a 6% reduction in emissions on top of existing policies.
- The recent ratification of the 6th carbon budget (78% 1990 levels) in April 2021 will require a much more comprehensive decarbonization plan to be developed to align UK's carbon emission trajectory.
- Despite these ambitions and policies, the UK is on track to exceed its 4th & 5th carbon budgets.
- Careful consideration of technology pathways and the additional policies required to support them is needed to ensure these targets are met.

1) As laid out in The Ten Point Plan for a Green Industrial Revolution. Cumulative numbers shown; 2) Emissions under existing policies, based on estimated net carbon account as published in CCC's 2020 Progress Report; 3) 7th Carbon budget predicted based on a trajectory consistent with the balanced pathway.

Sources: Aurora Energy Research, BEIS, CCC

Considerable UK commitments on H_2 are colour agnostic but lack incentives for consumption and greater clarity is needed

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The United Kingdom's Energy White Paper

- The UK published its Energy White Paper in December 2020, which was informed by the 10 point plan released in November 2020, both documents contained hydrogen based targets and incentives.
- The announcements within the UK so far are production method agnostic – with mention of electrolysis, gas reformation and even use of runoff nuclear heat being used to improve efficiency of processes.

Policies and targets

- 5 GW of electrolyser capacity built by 2030, requiring about GBP4bn of private investment.
- Saving of 41 Mt of CO_2 between 2023 and 2032
  - Capturing 10 MT of CO_2 annually by 2030 using CCUS.
- Seeking to blend 20% hydrogen in the natural gas network by 2023.
- 60,000 jobs in hydrogen production and CCS.
- Release of hydrogen strategy document in spring 2021.

Thematic and incentive focus in the UK is spread throughout all three areas of hydrogen demand – focusing on pilot and demonstration projects, and development of a hydrogen ecosystem on a local scale.

The UK has announced many funds but support is combined across green and blue hydrogen, and actual production and consumption support mechanisms are not realised aside from some grid blending and home use pilot programs.

Incentives cover several business models

- Hydrogen technology development is included as able to participate in the GBP1bn energy innovation program.
- GBP20m in 2021 in zero emission hydrogen freight trials.
- Funding for 4,000 zero emissions buses (both battery and hydrogen fuelled).

If hydrogen fuel cell buses dominate this allocation, this will be by far the biggest hydrogen bus fleet in Europe.

- Plan to fund the expansion of hydrogen neighbourhood to hydrogen village by 2025.
- Investing GBP1bn in CCS deployment in two industrial clusters.
- GBP240m of investment in a "net zero hydrogen fund" until 2025.
- GBP315m of investment in the "Industrial Energy Transformation Fund" until 2024.

Sources: Aurora Energy Research, The Ten Point Plan for a Green Industrial Revolution, Energy White Paper

Future policy direction should consider the decarbonisation routes facilitated by different supply mixes in addition to fossil fuel usage

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1 abling deeper emissions reductions

- 2
  industrial processes, with nuclear H_2 particularly suited to production of synfuels to be used as drop-in replacement for fossil fuels in aviation and shipping, which are very hard to abate
  - A key advantage is the ability to locate supply near demand with nuclear H_2 gigafactories and offshore wind plants near ports and industrial clusters and refueling stations.
- Waste heat from nuclear can also provide low carbon district heating applications and increase efficiency of Direct Air Capture (DAC) of CO_2.[1]
- Impure H_2 from fossil based blue H_2 is only suitable for heating and H_2 combustion plants so uses are limited and may be associated with continued methane leaks from gas pipelines and undesirable combustion byproducts.

System resilience and reliance on fossil fuels

- Low carbon dispatchable capacity is required to manage short- and long-term fluctuations in variable RES output, particularly during consecutive days of low wind output when battery storage is unlikely to meet demand.
- Gas CCS is a useful transitional technology on the path to net-zero however it extends reliance on fossil gas and uncertainties remain on long term storage of CO_2.
- Large scale nuclear can provide flexibility but co-location with electrolysers enables plants to provide more flexibility to the grid by diverting electricity output to H_2 production, thereby displacing the role of gas CCS and fossil fuels.
- Small nuclear reactors have the added benefit of providing local flexibility in addition to reducing the risk of in-feed losses and reliance on back-up gas.

3 Mechanisms required to support low carbon supply

- provide sufficient economic incentives for low carbon capacity, particularly in low marginal cost systems with high shares of RES and/or nuclear and low wholesale market prices.
- The capacity mechanism is not an effective tool for decarbonization when used in isolation , as in the core scenarios, and may lead to inefficient spending. This is demonstrated by the lack of RES build in the core scenarios.
- Hybrid business models of RES or nuclear with H_2 production can boost project revenues and potential revenue support payments.
- Adopting a suite of mechanisms that provide either direct support for low carbon capacity or add value to grid services can lead to more efficient deployment of low carbon capacity and system spending.

4 **Broader economic benefits of RES and nuclear based H_2**

- **Hydrogen exports** to neighboring countries could enable GB to become a world leader in low carbon hydrogen supply due to very high resource availability enabling even high levels of H_2 supply than modelled in this report.
- **Creation of jobs** due to the development of the offshore wind, electrolyser and nuclear industries.
- **Retention of industry** due to the abundance of low cost, low carbon H_2 preventing relocation to cheaper areas.

1) Funding awarded for Sizewell C to explore designs to use waste heat for DAC.

Source: Aurora Energy Research

A range of mechanisms are available to encourage deployment of low carbon supply

	Description	Benefits	Limitations	Solutions it supports
Contract for Different (CfD)	▪ Long term contracts awarded in a competitive auction that guarantee a fixed price for generation.	▪ High degree of revenue certainty, reduces cost of capital, clear pipeline of auctions, auctions across different technology buckets.	▪ Not market led, reduces market dispatch signals.	▪ RES (offshore wind, onshore wind, solar) and emerging techs (floating offshore wind).
Capacity Market (CM)	▪ Long & short term contracts to procure sufficient firm capacity to meet demand.	▪ Competitive auction.	▪ Procures cheapest capacity resulting in deployment of unabated gas peaking plants.	▪ All with payments reflecting contribution to security of supply.
Carbon price	▪ Market based tool to increase costs associated with emissions.	▪ Increases SRMC for emitters and revenues for non-emitters.	▪ Trajectory highly uncertain, of limited use in low carbon systems.	▪ All non-emitting technologies.
Carbon CfD	▪ Payments to low carbon solutions relative to their carbon emissions savings.	▪ Reduces costs for low carbon solutions below emissions intensive alternatives, multi-sector applicability.	▪ Some complexity associated with new policy design.	▪ All low-carbon solutions.
Dispatchable CfD	▪ Guarantees payments to ensure low carbon assets dispatch ahead of unabated thermal.	▪ Ensures low carbon solutions displace unabated solutions in the merit order, guaranteeing higher output volumes.	▪ Reduces revenues for existing assets, potentially increasing costs elsewhere.	▪ Low carbon dispatchable (i.e. gas CCS, H_2 turbines for power).
Regulated Asset Base (RAB)	▪ Guarantees a fixed rate of return on investment, despite costs.	▪ Guaranteed return lowers financing costs and increases private investment where otherwise considered too risky.	▪ Consumers bear the significant risk of cost and time overruns as well as potential monopolisation.	▪ Capital intensive (i.e. large nuclear, CO_2 and H_2 transport and storage infrastructure).
Ancillary services (AS)	▪ Contracts for targeted grid services (i.e. STOR, Black Start, Dynamic Containment, FFR).	▪ Able to meet specific grid needs.	▪ Occasionally opaque process for awarding contracts.	▪ Dependent on each ancillary service.

Source: Aurora Energy Research

A series of least regret options can be pursued to minimise risks to the transition towards net-zero

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1 **Continued revenue support for low carbon technologies**
To incentivise deployment of low-carbon capacity despite low wholesale market revenues as a result of high penetrations of low marginal cost supply. A level playing field for all technologies is required.

2 **Limit participation of unabated thermal in the CM**
To prevent locking in reliance on new unabated thermal assets, that will remain online for 25 years, by only procuring low carbon alternatives.

3 **Studies on the role of green H_2 from RES and nuclear to displace fossil fuels**
Further investigations of H_2 only business models for RES and nuclear to create low cost H_2 without fossil fuels.

4 **Conduct in depth siting and feasibility studies for nuclear and RES deployment**
To ensure target deployment can be met.

5 **Assess infrastructure requirements of decarbonisation pathways**
To assess need, cost, development time and ecological impact for required infrastructure to be deployed in time for assets to online.

6 **Examine the role existing nuclear can play in green H_2 production**
Co-location of electrolysers with existing nuclear can unlock additional revenue streams whilst providing additional power system flexibility.

7 **Explore support for a construction pipeline of small modular reactors**
To enable deployment, costs reductions and assess feasibility of large scale deployment.

8 **Explore support options for nuclear business models for power + H_2**
To compare against other low carbon technologies.

9 **Further investigate the benefits of high temperature nuclear (Gen IV)**
High temperature reactors could unlock very high H_2 conversion efficiencies using waste heat, with potential for cost reductions.

10 **Development of clear business models for H_2 and CO_2 infrastructure**
To assess costs and incentivise investment.

Source: Aurora Energy Research

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VII. Policy implications

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1. Modelling methodology
2. Additional model results
3. Additional assumptions

Unique, proprietary, in-house modelling capabilities underpin Aurora's superior analysis of the power system

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Global Commodities (AER-GLO) ⟷ **Power markets (AER-ES)** ⟷ **Gas (AER-GAS)**

INPUTS

- Technology
- Policy
- Demand
- Commodity prices[1]
- Weather patterns

Dispatch model

- Hourly granularity
- Iterative modelling
- Dynamic dispatch of plant
- Endogenous interconnector flows

Continuous iteration until an equilibrium is reached

Investment decisions module

- Capacity market modelling
- Capacity build / exit / mothballing
- IRR / NPV driven
- Detailed technology assessments

OUTPUTS

- Capacity mix
- Generation mix
- Wholesale & imbalance prices
- Profit / Loss and NPV
- Electric vehicle charging

Up to 70 specifications modelled for each plant

c. 85k investment hours on modelling capabilities

3k - 4k model runs per week

30+ strength of modelling team globally

Advantages of Aurora approach

- Flexible and nimble because we own the code.
- Transparent results.
- State-of-the-art infrastructure.
- Zero dependence on black-box third-party software (e.g. Plexos).
- Constantly up to date through subscription research.
- Ability to model complex policy changes very quickly.

1) Gas, coal, oil and carbon prices fundamentally modelled in-house with fully integrated commodities and gas market model.

Source: Aurora Energy Research

Methodology for calculating total system spending across scenarios

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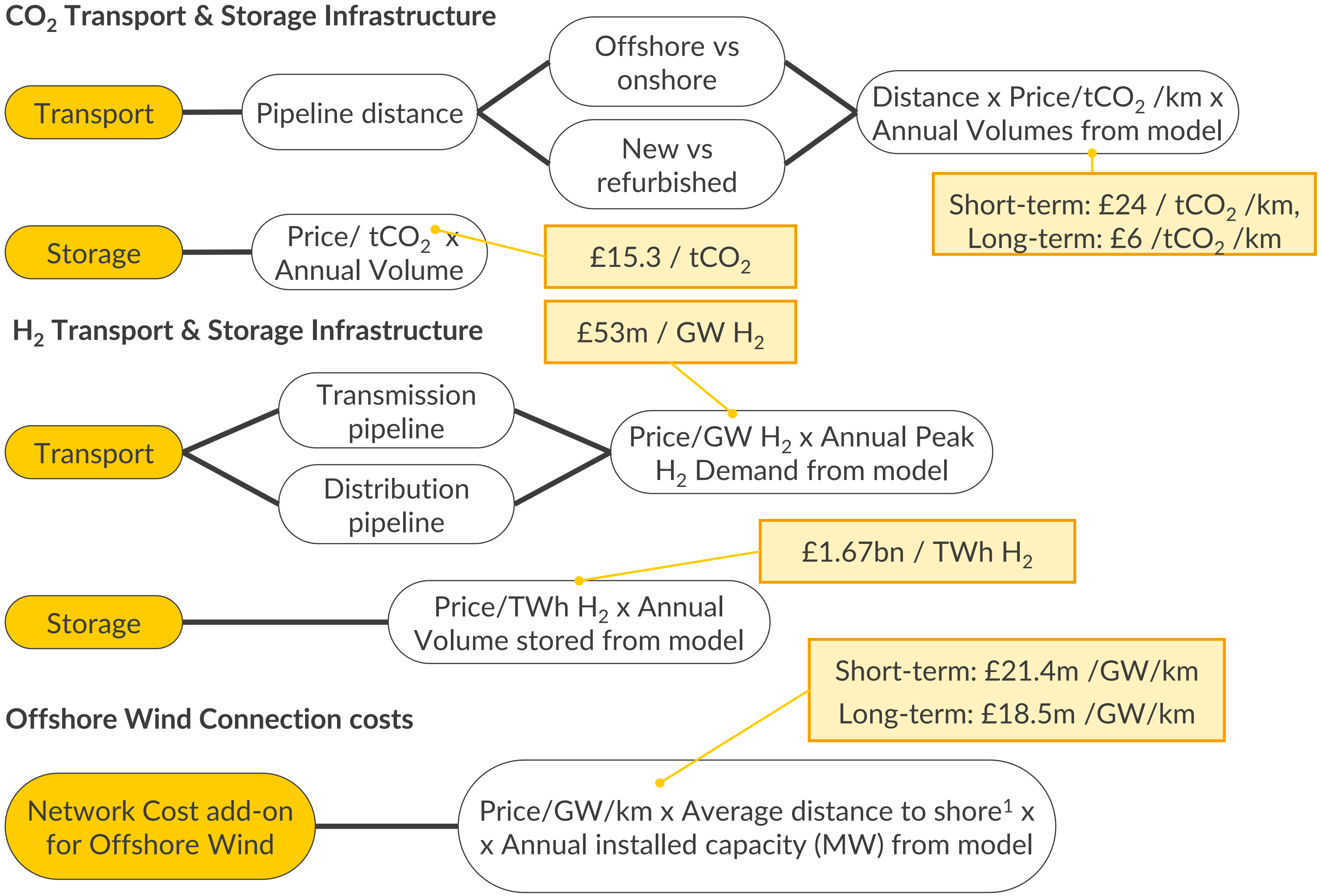
System cost component	Approach
Electricity market	Includes the total spend in the wholesale electricity market (i.e. wholesale price x demand, assuming 8% transmission losses) and the electricity balancing market to match outturn supply and demand.
Electricity market support payments	▪ Subsidy payments to plants with existing support contracts (e.g. ROC, FiT, CfD). ▪ Capacity Market payments to ensure acceptable returns are met for sufficient capacity to build to meet security of supply targets. ▪ Additional top-up payments required for assumed capacity additions to breakeven.
Network costs (TNUoS, DUoS)	Estimate of the costs required to expand the network to connect new capacity (accounting for retirements), and the costs to operate and maintain the existing network (underestimates the cost of connecting offshore wind).
Hydrogen market costs	Includes the total spend in the hydrogen market (i.e. wholesale hydrogen market price x demand, hydrogen price achieved by PEM electrolysers at vehicle charging points x demand).
Additional infrastructure costs (see following slide)	▪ Estimate of additional costs of connecting offshore wind to the transmission network not accounted for in network costs. ▪ Estimate of the costs of hydrogen storage and pipeline infrastructure. ▪ Estimate of the costs of CO_2 storage and pipeline infrastructure.

Source: Aurora Energy Research

Methodology for estimating additional infrastructure costs

AURORA



- Our proposed methodology is influenced by the IEA 2020 Special Report on CCUS.
- We propose to ignore shipping as a means of transport as it is competitive with pipelines only for long-haul transport of small CO_2 volumes.

- Infrastructure cost estimates for the Hydrogen system are based on the assumption that large parts of existing gas network infrastructure can be refitted to carry H_2.
- Price points are averaged from project cost estimates spanning multiple reports and were agreed upon by the consortium behind Aurora's 2020 Hydrogen Study.

- Price/ km estimate will be based on recent greenfield and brownfield transactions for offshore transmission infrastructure.
- Average distance to shore and Number of offshore sites per MW will be calculated by analysing the existing fleet.

1) Average distance to shore increases over time to reflect future sites building far away from present ones. It also reflects increasing penetration of floating offshore wind.

Sources: Aurora Energy Research, IEA, Pale Blue Dot, EU ZEP, H21, Co2 Stored, Element Energy, Inframation, WindEurope, Energy White Paper

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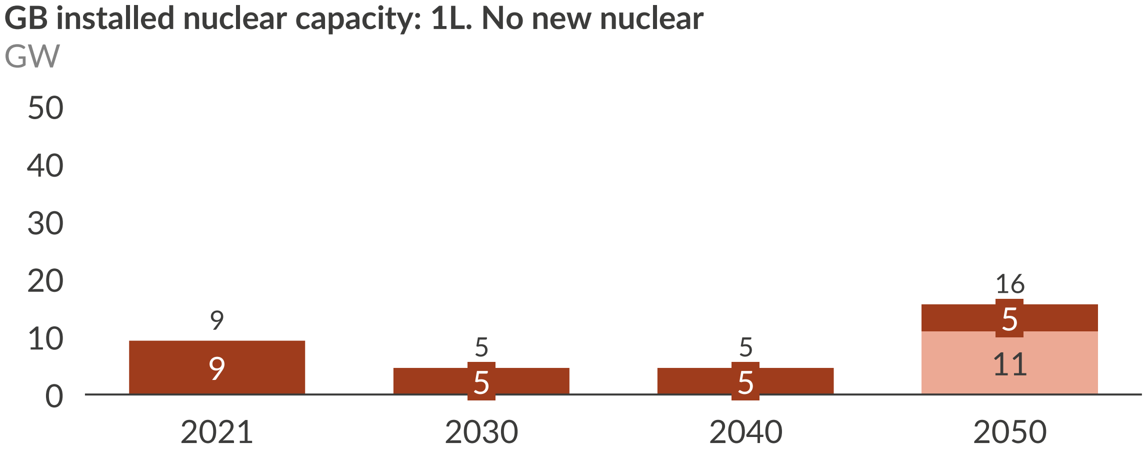
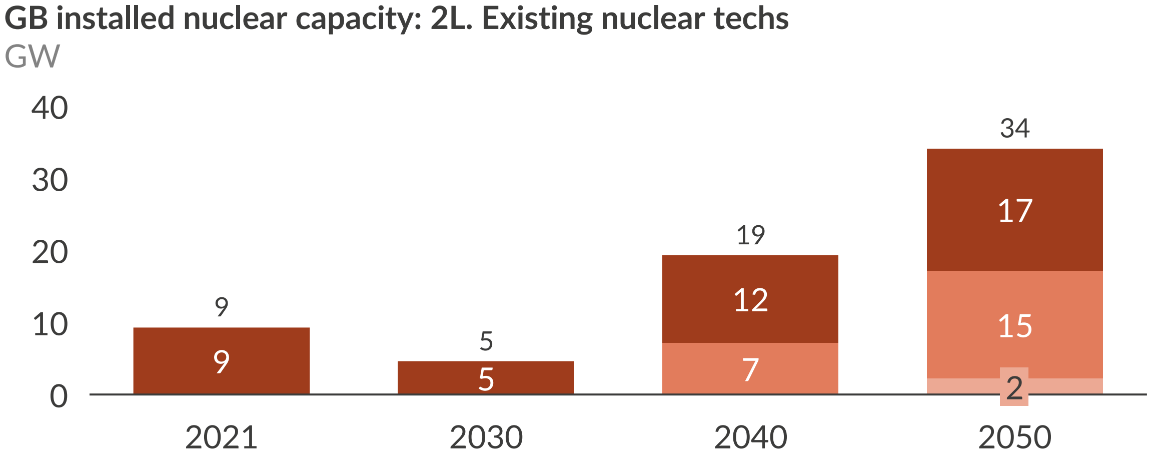
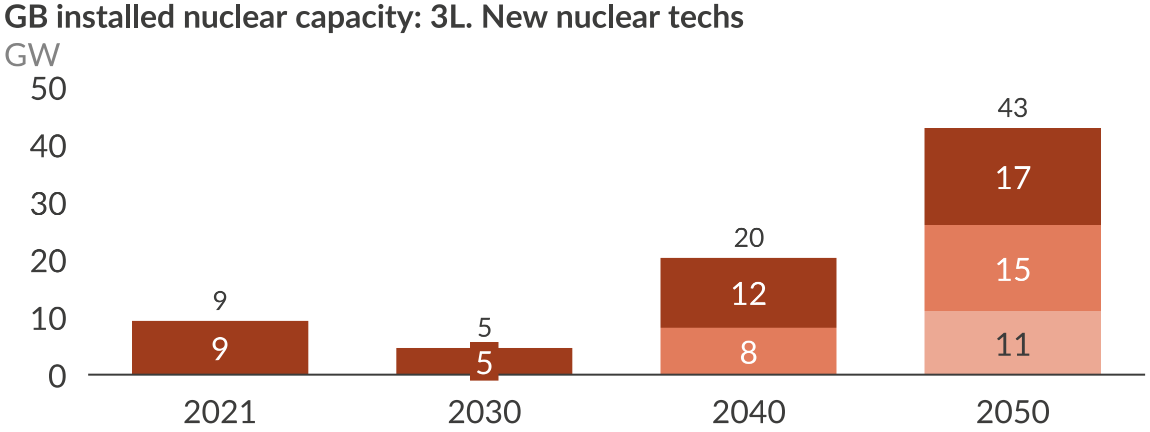
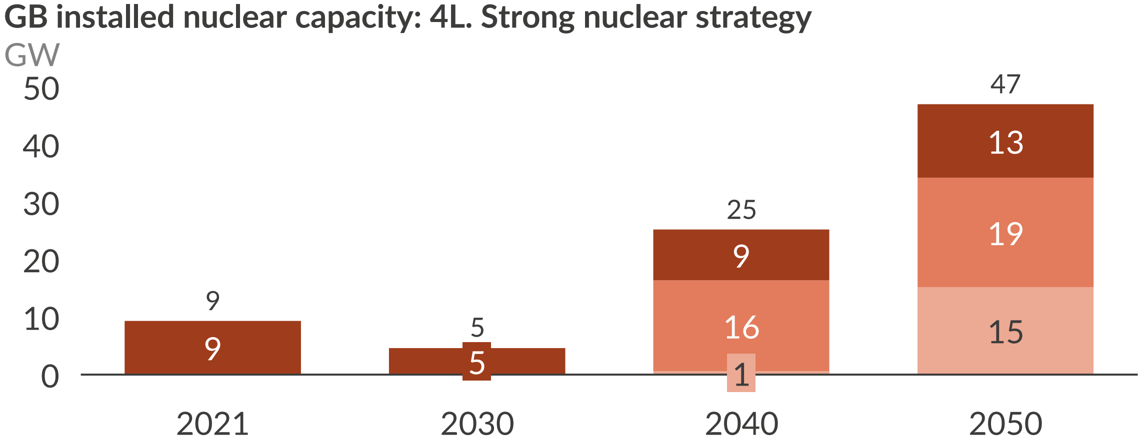
Nuclear capacity forecast by scenario









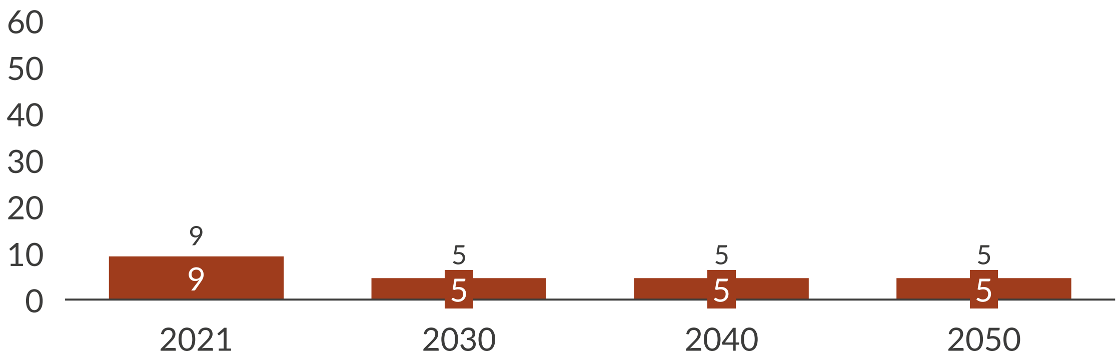
Nuclear | Small Modular Reactor | Gen IV with electrolyser

1) Other RES includes EfW and marine; 2) Other thermal includes embedded CHP; 3) Gas CCGT includes abated and unabated plants.

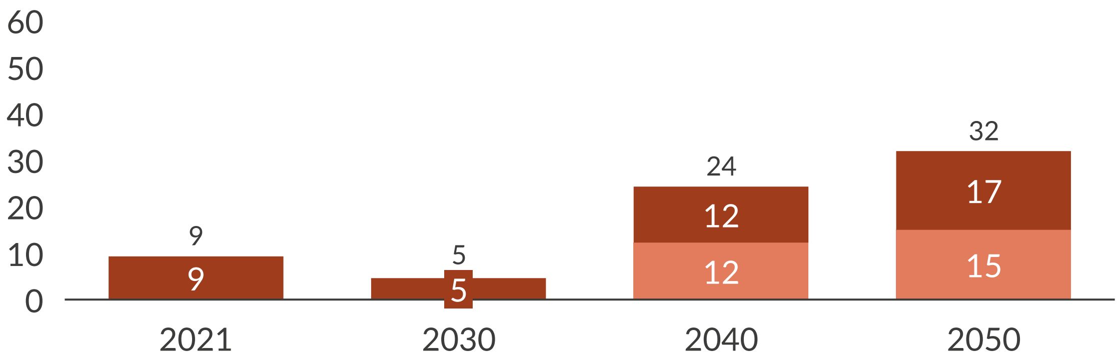
Source: Aurora Energy Research

Power market capacity forecast by scenario

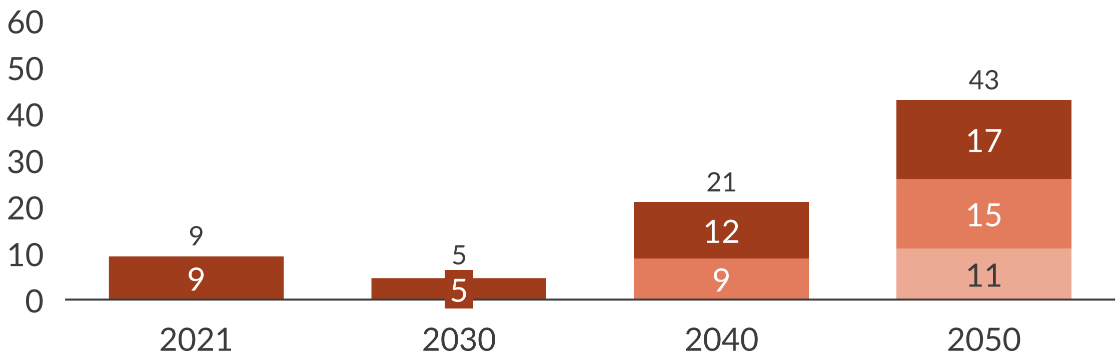
GB installed nuclear capacity: 1H. No new nuclear
GW



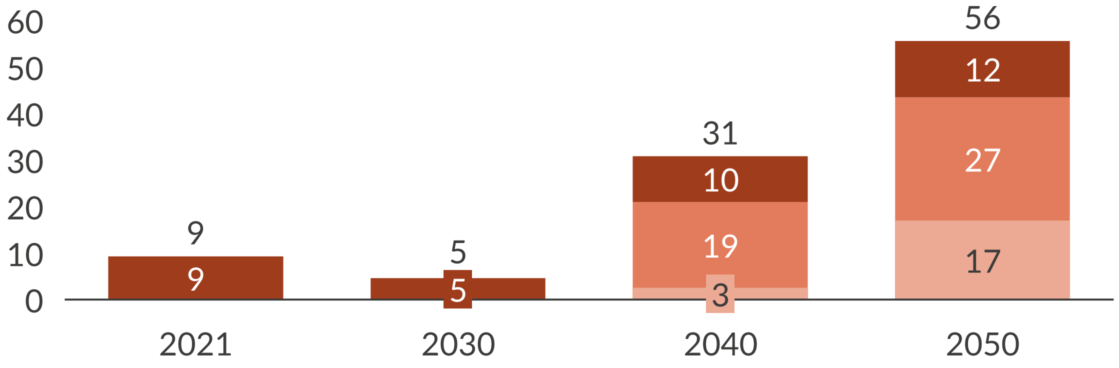
GB installed nuclear capacity: 2H. Existing nuclear techs
GW



GB installed nuclear capacity: 3H. New nuclear techs
GW



GB installed nuclear capacity: 4H. Strong nuclear strategy
GW

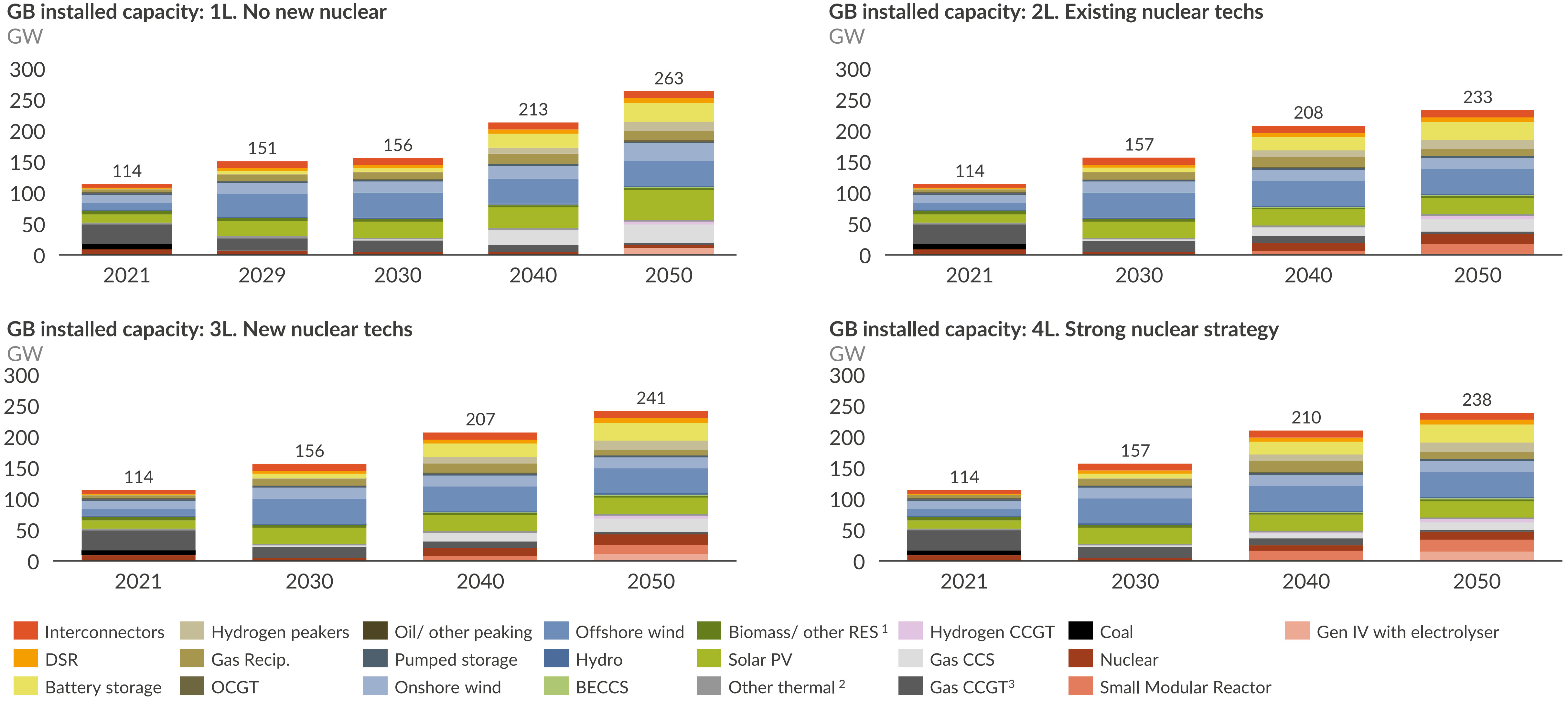


Nuclear | Small Modular Reactor | Gen IV with electrolyser

1) Other RES includes EfW and marine; 2) Other thermal includes embedded CHP; 3) Gas CCGT includes abated and unabated plants.

Source: Aurora Energy Research

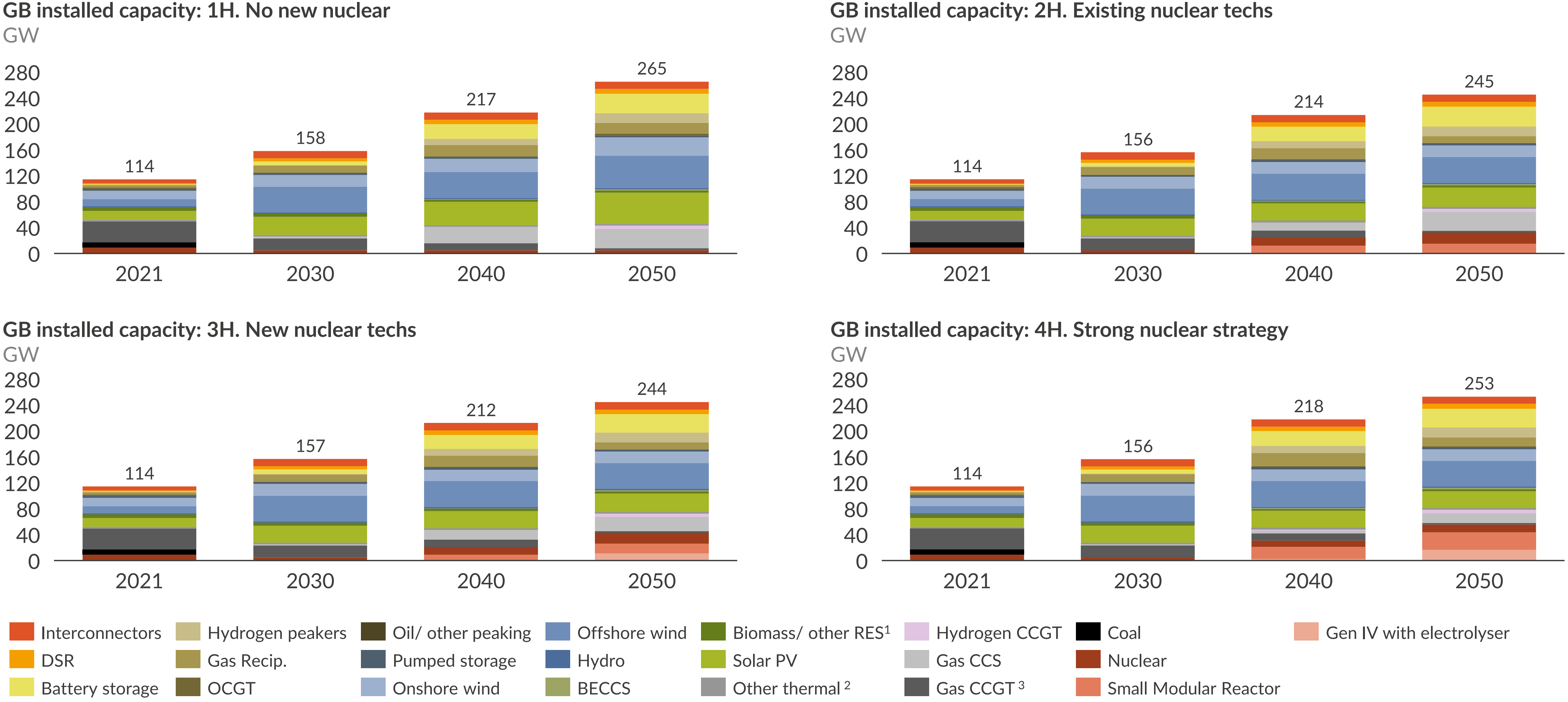
Power market capacity forecast by scenario



1) Other RES includes EfW and marine; 2) Other thermal includes embedded CHP; 3) Gas CCGT includes abated and unabated plants.

Source: Aurora Energy Research

Power market capacity forecast by scenario



1) Other RES includes EfW and marine; 2) Other thermal includes embedded CHP; 3) Gas CCGT includes abated and unabated plants.

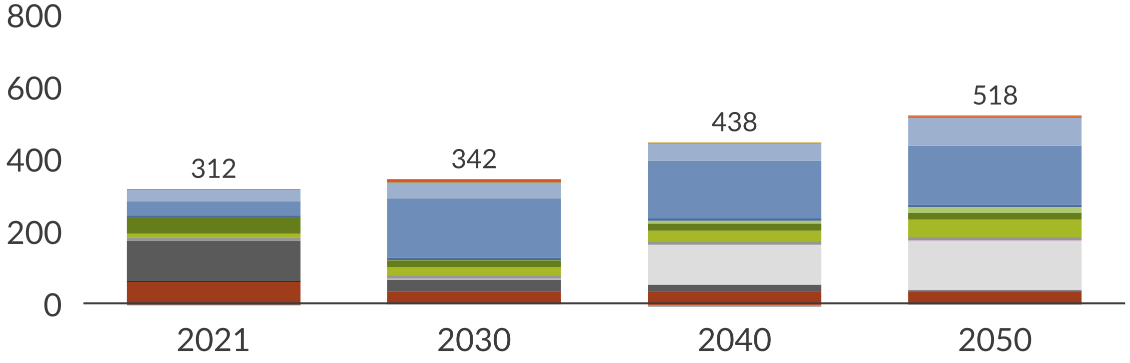
Source: Aurora Energy Research

Power market generation forecast by scenario

AURORA

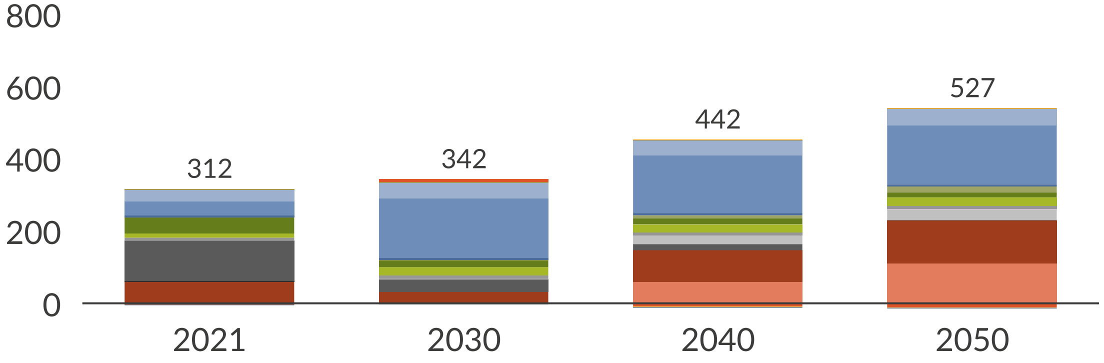
Electricity production and net imports: 1L. No new nuclear

TWh



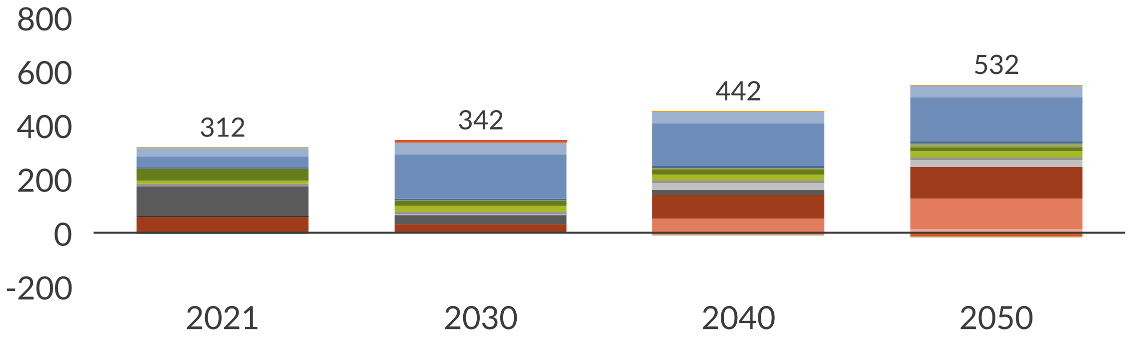
Electricity production and net imports: 2L. Existing nuclear techs

TWh



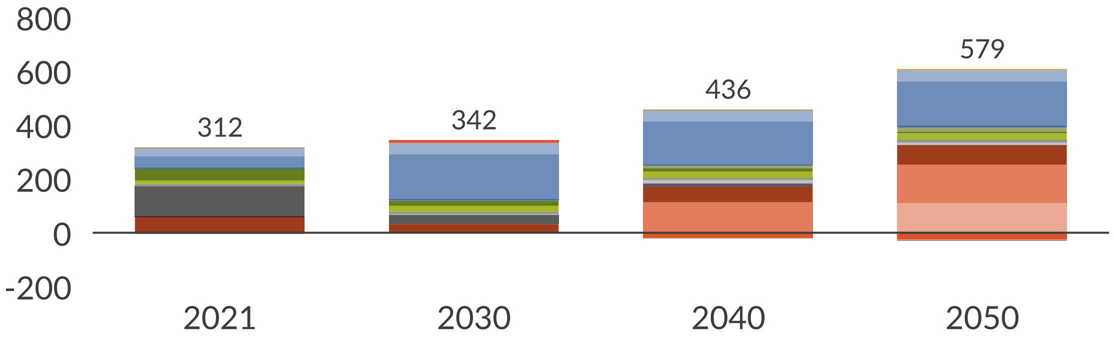
Electricity production and net imports: 3L. New nuclear techs

TWh



Electricity production and net imports: 4L. Strong nuclear strategy

TWh

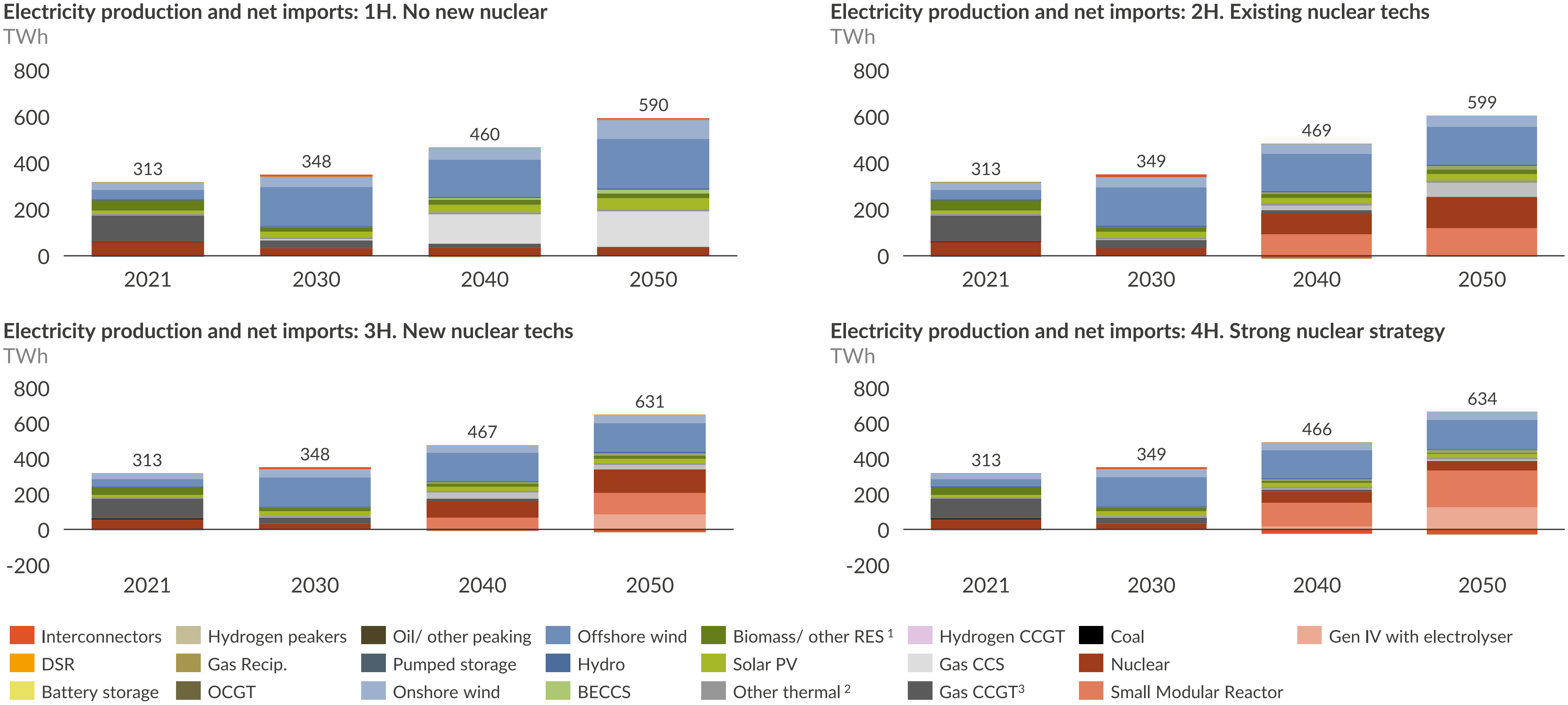


Interconnectors, Hydrogen peakers, Oil/ other peaking, Offshore wind, Biomass/ other RES [1], Hydrogen CCGT, Coal, Gen IV with electrolyser, DSR, Gas Recip., Pumped storage, Hydro, Solar PV, Gas CCS, Nuclear, Battery storage, OCGT, Onshore wind, BECCS, Other thermal [2], Gas CCGT[3], Small Modular Reactor

1) Other RES includes EfW and marine; 2) Other thermal includes embedded CHP; 3) Gas CCGT includes abated and unabated plants.

Source: Aurora Energy Research

Power market generation forecast by scenario



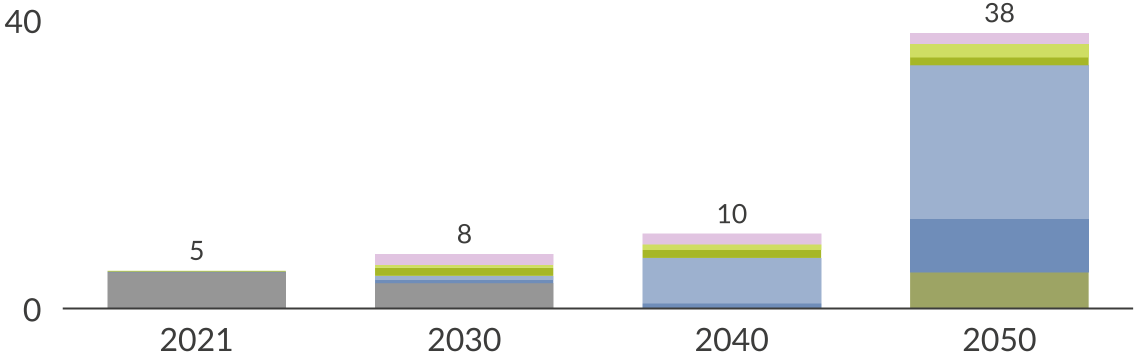
1) Other RES includes EfW and marine; 2) Other thermal includes embedded CHP; 3) Gas CCGT includes abated and unabated plants.

Source: Aurora Energy Research

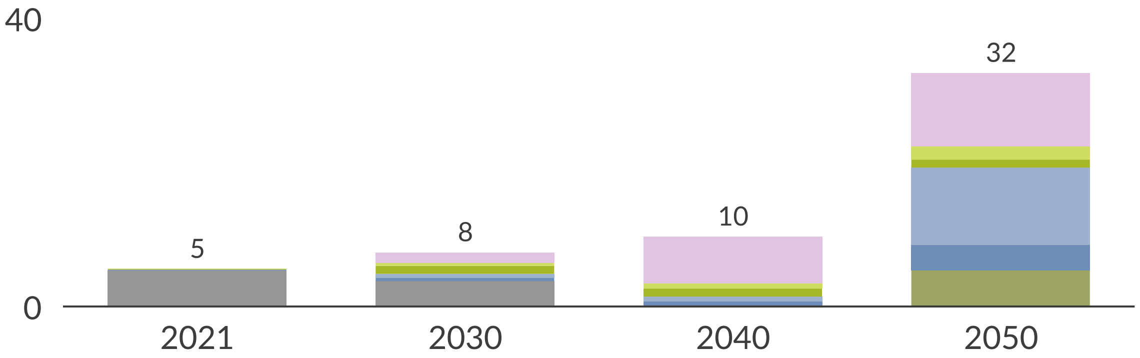
Hydrogen market capacity forecast by scenario

AURORA

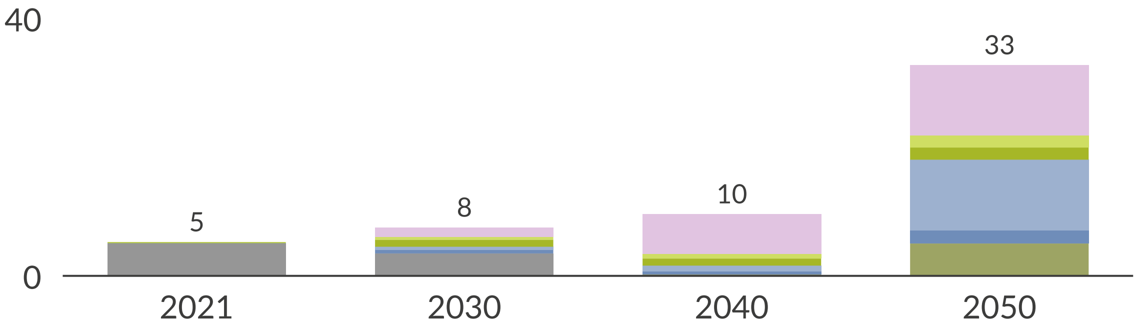
GB H_2 installed capacity: 1L. No new nuclear
GW H_2



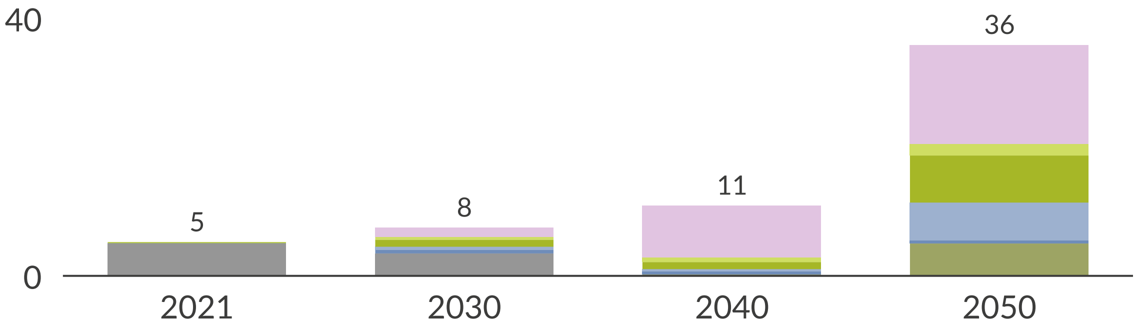
GB H_2 installed capacity: 2L. Existing nuclear techs
GW H_2



GB H_2 installed capacity: 3L. New nuclear techs
GW H_2



GB H_2 installed capacity: 4L. Strong nuclear strategy
GW H_2

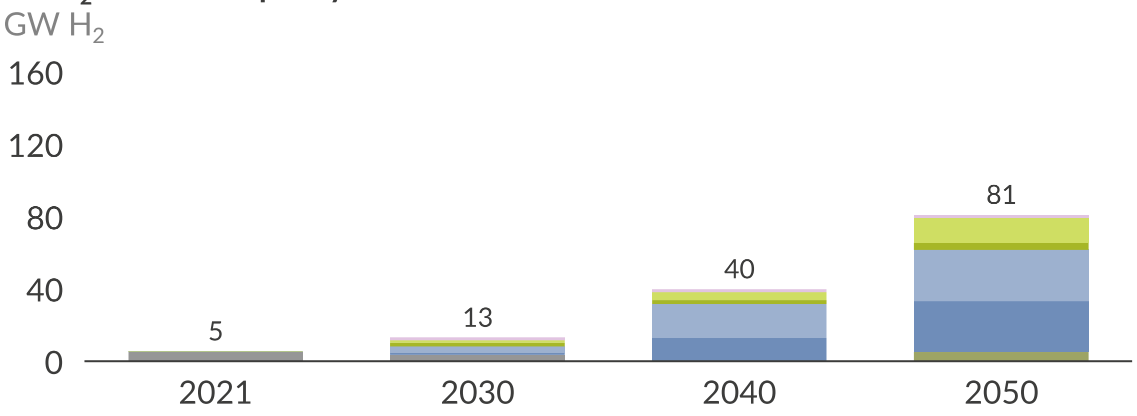


SMR | H_2 BECCS | SMR+CCS | ATR+CCS | Alkaline | PEM | SOE | Gigafactory

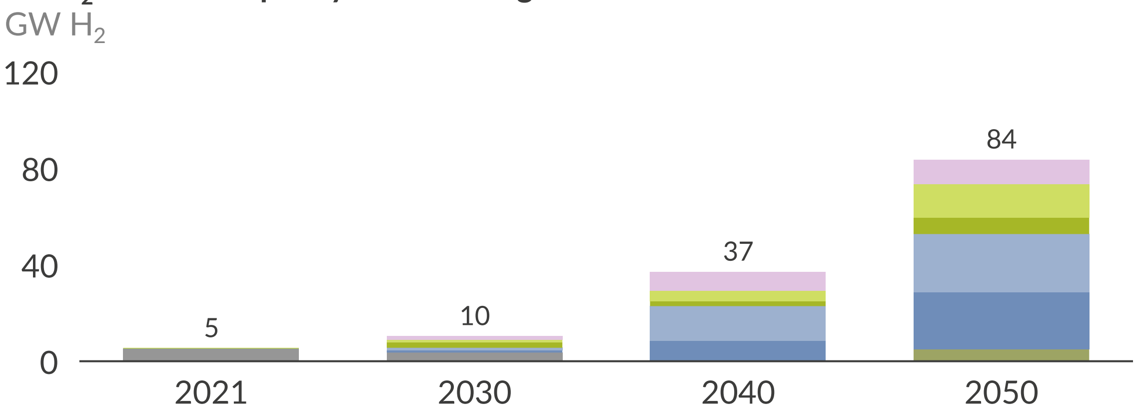
Source: Aurora Energy Research

Hydrogen market capacity forecast by scenario

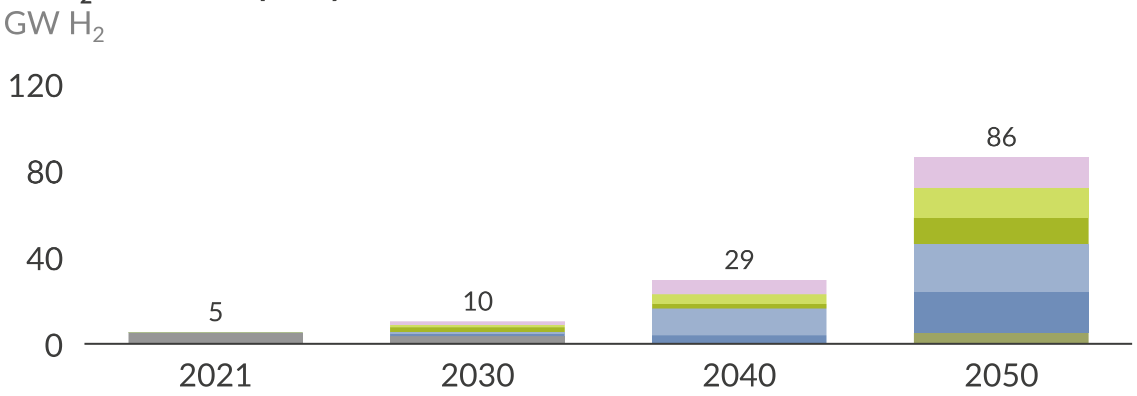
GB H_2 installed capacity: 1H. No new nuclear



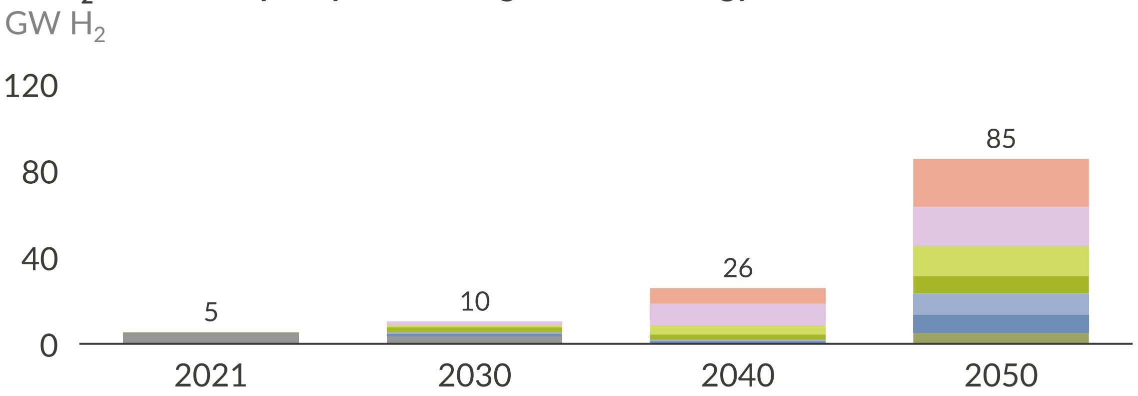
GB H_2 installed capacity: 2H. Existing nuclear techs



GB H_2 installed capacity: 3H. New nuclear techs



GB H_2 installed capacity: 4H. Strong nuclear strategy



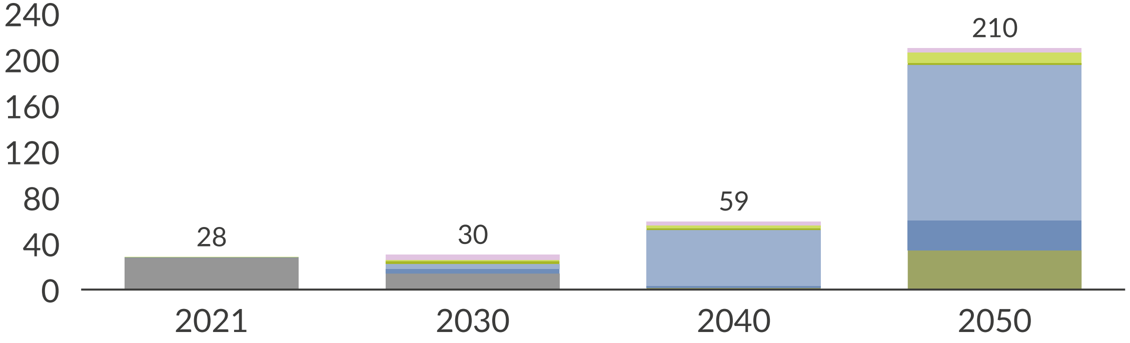
SMR | H_2 BECCS | SMR+CCS | ATR+CCS | Alkaline | PEM | SOE | Gigafactory

Source: Aurora Energy Research

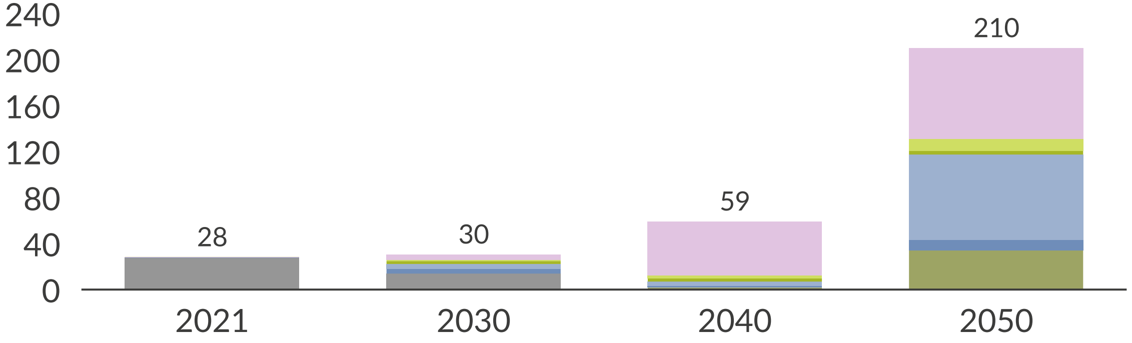
Hydrogen market generation forecast by scenario

AURORA

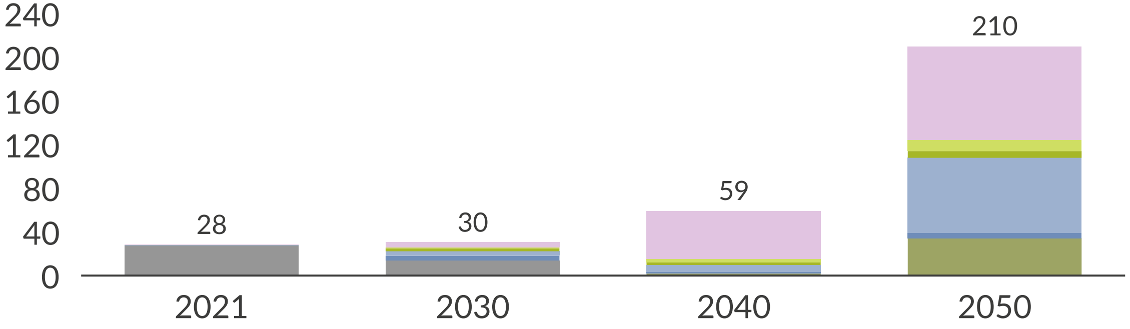
GB gross H_2 production : 1L. No new nuclear
TWh H_2



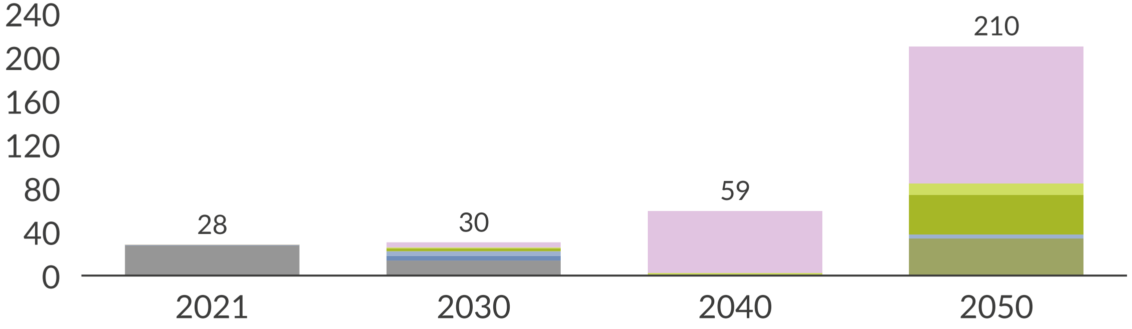
GB gross H_2 production : 2L. Existing nuclear techs
TWh H_2



GB gross H_2 production : 3L. New nuclear techs
TWh H_2



gross H_2 production : 4L. Strong nuclear strategy
TWh H_2



SMR | H_2 BECCS | SMR+CCS | ATR+CCS | Alkaline | PEM | SOE | Gigafactory

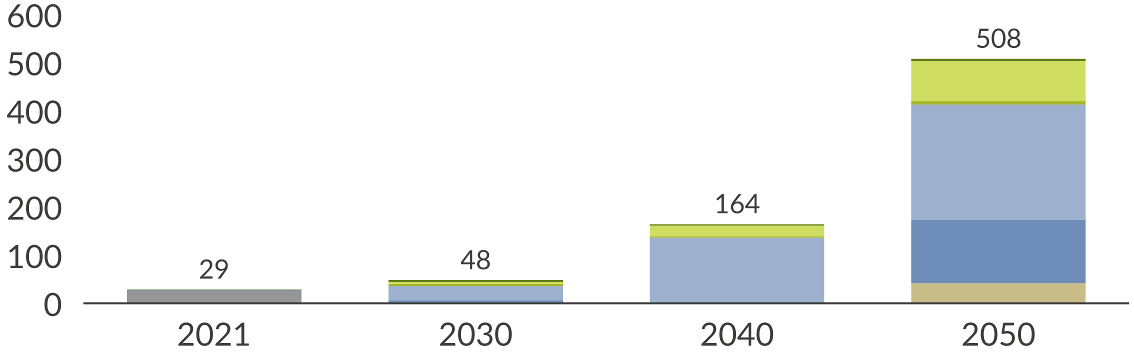
Source: Aurora Energy Research

Hydrogen market generation forecast by scenario

AURORA

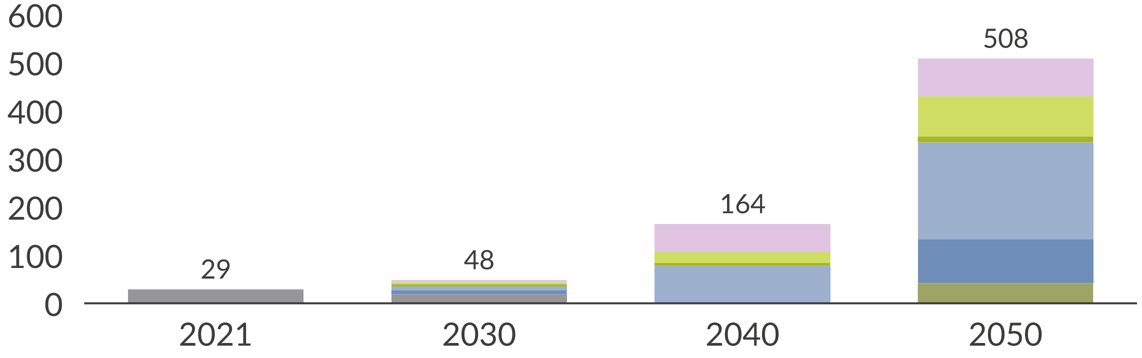
GB gross H_2 production : 1H. No new nuclear

TWh H_2



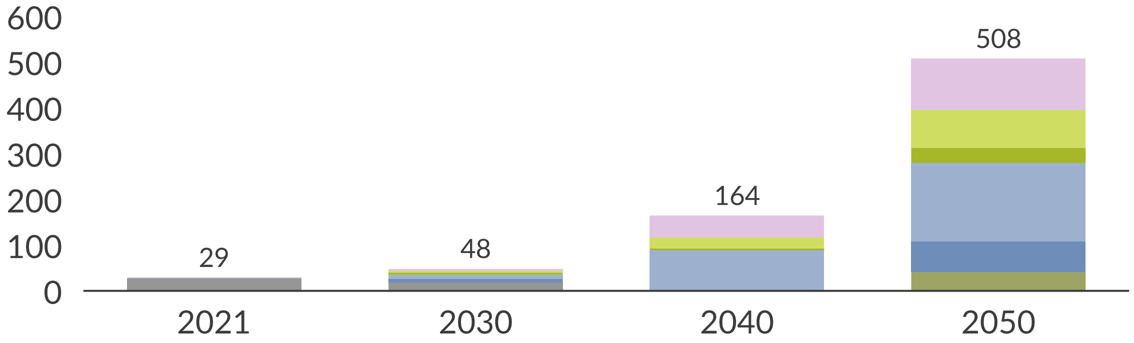
GB gross H_2 production : 2H. Existing nuclear techs

TWh H_2



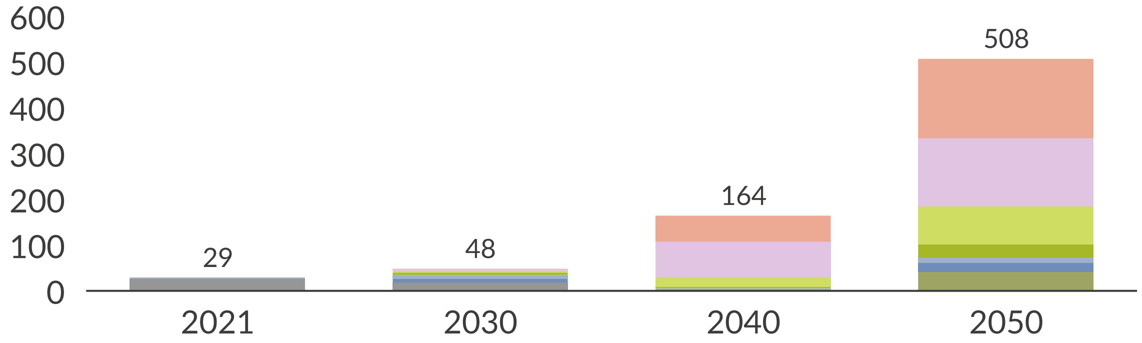
GB gross H_2 production : 3H. New nuclear techs

TWh H_2



GB gross H_2 production : 4H. Strong nuclear strategy

TWh H_2

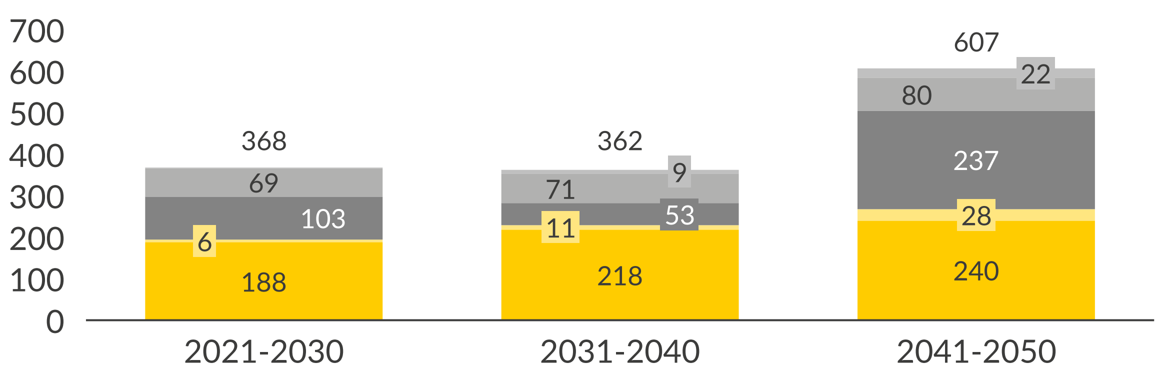


SMR | H_2 BECCS | SMR+CCS | ATR+CCS | Alkaline | PEM | SOE | Gigafactory

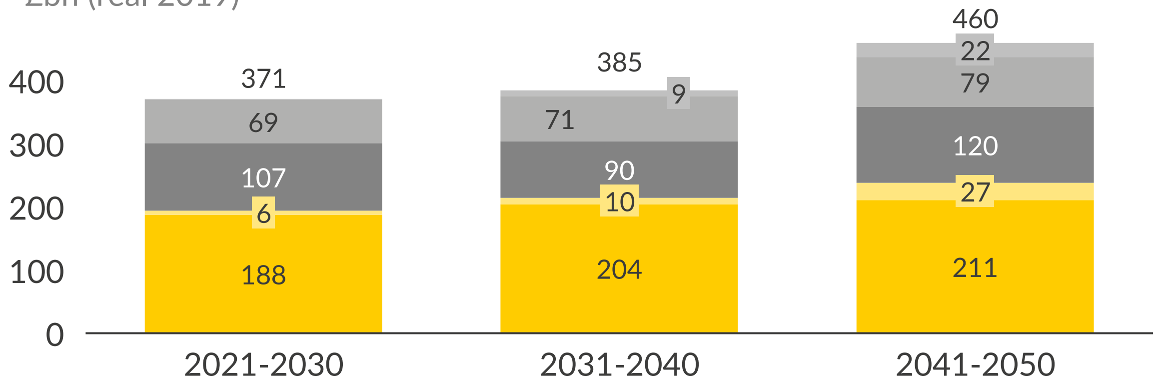
Source: Aurora Energy Research

Total system costs by scenario

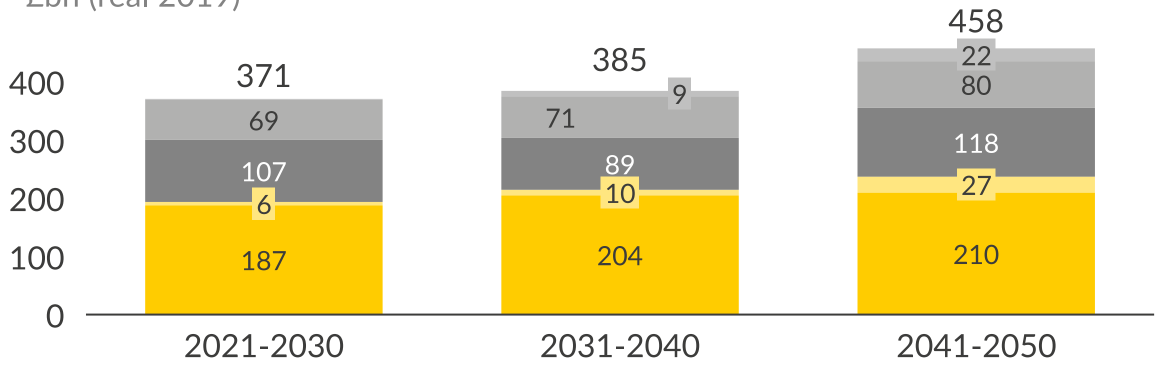
GB total system spend: 1L. No new nuclear
£bn (real 2019)



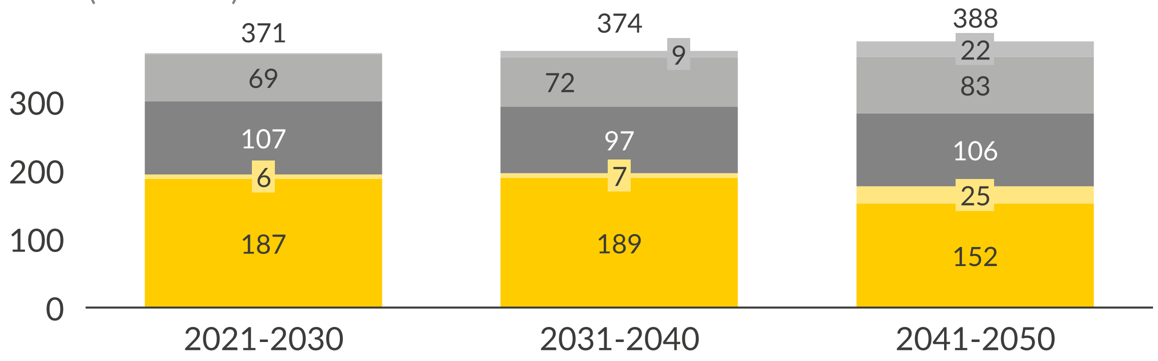
GB total system spend: 2L. Existing nuclear techs
£bn (real 2019)



GB total system spend: : 3L. New nuclear techs
£bn (real 2019)



GB total system spend: 4L. Strong nuclear strategy
£bn (real 2019)



Wholesale electricity | Wholesale hydrogen | Support costs (incl. CM & subsidies) | Electricity infrastructure | Hydrogen infrastructure | CO2 infrastructure

Source: Aurora Energy Research

Total system costs by scenario

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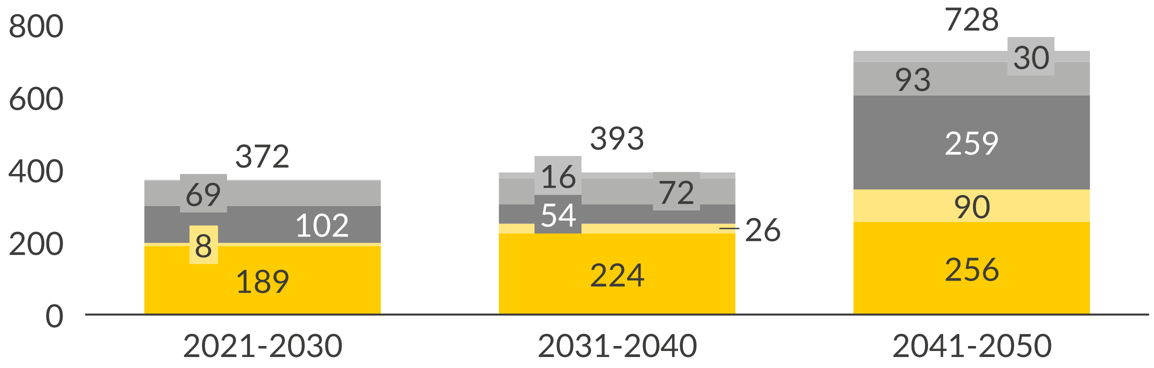
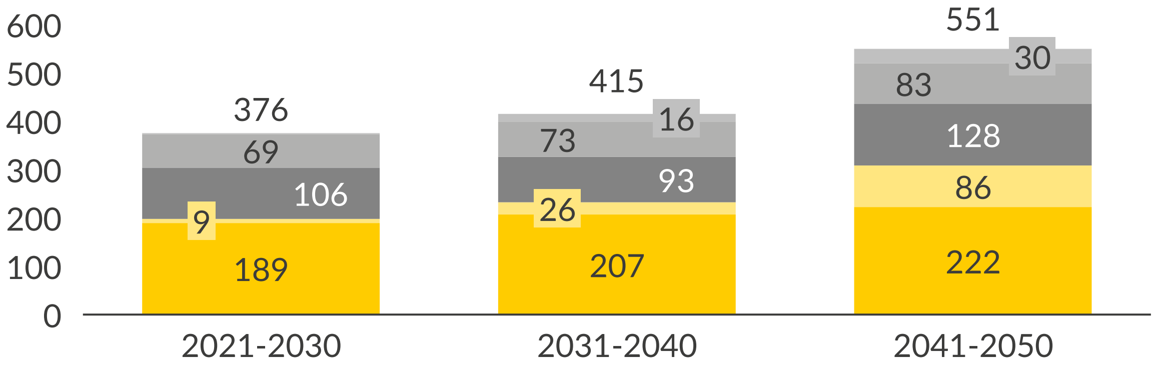
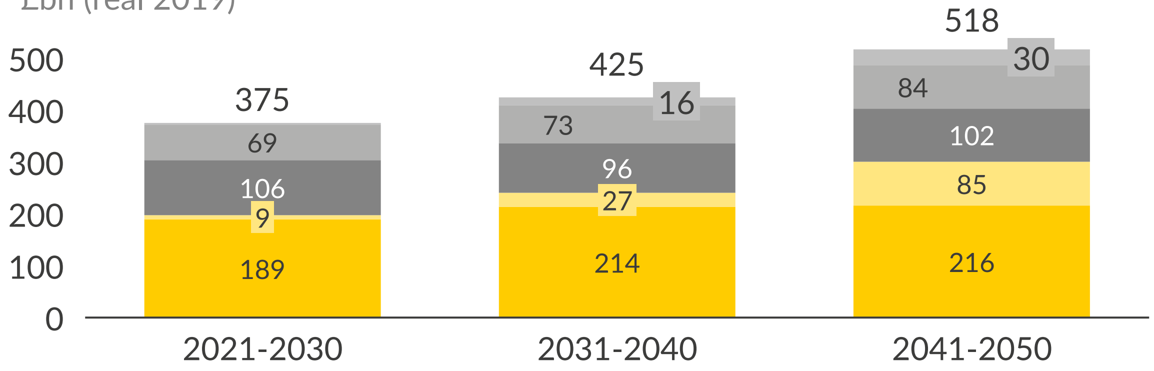
GB total system spend: 1H. No new nuclear
£bn (real 2019)



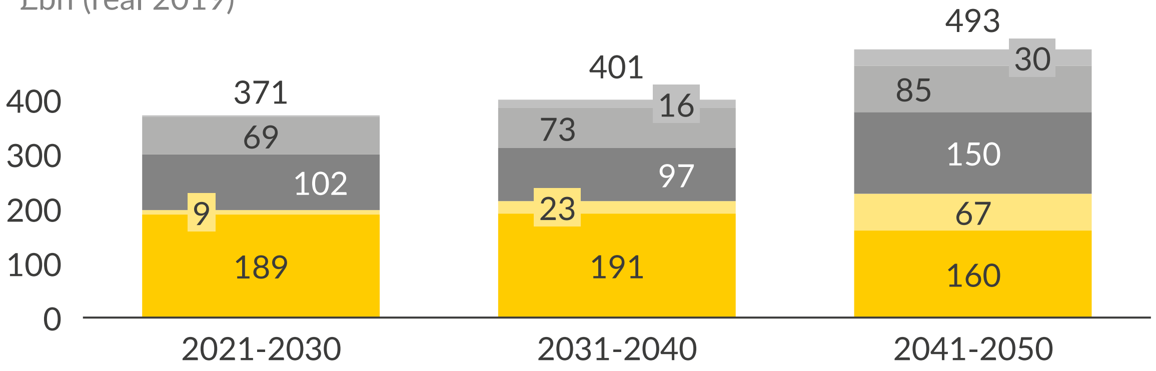
GB total system spend: 2H. Existing nuclear techs
£bn (real 2019)



GB total system spend: 3H. New nuclear techs
£bn (real 2019)



GB total system spend: 4H. Strong nuclear strategy
£bn (real 2019)

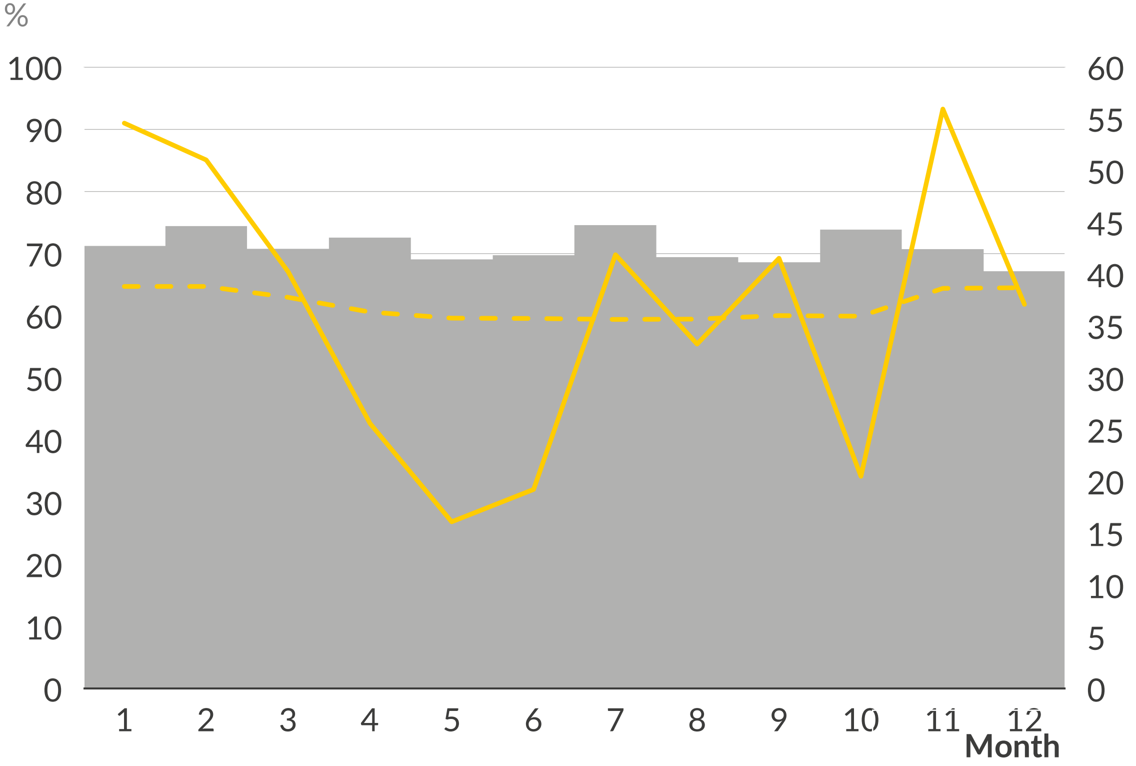


Wholesale electricity | Wholesale hydrogen | Support costs (incl. CM & subsidies) | Electricity infrastructure | Hydrogen infrastructure | CO2 infrastructure

Source: Aurora Energy Research

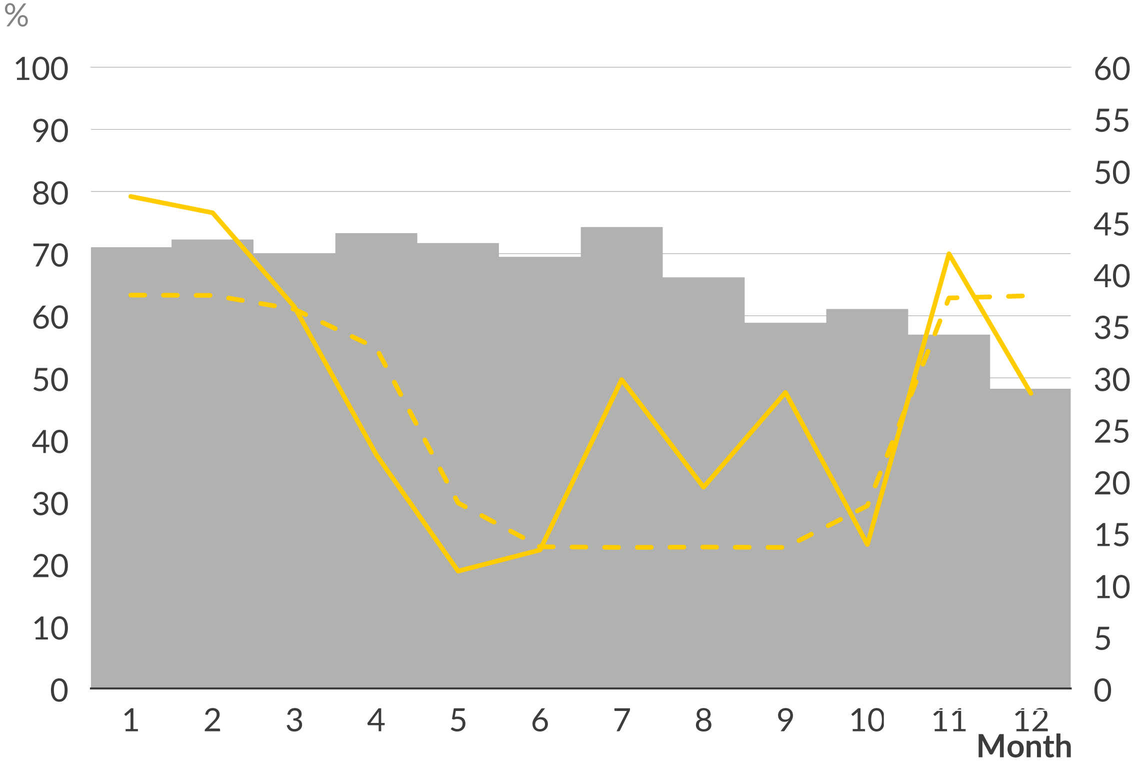
Seasonality in H_2 production from electrolysers paired with nuclear is minimal, with baseload operations preferred

Monthly load factor of SOE co-located with small nuclear 2045: scenario 3H. New nuclear techs



The load factor of the paired electrolyser has a weak relationship with captured power prices for the nuclear asset. Baseload operation at a c.70% load factor ensures maximum revenue in the H_2 market, to account for low overall captured prices in the power sector

Monthly load factor of SOE co-located with small nuclear 2045: scenario 4H. Strong nuclear strategy



In scenario 4H, electrolyser output declines toward the end of the year in order to capture slightly higher returns in the power sector once storage capacity has been filled over the summer months

Load factor Power price H2 price

Source: Aurora Energy Research

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V. The impact of differing levels of RES and nuclear on power and H_2 markets

VI. Risks to the transition

VII. Policy implications

VIII. Appendix

1. Modelling methodology
2. Additional model results
3. Additional assumptions

A Net-Zero scenario is consistent with low gas prices and high carbon prices

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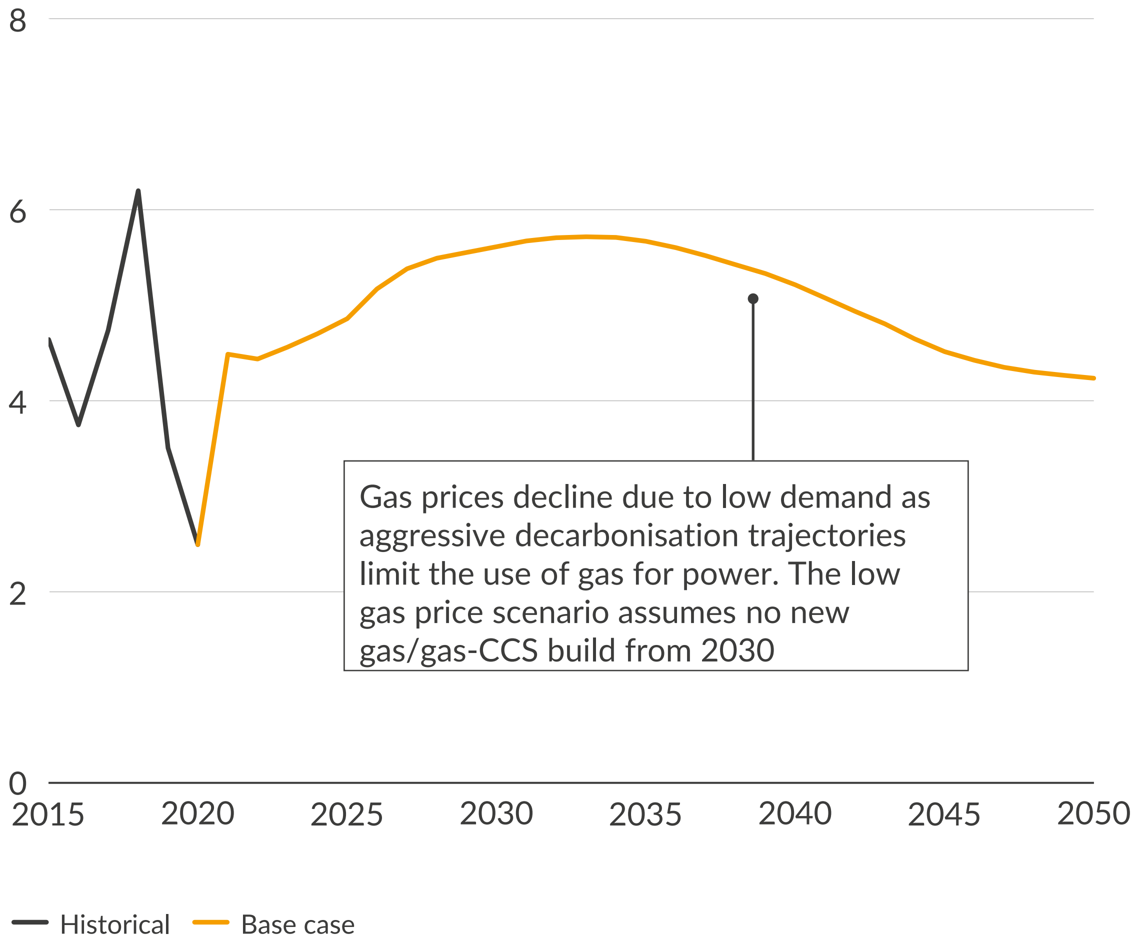
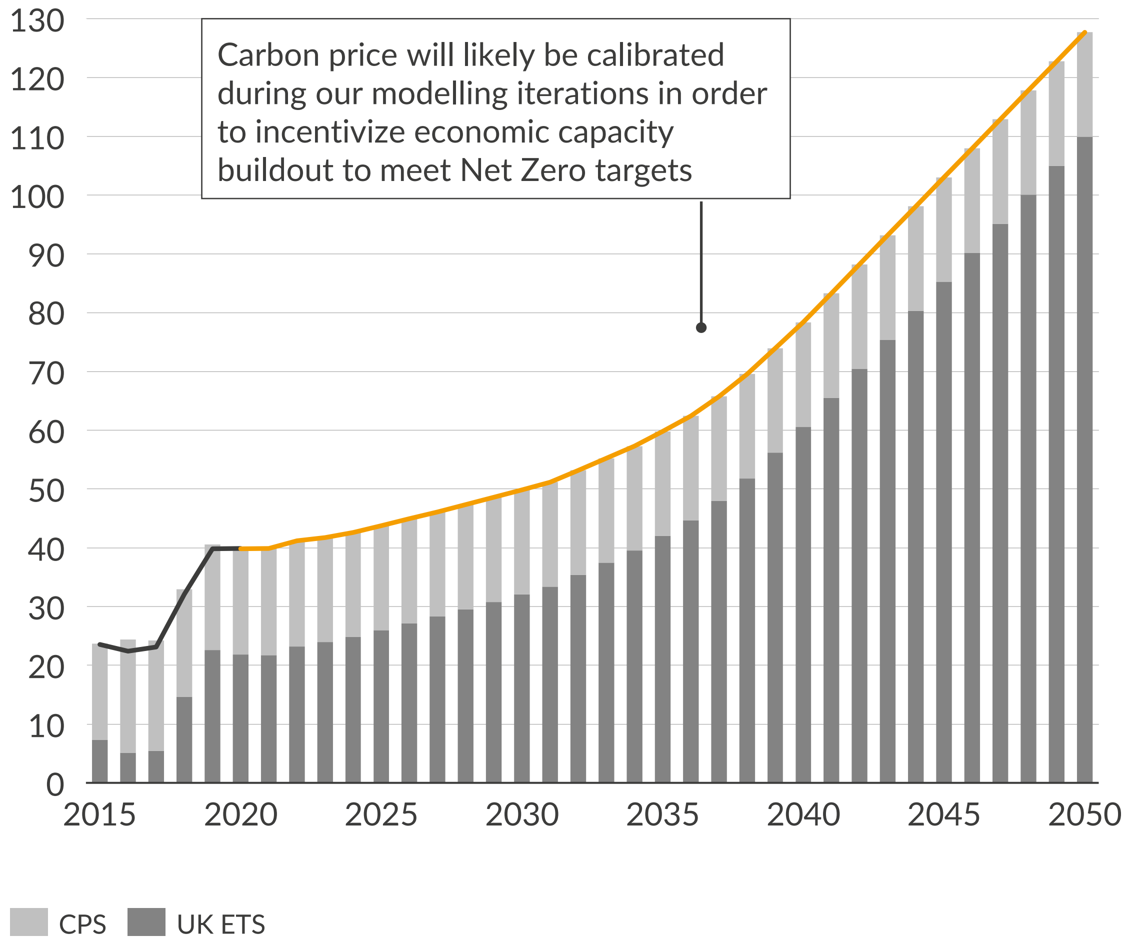
GB gas prices[1]
£/MMBtu (real 2019)



GB carbon prices[1]
£/tCO_2 (real2019)



1) For years 2021-2025, the prices shown take into account current futures prices for the years in question, with declining weights. Prices are displayed from 2021 onward, reflecting 30-day historical average as of 2 December 2020.

Source: Aurora Energy Research

Aurora's high hydrogen demand scenario sees significant adoption of across transport, heating and industry

Overview of Aurora's GB H_2 demand scenarios – scrutinised by over 18 market participants

	Low Hydrogen	Central Hydrogen (not modelled in this report)	High Hydrogen
Transport	Low penetration of FCEVs for private transport with moderate use of Hydrogen for in freight and public transport, where use of natural gas prevails. **18 TWh H2 in 2050**	Low penetration of FCEVs for private transport with moderate use of Hydrogen for in freight and public transport, where use of natural gas prevails. Adoption of H_2 for maritime and rail transport. **116 TWh H2 in 2050**	Moderate presence of H_2 in private transport, with higher uptake in public transport and freight. Adoption of H_2 for maritime and rail transport. **162 TWh H_2 in 2050**
Heating	H_2 serves certain areas in the country with advantageous conditions, but use is not widespread. **110 TWh H2 in 2050**	H_2 serves certain areas in the country with advantageous conditions but is moderately widespread. **153 TWh H2 in 2050**	Gas networks are converted to hydrogen with 14 million H_2 boilers present in 2050. **230 TWh in 2050**
Industry	H_2 use for high-grade heat applications along with CCS, electricity serving with low-grade heat requirements. Use as feedstock remains. **82 TWh by 2050**	Greater H_2 use for high-grade heat applications along with CCS and some low-grade heat requirements. Use as feedstock remains. **96 TWh by 2050**	H_2 used for both high and low-grade heat applications, as well as for industrial feedstock. **114 TWh by 2050**

Source: Aurora Energy Research

Heating could become the largest demand segment for H_2 but will closely compete with electric heat pumps

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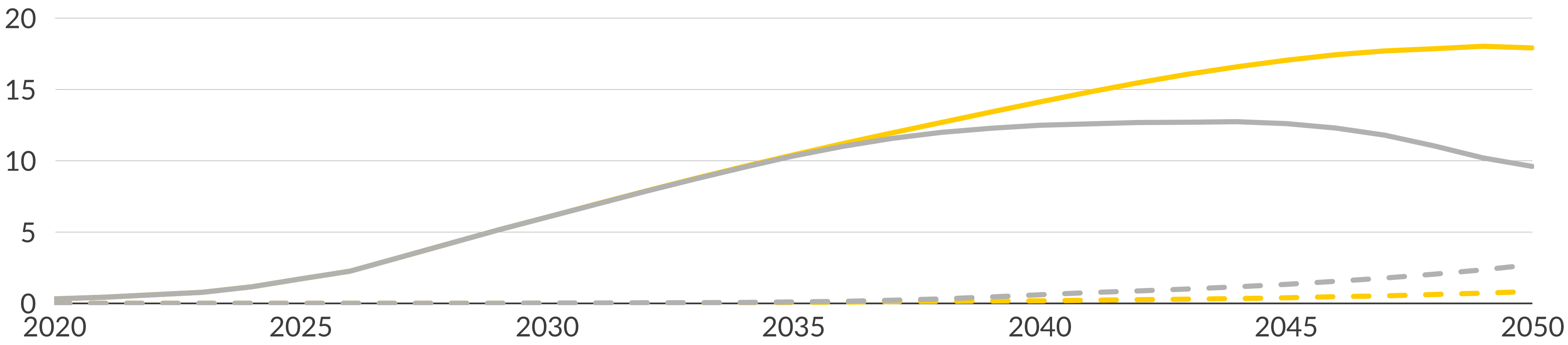
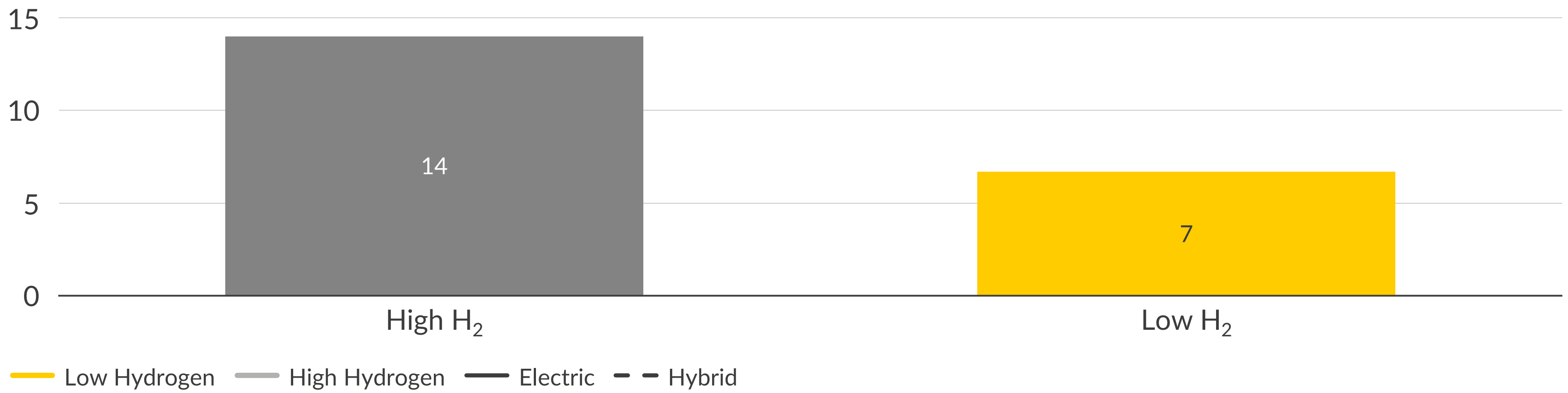
GB number of heat pumps
Millions of units



GB number of H_2 boilers by 2050
Millions of units



- Significant electrification of heat, despite extensive H_2 penetration will be required to reach net-zero.
- Electrification hurdles could drive H_2 uptake:
  - change in consumer preferences
  - high investment needs for energy efficiency[1]
  - power network upgrades.
- Use of H_2 in residential and commercial heating carries safety concerns and would require infrastructure adequation, and appliance replacement / refurbishment.
- Many projects in the UK and continental Europe show promise for these applications.
- Biogas is likely to play a role at a municipal level.

1) High grades of energy efficiency are required for heat pumps to work at high efficiencies and effectively condition spaces (without the need for heat pump oversizing).

Source: Aurora Energy Research

The entire road fleet is assumed to decarbonise by 2050, with the technology mix depending on the degree of hydrogen penetration

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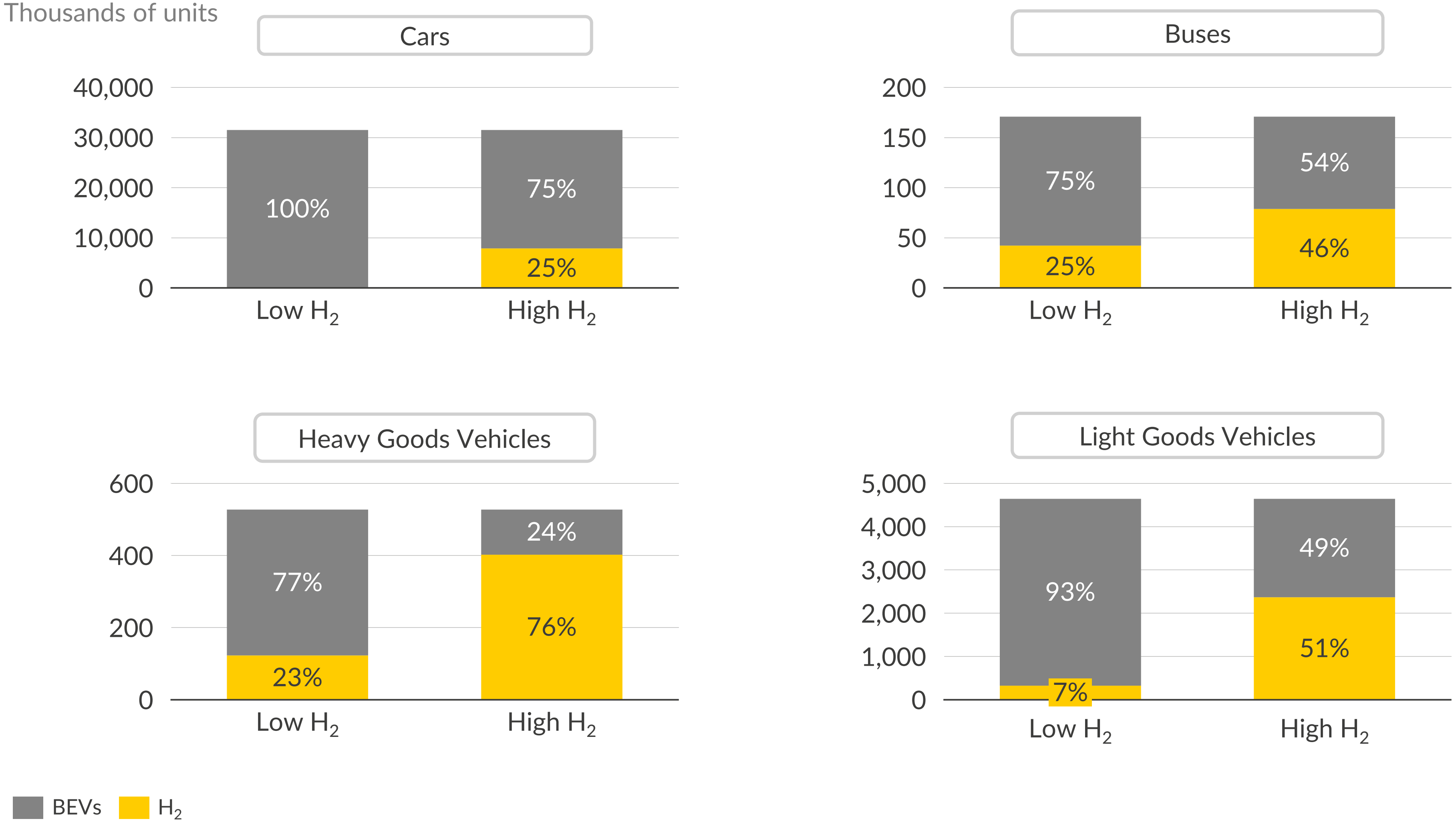
GB number of vehicles in 2050 by type and scenario
Thousands of units

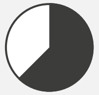


- For private cars, customer choice is expected to lean towards BEVs[1], with higher FCEV[2] uptake for high-mileage and commercial cars.
- The convenient of shorter H_2 refueling times relative to electric charging could drive uptake in light and heavy goods vehicles, as well as buses.
- The HGV segment is expected to be an early adopter of H_2 in the mid-2030s, followed by LGVs and buses in the early-2040s.
- H_2 demand in this sector will be highly dependent on the availability of refuelling infrastructure and is expected to compete with electrification throughout the analysis horizon.

1) Battery-Electric Vehicles; 2) Fuel Cell Electric Vehicles.

Source: Aurora Energy Research

Other transport segments were considered only in our High H_2 scenario, but likelihood of uptake is still uncertain

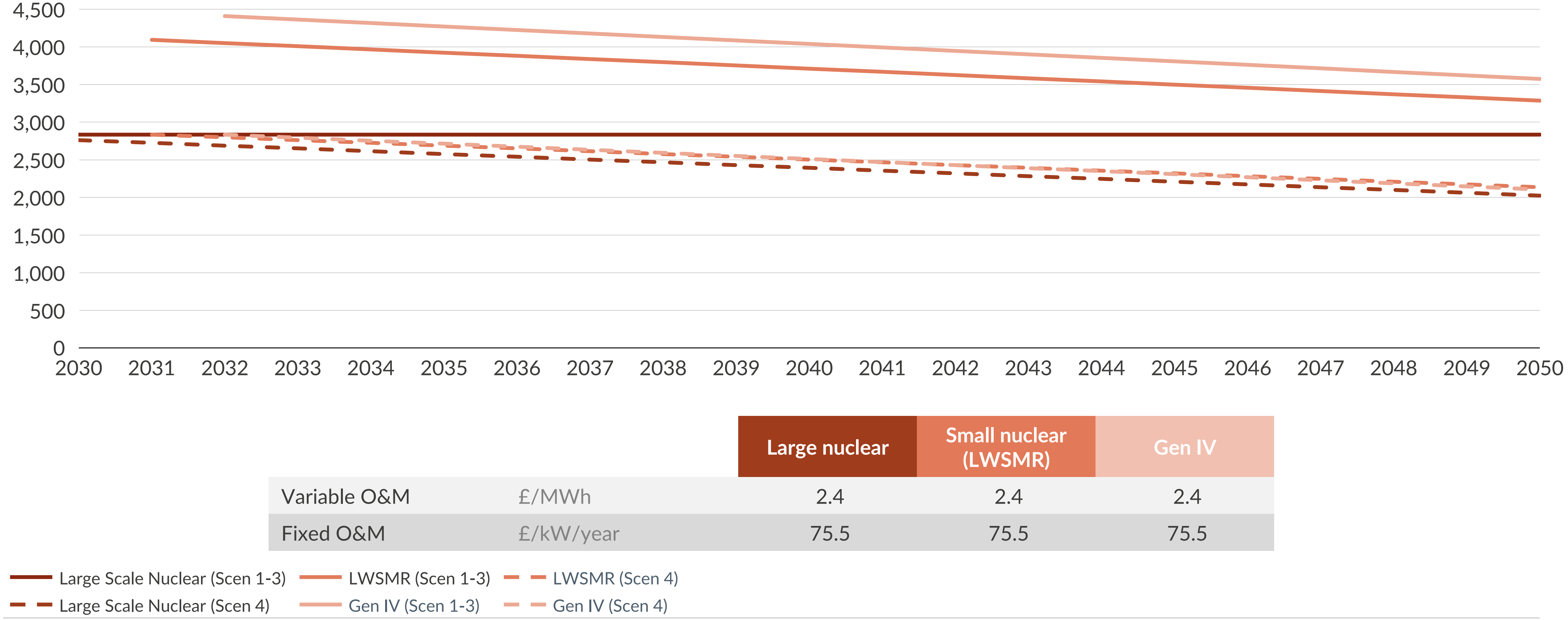
	GB outlook for H_2 Adoption	Likelihood	GB High H_2 Scenario Assumption[3]
Railway 	▪ Most promising options for rail decarbonisation include electrification and fuel switching to biofuels or H_2. ▪ There are concerns on supply limitations for biofuels and, in some areas, cost and infrastructure disruption could make electrification prohibitive, making a case for H_2 adoption.		**29 TWh by 2050** Equivalent to a third of all trains in the UK switching fuel use to H_2
Aviation 	▪ Prospective measures include increasing efficiency, reducing allowed cargo and using alternative fuels. ▪ Even with all these measures, the sector will likely face disruption or high abatement needs in order to reach Net Zero. ▪ Although small demonstration projects seek to prove feasibility, H_2 uptake in the sector is highly uncertain.		**No demand** was assumed for this sector in the high H_2 scenario, however higher H_2 demand scenarios could see adoption in aviation
Shipping 	▪ International Maritime Organisation has enacted a mandate to cut the sector's CO_2 emissions by 50% (relative to 2008 levels) by 2050. ▪ Organisations have stated that without the use of alternative fuels this is likely to be missed. ▪ Despite technical and financial challenges, potential for H_2 uptake in the sector is considered high, either through direct use or as ammonia.[1]		**11 TWh by 2050** Equivalent to the forecasted fuel demand for the sector[2]

1) ICCT; 2) BEIS' forecast extrapolated to 2050; 3) None of these segments were considered in our Low H_2 scenarios.

Sources: Aurora Energy Research, ICCT

Our scenarios explore different plausible trajectories for the development of advanced nuclear technologies

GB Nuclear – CAPEX
£/kW (real, 2019)



		Large nuclear	Small nuclear (LWSMR)	Gen IV
Variable O&M	£/MWh	2.4	2.4	2.4
Fixed O&M	£/kW/year	75.5	75.5	75.5

Sources: Aurora Energy Research, Lucid Catalyst

Global deployment of electrolysers will drive significant CAPEX, efficiency and lifetime gains

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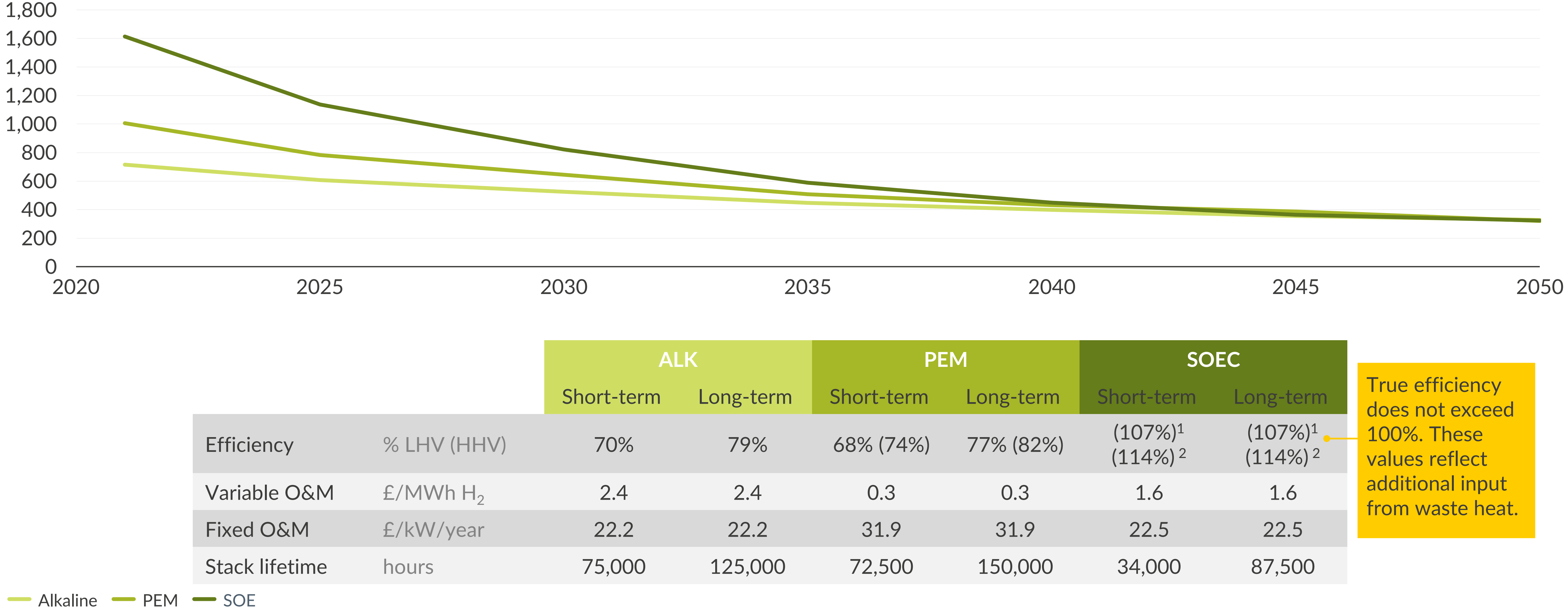
GB electrolyser – CAPEX
£/kW H_2 (real, 2019)



		ALK		PEM		SOEC	
		Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
Efficiency	% LHV (HHV)	70%	79%	68% (74%)	77% (82%)	(107%)[1] (114%)[2]	(107%)[1] (114%)[2]
Variable O&M	£/MWh H_2	2.4	2.4	0.3	0.3	1.6	1.6
Fixed O&M	£/kW/year	22.2	22.2	31.9	31.9	22.5	22.5
Stack lifetime	hours	75,000	125,000	72,500	150,000	34,000	87,500

True efficiency does not exceed 100%. These values reflect additional input from waste heat.

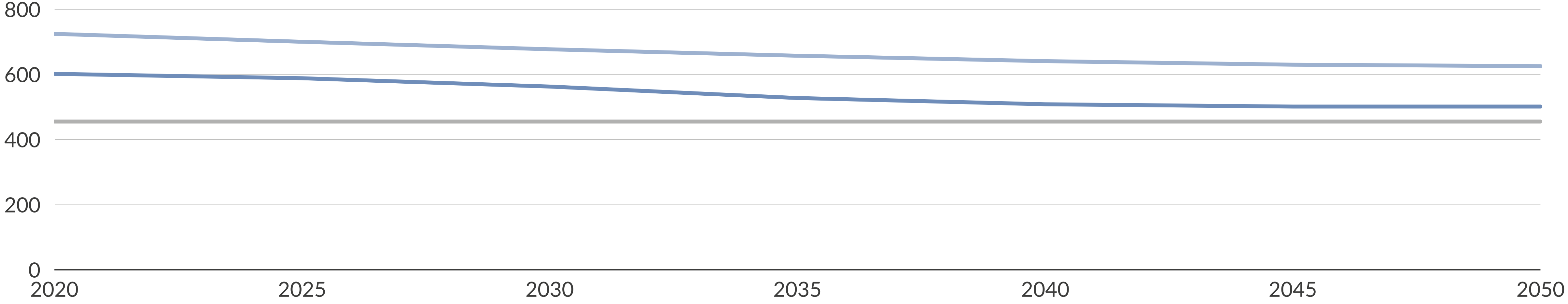
Notes: Variable O&M includes all non-fuel costs; 1) Low temperature heat efficiency; 2) High temperature heat efficiency.

Sources: Aurora Energy Research, IEA, CCC, IRENA, Element Energy, Jacobs Consulting, Equinor, Lucid Catalyst

Abated gas reforming can also benefit from deployment at scale, albeit to a lesser degree than electrolysers

GB gas reforming technologies – CAPEX

£/kW H_2 (real, 2019)



		SMR		SMR + Carbon capture		ATR + Carbon capture	
		Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
Efficiency	%	80%	80%	73%	76%	74%	80%
Variable O&M	£/MWh H_2	1.0	1.0	1.0	1.0	1.0	1.0
CO_2 capture	£/MWh H_2	-	-	2.4	2.4	2.4	2.4
Fixed O&M	£/kW/year	17.9	17.9	22.1	18.7	17.9	15.3
Reduction in CO_2 footprint	%	-	-	90%	90%	95%	95%
		GREY HYDROGEN		BLUE HYDROGEN			

Notes: Variable O&M includes all non-fuel costs (neither gas nor oxygen for ATR).

Sources: Aurora Energy Research, IEA, CCC, IRENA, Element Energy, Jacobs Consulting, Equinor

The continuation of historical learning rates will lead to significant cost declines, particularly for offshore wind and solar PV

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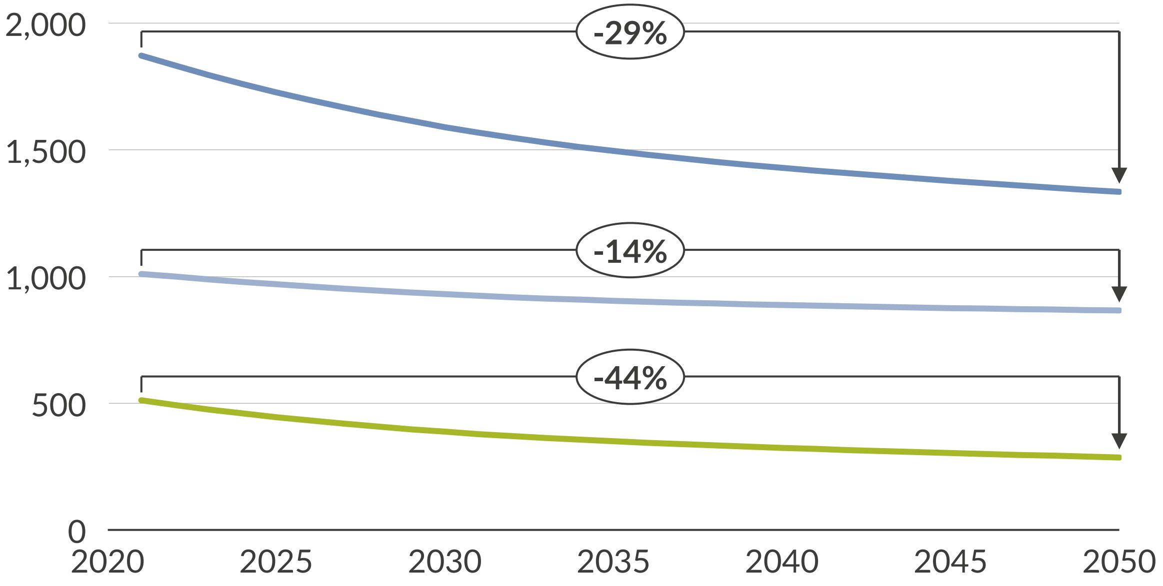
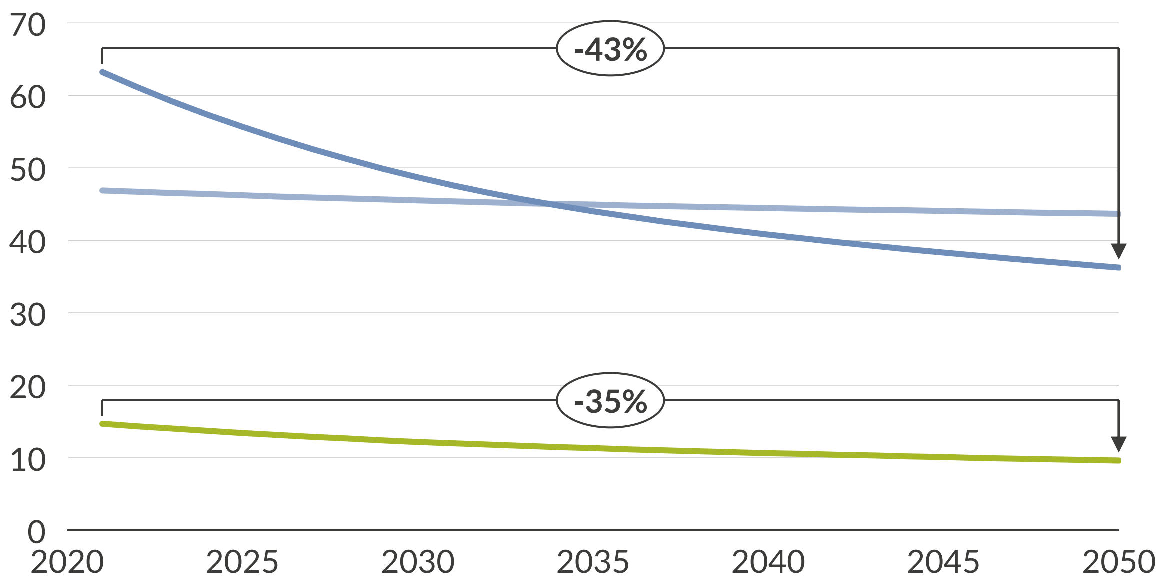
GB CAPEX
£/kW (real, 2019)



GB FOM
£/kW (real, 2019)



- Offshore wind benefits from more efficient supply chains and economies of scale as the industry matures, driving strong cost declines for turbines and supporting infrastructure.
- Cost reductions related to onshore wind turbine procurement and development are offset by rising grid connection costs.
- Solar CAPEX declines the most, driven mainly by expected module cost reductions.

Onshore Wind — Offshore Wind — Solar PV

Source: Aurora Energy Research

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