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Decarbonising hydrogen in a net zero economy

Executive summary

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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 Renewable Energy Sources (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?

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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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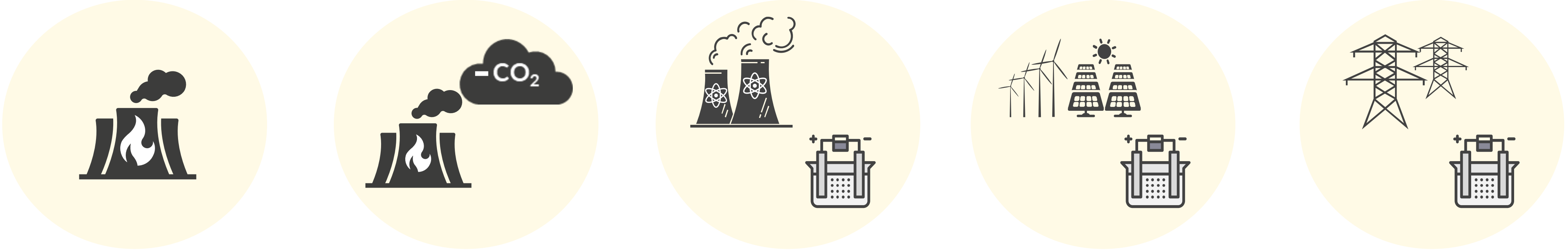
Sectors considered in report

	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

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

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.

Results included in executive summary (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

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

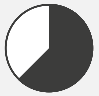
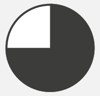
Two hydrogen demand scenarios reflecting differing levels of ambition are modelled in this report

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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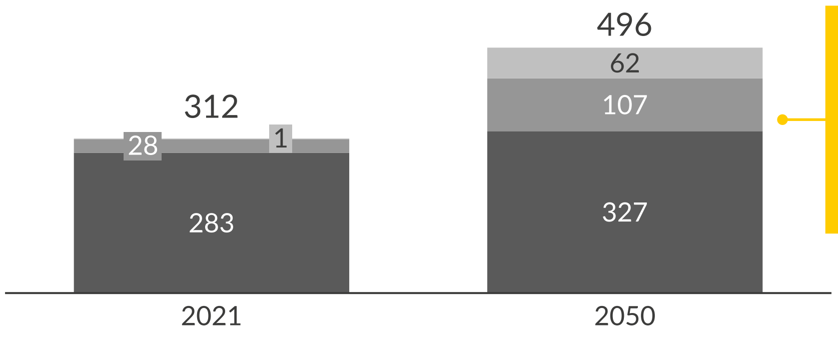
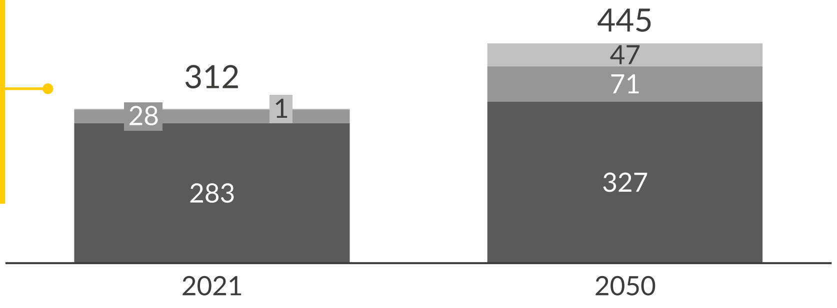
Low H_2 demand	High H_2 demand

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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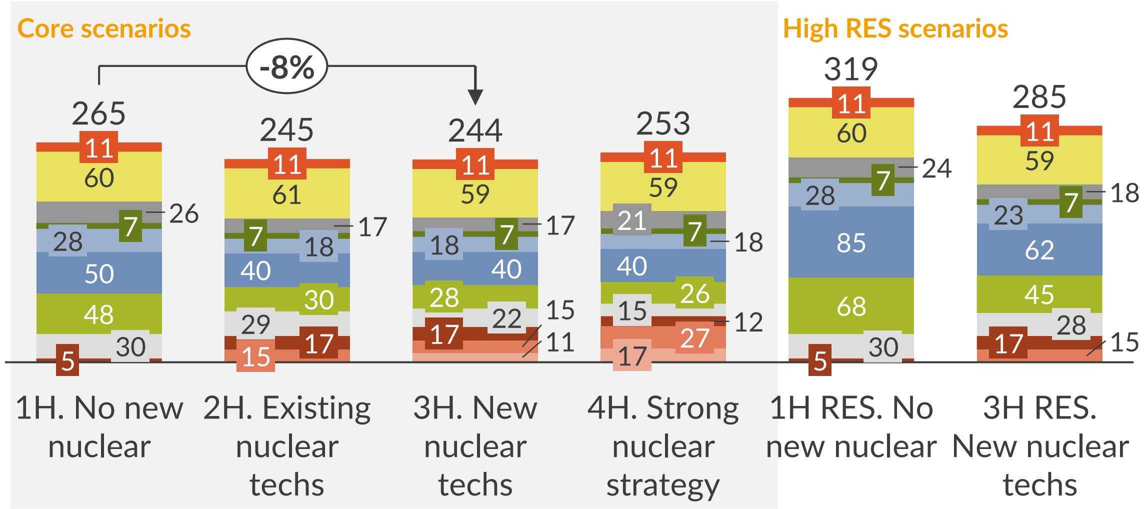
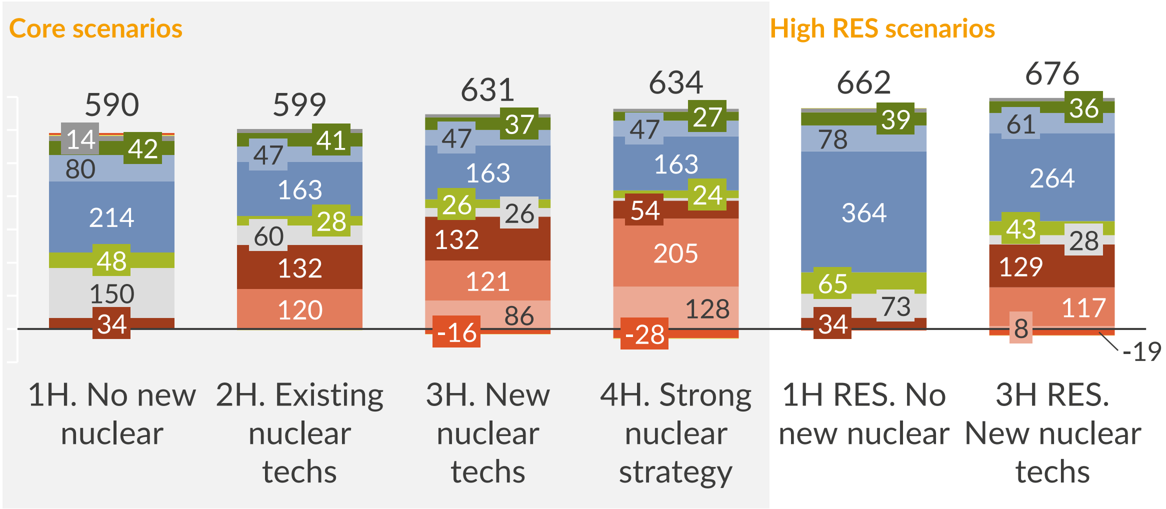
GB installed capacity in 2050
GW



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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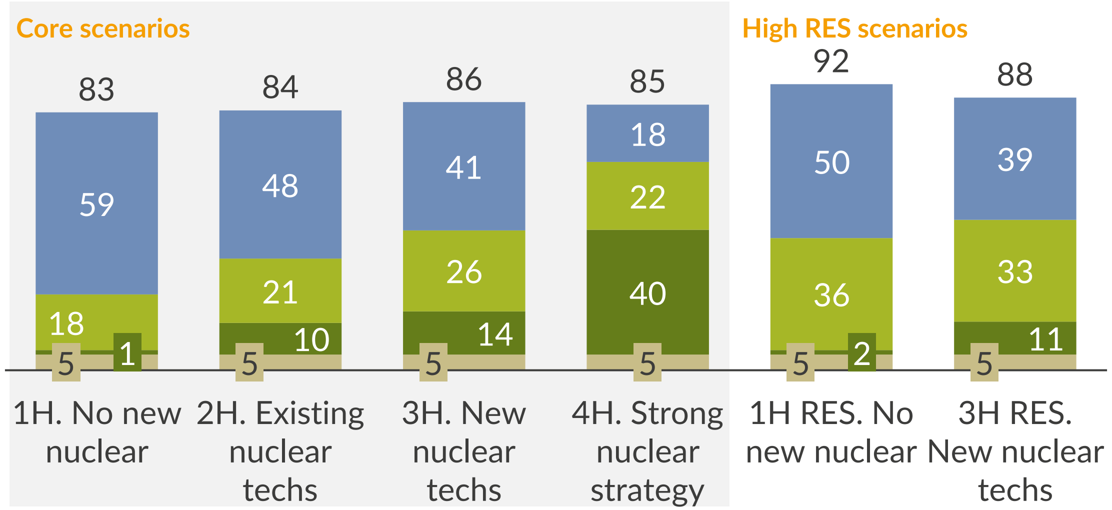
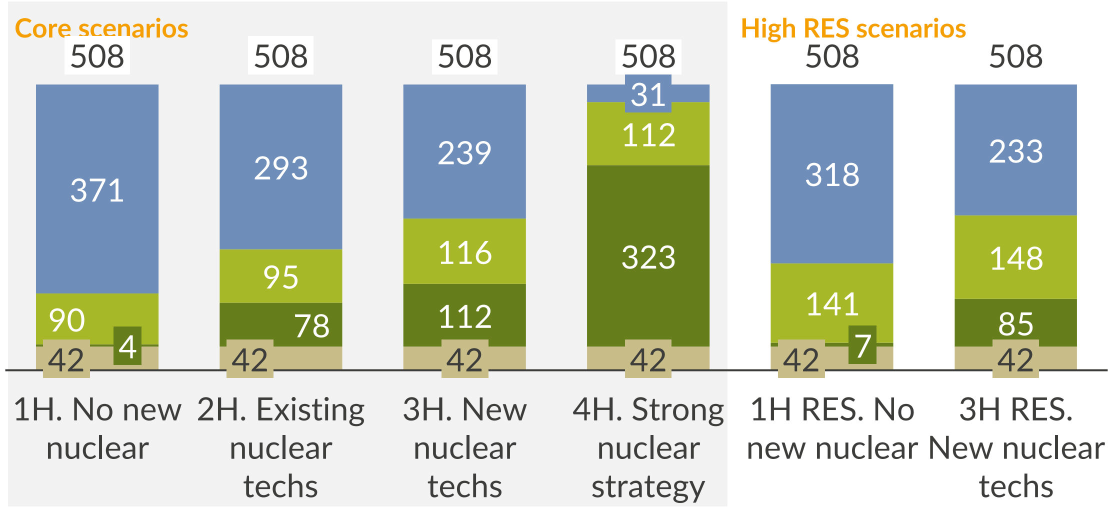
GB installed capacity in 2050

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

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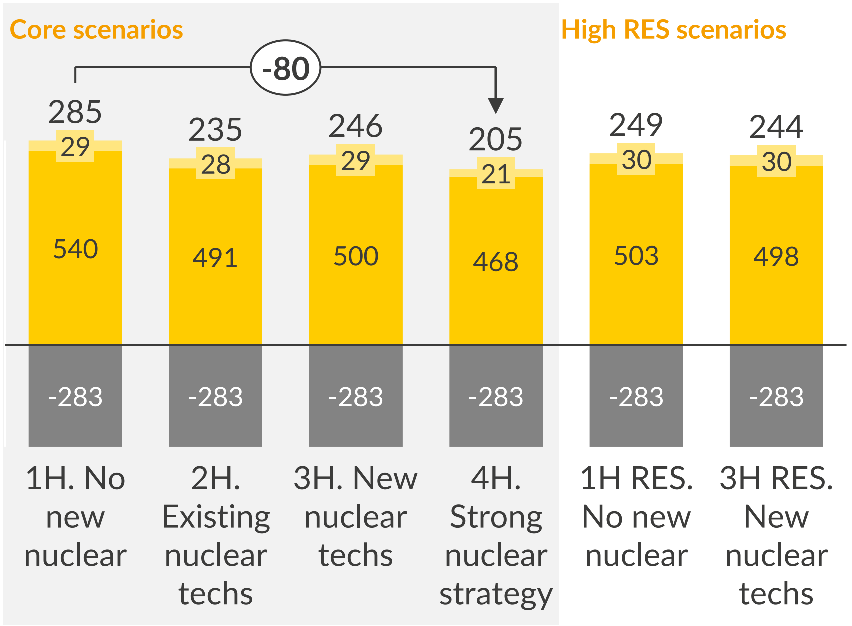
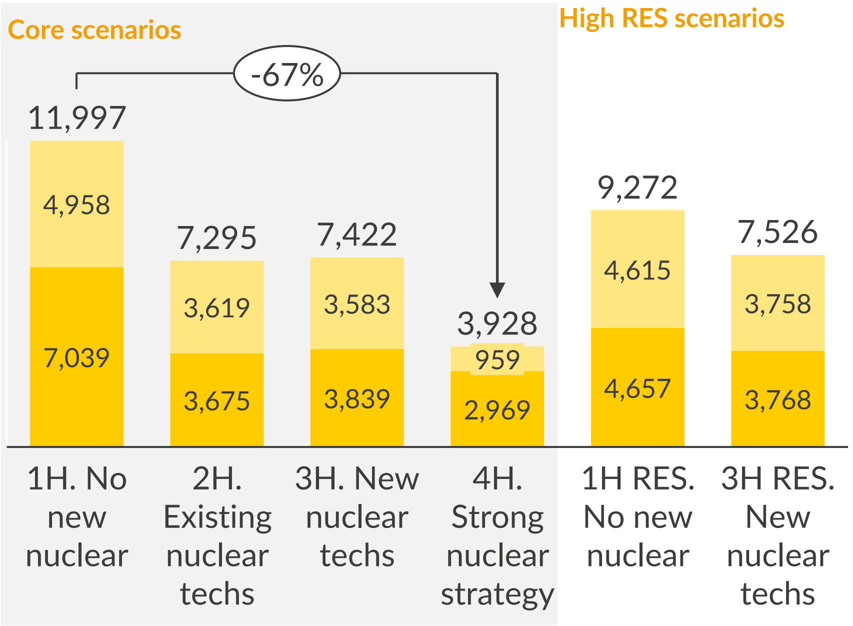
GB cumulative emissions from electricity and H_2 production (2021-50)
$MtCO_2$



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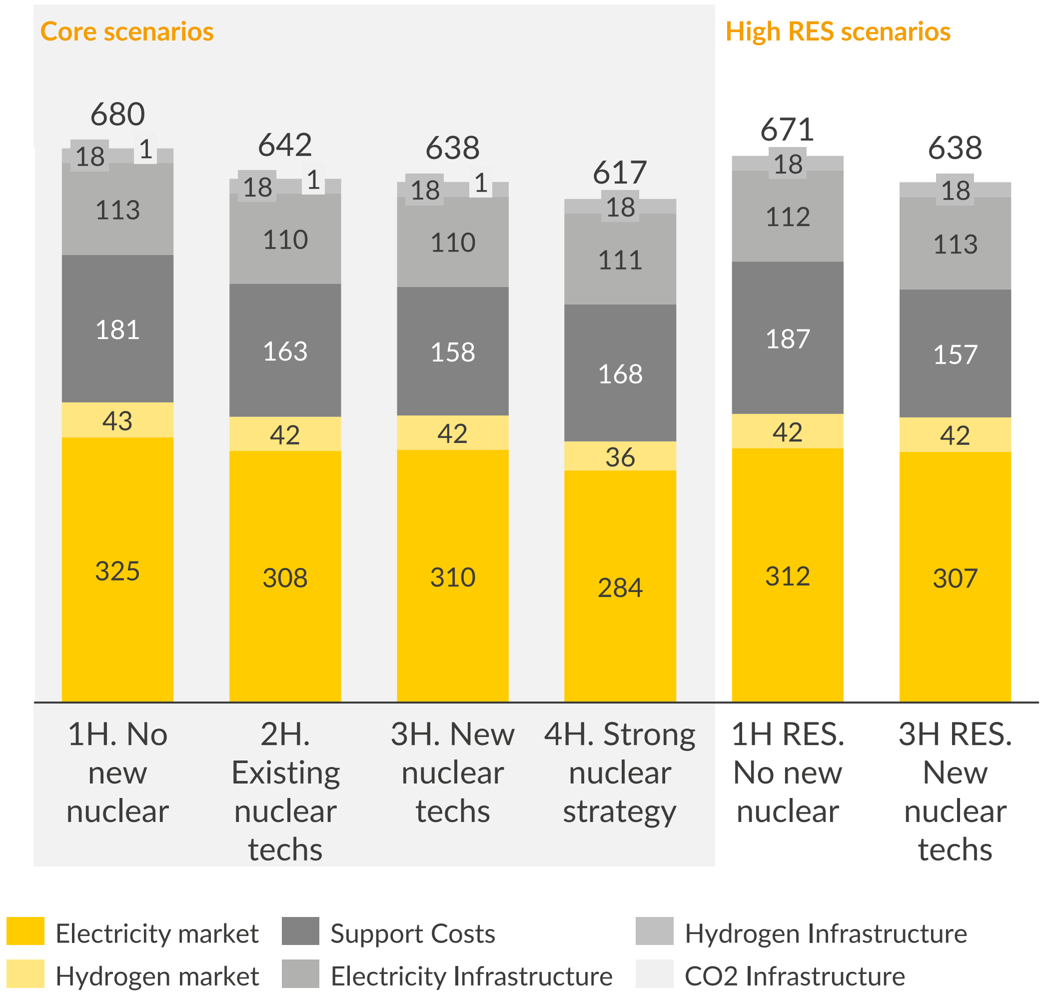
GB NPV total system spend from 2021 - 2050[1]
£bn



- **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

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