July 2024

Future Energy Scenarios:

ESO Pathways to Net Zero

ESO

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Foreword

Claire Dykta
Director of Strategy & Policy

The evolving dynamics of the energy system call for decisive action within the next two years to deliver the fundamental changes required to achieve a fair, affordable, sustainable and secure clean energy system by 2050. This means we must prioritise steps that will enable the delivery of cleaner, cheaper energy generation whilst ensuring a resilient system that delivers security of supply for consumers.

As the Electricity System Operator (ESO), we have set a target to be able to operate a net zero carbon electricity system for short durations by next year, which sets us up to be able to operate a clean power system throughout the year in the 2030s. Ongoing global conflict continues to create international uncertainty in energy markets, with the long-term consequences yet to be determined, and the cost-of-living and energy crisis continues to impact households and businesses across Great Britain.

Later this year, we will transform to become the National Energy System Operator (NESO). We will put our customers, homeowners, businesses and local communities at the heart of our work; building on the strong foundations of the ESO we will deliver a future where everybody has access to clean, reliable, affordable energy.

As NESO, we will take a holistic approach to planning and facilitating whole energy system decarbonisation. We will be involved in the strategic planning of gas and electricity networks, integrating them for the first time to develop a comprehensive whole system plan for future network development. We will develop a whole energy system view of future market direction so we can recommend actions to optimise markets across vectors and reduce costs for consumers. And we will also provide independent advice to Government and Ofgem on energy policy developments.

Decarbonisation of the energy system is the challenge of our generation. In recognition of the expansive industry transformation required to Great Britain's energy network planning, this year's Future Energy Scenarios (FES) framework has evolved from 'scenarios' to 'pathways' to explore narrower ranges and strategic, credible choices to propel us on the route to decarbonisation. This transition has also been reflected in our new publication name - Future Energy Scenarios: ESO Pathways to Net Zero.

FES creates the foundation upon which our future network investment plans will be built. We look forward to working with industry, the Government, Ofgem and our stakeholders and customers as we transition to NESO and build upon our analysis and insights to deliver on our critical role for society and the economy.

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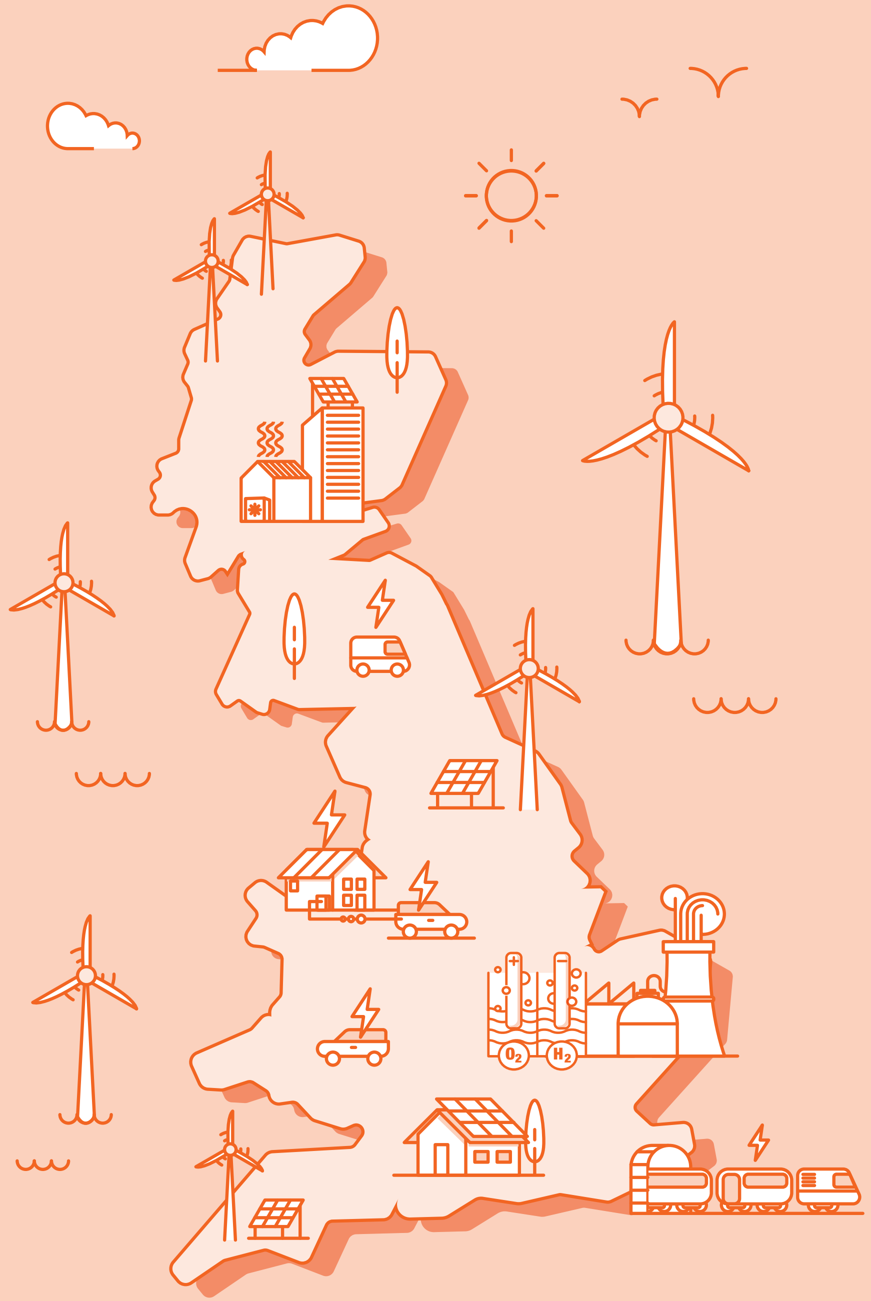
Introduction



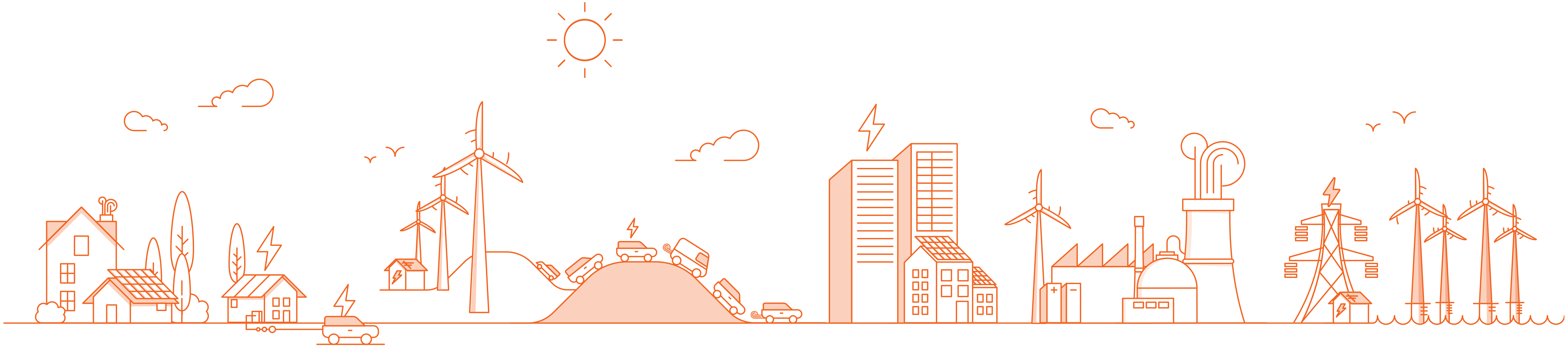
Overview

"Decisive action is needed within the next two years to deliver the fundamental change required for a fair, affordable, sustainable and secure net zero energy system by 2050."

It is time to go further and faster. To help enable this, our analysis is evolving to align with the strategic network investment needed across Great Britain. While we continue to produce supply and demand projections, we have transitioned from scenarios to pathways.

FES was originally established to provide data for input into network planning processes, with our Five Year Forecast designed for use in security of supply (SoS) planning and capacity market auctions. Our framework must continue to underpin these critical planning activities and recognise the wider applications our publication supports, including various regulated energy system activities alongside policy recommendations and private sector investment.

Our net zero pathways identify three credible, strategic routes to reach net zero. These pathways outline a narrower range of outcomes than our previous scenarios, to help drive forward Great Britain's strategic investment needs and to support the rapid and fundamental change that is required.



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The evolution of Future Energy Scenarios framework

FES has evolved over the years. To access the FES archives visit the **FES homepage**.

2011

Future Energy Scenarios is published for the first time, moving away from National Grid's single forecast of gas and electricity demand.

FES 2011 features three scenarios - Gone Green, Accelerated Growth & Slow Progression.

2013

FES 2013 retires the Accelerated Growth scenario, and develops Gone Green and Slow Progression.

The axioms that underpin the two scenarios are published as part of the publication framework.

2014

FES 2014 expands its framework to four scenarios - Gone Green, Low Carbon Life, Slow Progression and No Progression.

These scenarios reflect the energy trilemma, and are plotted on a 2D axis of affordability and sustainability.

2015

FES 2015 maintains a four-scenario approach with Gone Green, Consumer Power, Slow Progression and No Progression.

The scenarios are plotted on a 2D axis of prosperity and green ambition, and the axioms are replaced with five high-level primary assumptions - economic, political, social, technological and environmental.

2017

The FES framework develops once more, with the scenarios now named Two Degrees, Consumer Power, Slow Progression and Steady State.

The scenarios remain on a 2D axis of prosperity and green ambition.

2018

The FES 2018 framework shifts while maintaining four scenarios: Community Renewables, Two Degrees, Consumer Evolution and Steady Progression.

These scenarios are now based on the speed of decarbonisation and level of decentralisation.

2020

A set of four new scenarios are published in FES 2020, named Leading the Way, Consumer Transformation, System Transformation and Steady Progression.

These scenarios are based on the level of societal change and speed of decarbonisation.

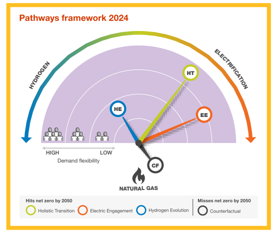
2022

The FES 2022 framework stays the same, but Steady Progression is renamed to Falling Short.

2024

Our framework shifts from scenarios to pathways, featuring three new net zero pathways: Holistic Transition, Electric Engagement and Hydrogen Evolution.

Our framework also features a Counterfactual, which does not meet net zero.



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Future Energy Scenarios 2024 framework

Our enhanced framework and net zero pathways

Previous FES frameworks assessed the future of energy supply and demand through scenarios, exploring a wide range of credible outcomes for how Great Britain could meet net zero. Our new framework marks a move from reactive scenarios to strategic network planning and seeks to identify credible, strategic routes to net zero.

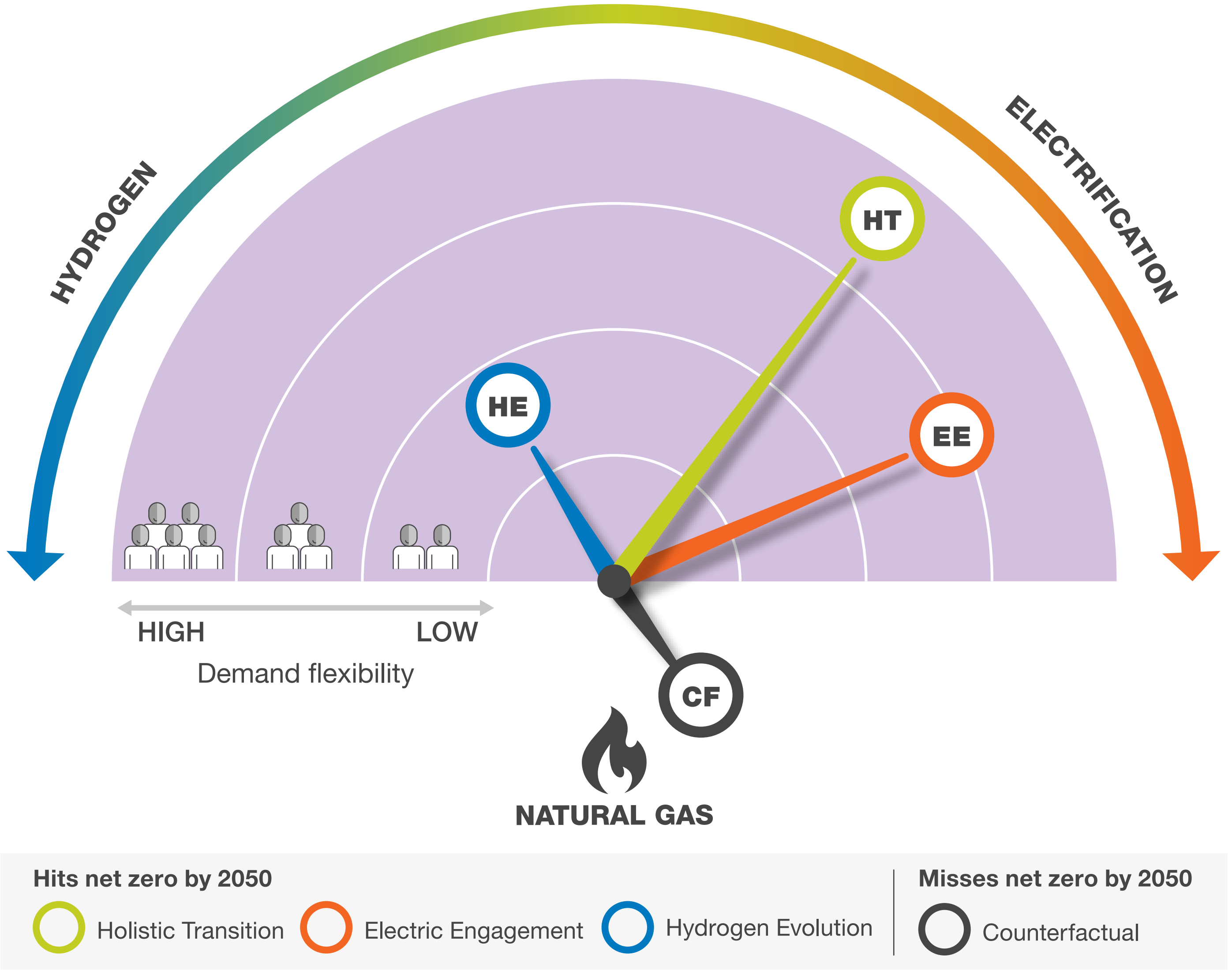
With this in mind and through consultation, analysis and stakeholder engagement, our new framework:

- Replaces the four scenarios with three net zero 'pathways'
- Includes a 'Counterfactual' which does not meet the 2050 net zero target
- Retains our Five Year Forecast (5YF) in our data workbook.

The range presented in our pathways no longer represents the widest credible possible outcomes, but a narrower set of routes to net zero. It is important to note that there is still considerable uncertainty and there remains some variation across the pathways in some key areas, such as the level of consumer engagement and interactions between different fuels, as shown on our new framework diagram to the right. Further areas, such as the energy supply mix, are shown in our "Comparing our pathways" summary, which can be found in the Executive Summary chapter *(page 20)*.

Our pathways are a subset of the envelope of possible outcomes. They are ambitious and will require decisive action if we are to move away from the Counterfactual and achieve net zero targets.

Pathways framework 2024



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The pathways and our modelling

How do our new pathways differ from the previous scenarios?

Scenarios	Pathways
Range of credible outcomes for how Great Britain could meet net zero. Not all scenarios meet net zero.	Routes showing strategic direction to net zero. All pathways must meet net zero.
Wide range of possible outcomes.	Provide a narrower, strategic range.
Create scenarios that are cost agnostic.	Bring in additional economic modelling.
Potential efficiency savings through interactions between electricity and hydrogen networks are highlighted but not assessed.	Whole system optimisation fundamental to finding most efficient future energy system across all energy vectors (*in development for future iterations*).
Built to emissions and SoS targets.	Consider whole energy trilemma.
Seek out the edges of credibility to ensure scenario range is wide enough to encompass uncertain future.	Explore a narrower range of outcomes to drive more strategic, credible routes to net zero.
Assume unconstrained network.	Assess the impact of network constraints.

Our modelling

Our modelling starts with a view of how demand will change into the future. This is conducted through sub-sector models which inform the levels and profiles of electricity, natural gas, hydrogen and other vectors.

Our FES energy demand analysis directly models Great Britain electricity, gas, hydrogen and bioenergy demand for road transport, heat, industry, commercial and residential end uses.

For sectors that fall outside our modelling, we use the Climate Change Committee (CCC) "Balanced Pathway" from its Sixth Carbon Budget analysis, adjusted to reflect the latest recorded sector emissions from 2022.

This view of demand provides the target that supply side models must meet in optimising the production of energy, dispatch of assets and utilisation of flexible solutions.

For more detail on our modelling process, see our "FES Modelling Methods 2024[1]" document on the FES pages of the National Grid ESO website. Our "FES 2023 Pathway Assumptions[1]" and "FES 2024 Data Workbook[1]" are also published on the same website, which provides a summary of our modelling inputs and assumptions.

1 nationalgrideso.com/future-energy/future-energy-scenarios-fes/fes-documents

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Stakeholder engagement

Engaging with our stakeholders for FES 2024 began in the summer after the publication of FES 2023.

Stakeholder engagement underpins our modelling and analysis for every FES cycle, and for FES 2024 we engaged with **2,627 stakeholders** through various methods, representing a total of **561 organisations**. Throughout the year, these engagement activities have included the FES 2023 physical launch, bilateral meetings, our Call for Evidence survey, our London-based Table Topic Talks event, and other ongoing engagement through our FES email.

To ensure we maximise the breadth of stakeholder views, we continually engage with all nine stakeholder categories identified for FES, with organisations across sectors including motor manufacturing, home building associations, universities, energy suppliers, trade bodies and more.

You can find our full suite of FES 2024 documentation on the National Grid Electricity System Operator website:

- FES 2024 Data Workbook
- Future Energy Scenarios: Pathways at a Glance
- Future Energy Scenarios: ESO Pathways to Net Zero
- Energy Background Document
- FES 2024 Pathway Assumptions
- FES Modelling Methods 2024

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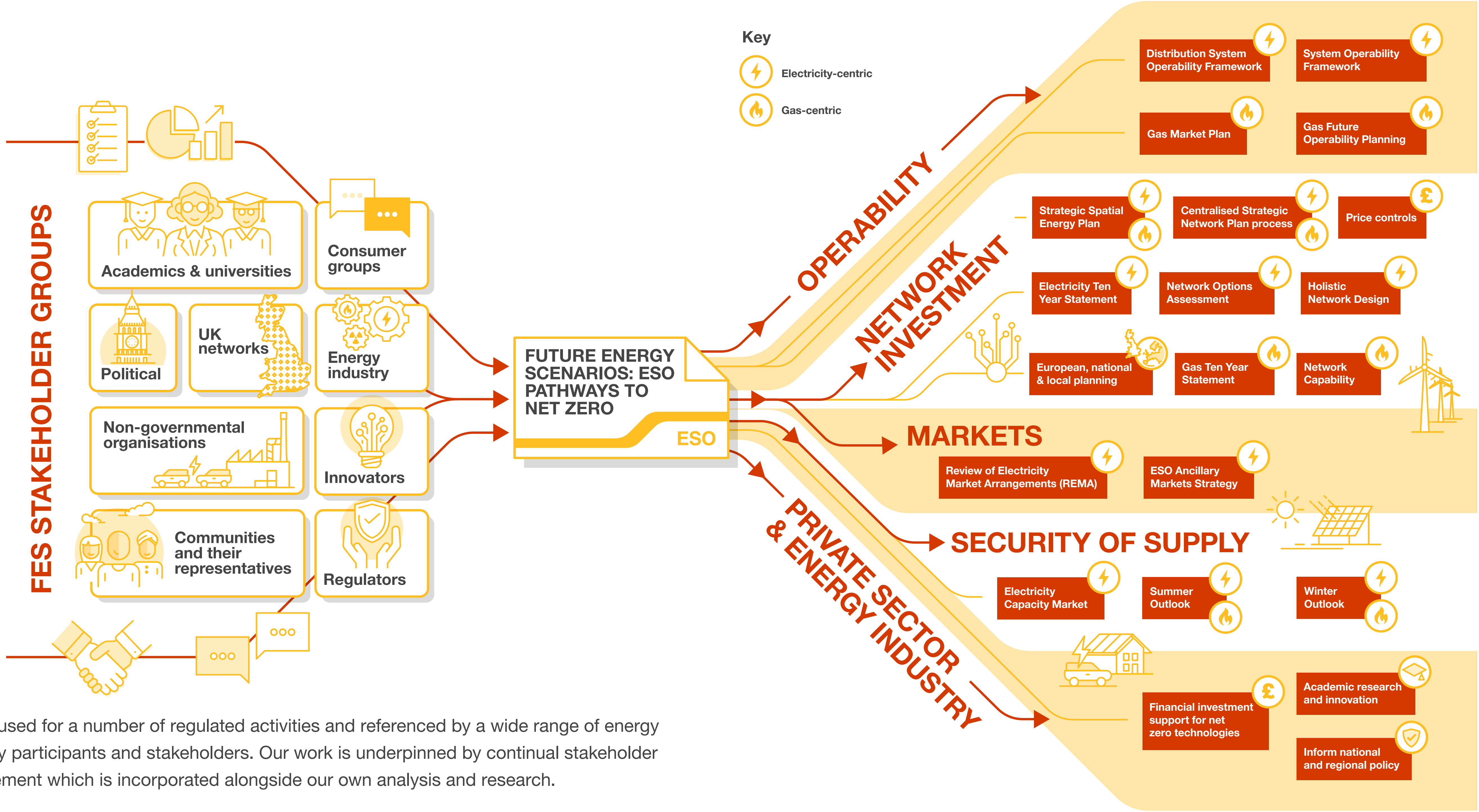
Who uses Future Energy Scenarios



FES is used for a number of regulated activities and referenced by a wide range of energy industry participants and stakeholders. Our work is underpinned by continual stakeholder engagement which is incorporated alongside our own analysis and research.

Establishment of the National Energy System Operator

As part of the plan to decarbonise Great Britain, the current Electricity System Operator (ESO) will transition to the National Energy System Operator (NESO) in 2024.

The enhancement of the FES 2024 framework forms part of this wider industry overhaul, with our modelling and analysis used as a key input in various strategic network planning processes, outlined over the following three pages.

The National Energy System Operator's roles

NESO will have a primary duty to act in the manner it considers best to promote net zero, energy security and efficiency and economy. The roles and responsibilities of the new organisation will include:

- Whole energy network planning – Strategic Spatial Energy Plan (SSEP) and Regional Energy Strategic Planner (RESP)
- Whole energy system coordination role for improving security and resilience of gas and electricity systems
- Onshore electricity network competition
- Whole energy market development
- Provision of independent advice to Ofgem and UK Government.

Crucial to its responsibilities, NESO will consider the effect of its activities on customers and local communities, competition in the energy sector, the whole energy system and on the facilitation of innovation.

	Day 1	Full ambition
STRATEGIC PLANNING	Plan gas and electricity networks	Provide whole system view of the energy sector
MARKET DEVELOPMENT	Support Department for Energy Security and Net Zero (DESNZ) with market development across gas and electricity	Advise on whole energy market strategy
RESILIENCE	Identify gaps, risks, interactions and opportunities within a whole system	Coordinate emergency response
SECURITY OF SUPPLY	Enable electricity security of supply and advise on gas security of supply	Enable security of supply across Great Britain's whole energy system
NET ZERO ENERGY INSIGHTS	Deliver energy insights and advice to Government	Advisory grows into new vectors

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Establishment of the National Energy System Operator

Strategic Network Planning

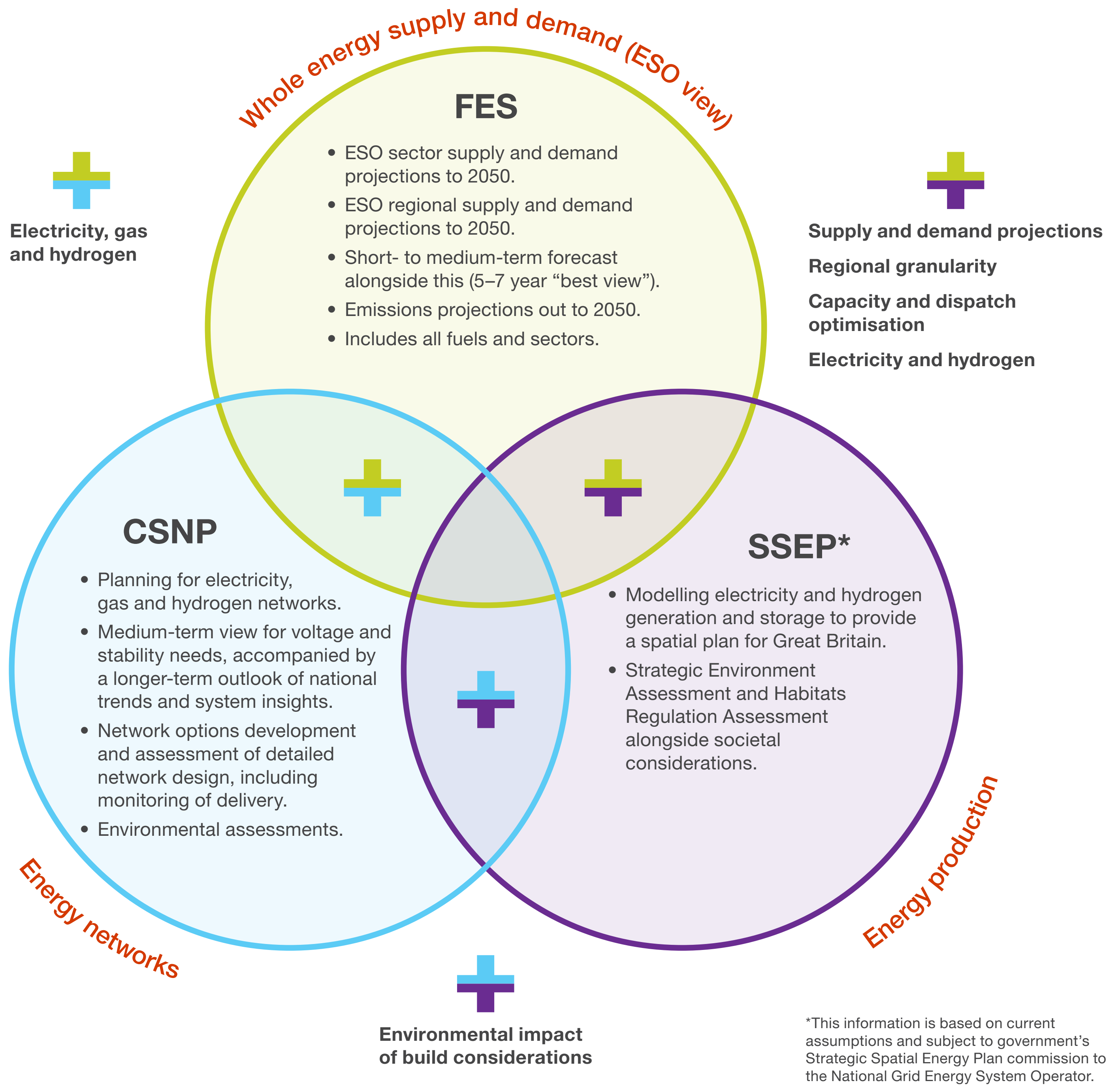
As NESO, we will coordinate system design and planning efforts across the whole energy industry so that planning and investment decisions can be optimised to deliver Britain's net zero objectives at the lowest sustainable cost to consumers. This means bringing together the strategic planning of the gas and electricity networks and recommending whole energy solutions to resolve network constraints across gas, electricity and hydrogen. As the strategic energy planner, NESO will have responsibility for the Centralised Strategic Network Plan (CSNP), SSEP and RESP processes.

Strategic Spatial Energy Plan

The SSEP is intended to bridge the gap between government policy and network development plans across the whole energy system (both land and sea) across Great Britain by providing greater clarity for industry on the shape of the future energy system.

When commissioned, the first iteration of the SSEP will cover power generation, including offshore generation in British waters and hydrogen assets to determine the optimal location of energy infrastructure needed.

The SSEP will act as a blueprint from which more granular plans, such as the CSNP, will flow.



*This information is based on current assumptions and subject to government's Strategic Spatial Energy Plan commission to the National Grid Energy System Operator.

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Establishment of the National Energy System Operator

Centralised Strategic Network Plan

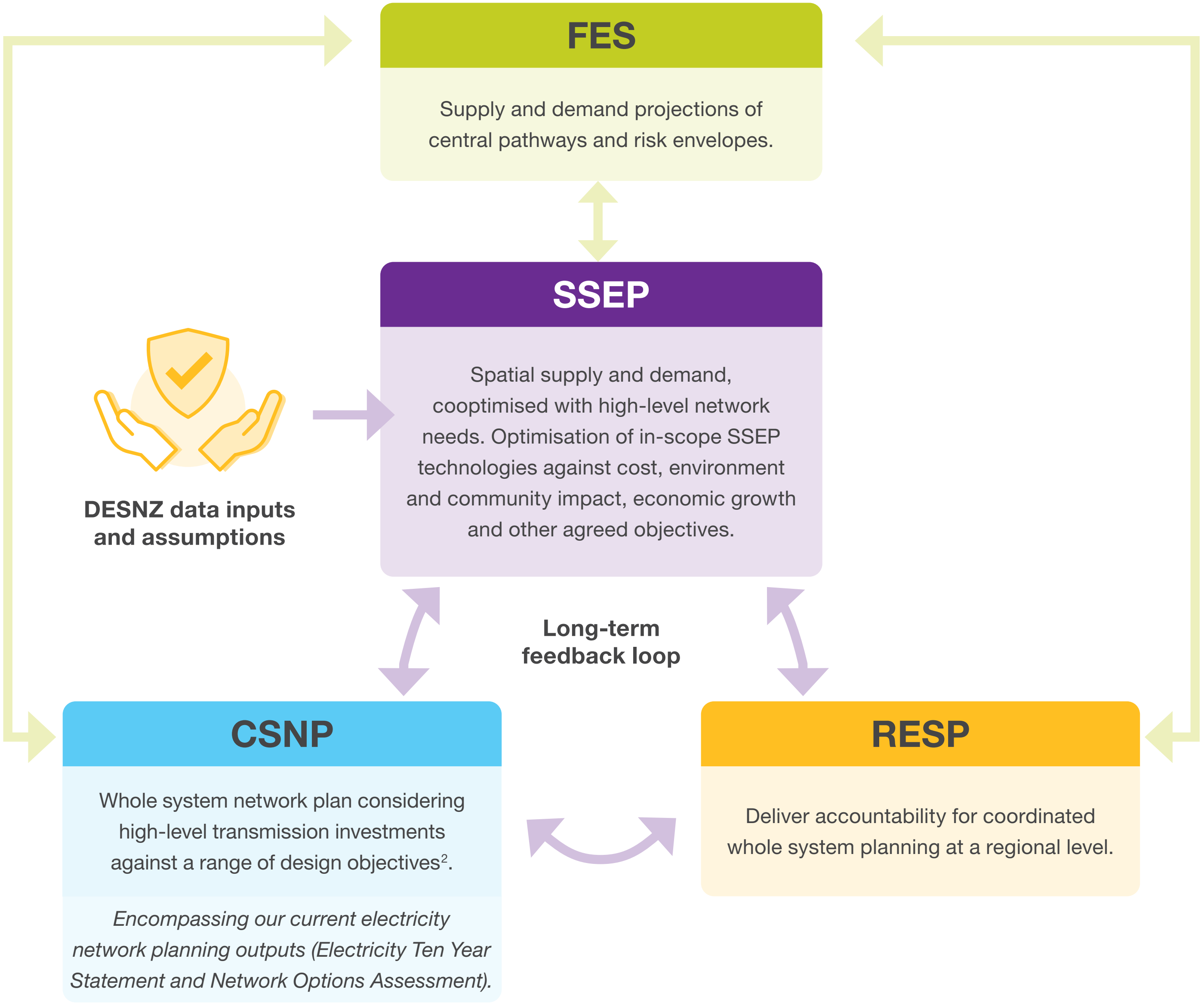
We are accountable for delivering the CSNP and providing an independent, coordinated and longer-term approach to wider network planning in Great Britain to help meet the UK Government's net zero ambitions. The CSNP will consist of a collection of plans focussing on electricity transmission network planning, as well as developments in natural gas transmission and hydrogen.

Regional Energy Strategic Planner

The regional energy strategic planning role is being established to support the rapid decentralisation and decarbonisation of generation and demand at a local level. RESP will coordinate regional planning in a cross-vector way, considering local priorities and aligning with national energy planning and ensuring that investment is made in a cost-effective manner. Ofgem is leading the detailed design of RESP and is developing its function, governance and boundaries. It will publish the outcomes as part of a policy framework consultation in 2024.

Future Energy Scenarios: Pathways to Net Zero 2024 will feed into all aspects of strategic network planning whilst continuing to play an important role in short-term market mechanisms, innovation, business planning and more. Long-term pathway projections will be used within the CSNP.

High-level interactions across FES and strategic planning



2 Encompassing our current electricity network planning outputs (ETYS and NOA).

Assessing the landscape

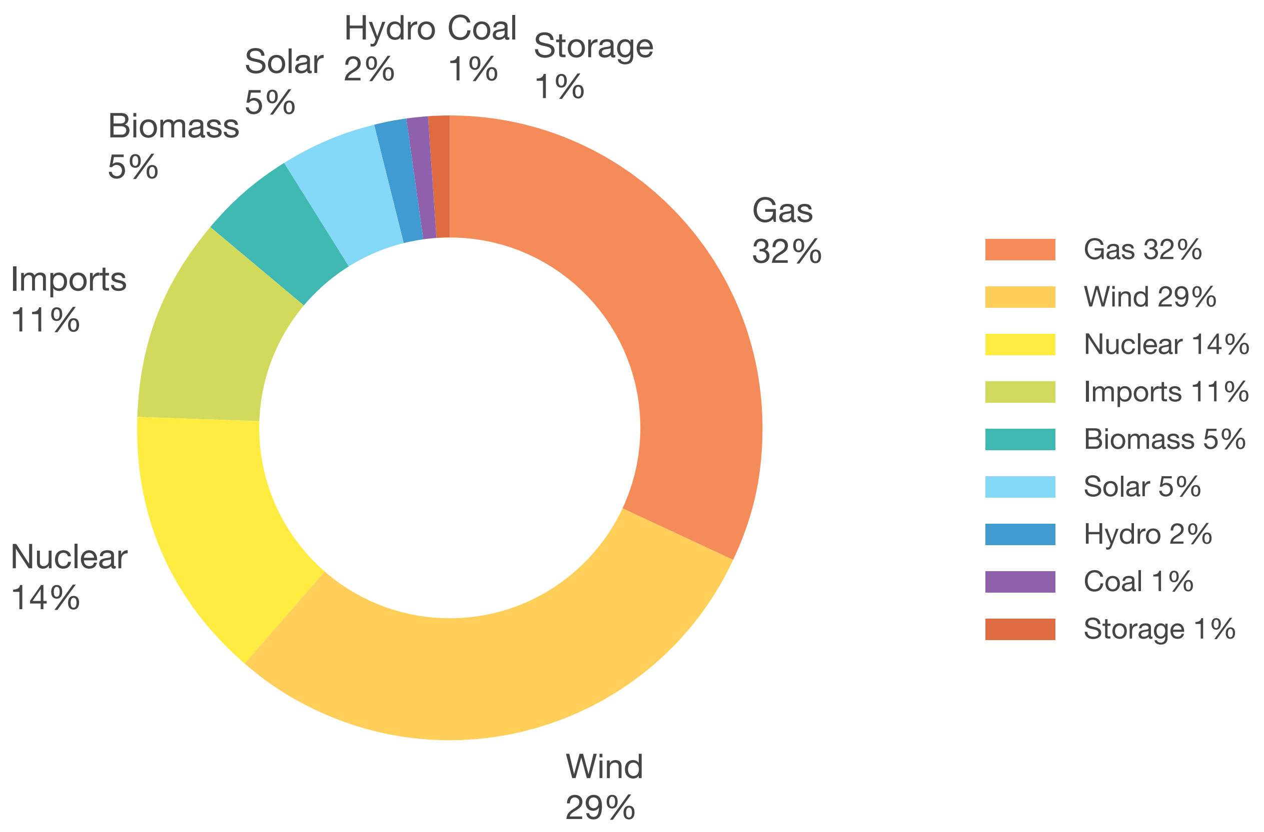
Reaching net zero greenhouse gas (GHG) emissions by 2050 is critical to limiting the negative impacts of climate change.

Progress in the power sector

2023 was a remarkable year for renewable energy generation in Great Britain. There was an unprecedented drop in fossil fuel use, with coal accounting for just 1% of energy generated and gas usage the lowest since 2015. Across the year, zero-carbon electricity sources also played a vital role in the generation mix and more than 50% of electricity came from these sources in January, July and October. We still rely heavily on energy from fossil fuels for security of supply and gas made up the largest share of the energy mix (32%) in 2023. However, high usage of renewables is enabling the carbon intensity of electricity generation to continue to fall.

On 5 April 2024 at around midday, we achieved a new low carbon intensity record of 21gCO_2/kWh, beating the previous record set on 18 September 2023 of 27gCO_2/kWh. Download our **carbon intensity app** to see real-time generation stats and our records.

Figure I.01: Electricity supply in 2023



Assessing the landscape

Cost of living

The impact of the cost of living continues to be felt across the UK and, while energy prices have fallen, they continue to be well above pre energy crisis levels. According to an Office for National Statistics (ONS) survey (January 2024), 41% of adults reported that it was 'very or somewhat difficult' to afford energy bills and 44% of adults are now using less fuel in their homes due to the increased cost of living[3]. The Consumer Prices Index, including owner occupiers' housing costs (CPIH), rose by 3.8% in the 12 months to March 2024[4].

UK clean energy investment

Analysis by Cornwall Insight[5] warned that the impact of schemes such as the Inflation Reduction Act in the United States and the EU's Green Deal Industrial Plan could divert financing away from the UK. Meanwhile, EY's biannual Renewable Energy Country Attractiveness Index (RECAI)[6] saw the UK fall to seventh place in the global rankings. The report referenced the Contracts for Difference (CfD) Allocation Round 5, in which no bids were received for offshore wind contracts. The report did, however, acknowledge that *"incentives for onshore wind projects offer some hope."*

The UK Government has since increased the maximum prices available for offshore wind by 66% for CfD Allocation Round 6 and has developed proposals to review applications from 2025 based on the environmental and economic sustainability of the industry.

UK climate policy – changes since FES 2023

Climate policy in the UK continues to evolve and shift. In 2023, the Government announced a five-year delay on the ban on the sale of new petrol and diesel cars from 2030 to 2035 and revised its target to ban gas boilers entirely in 2035 to a phasing out of 80%, citing the impact of imposing costs on consumers.

The Government committed to the launch of the Clean Heat Market Mechanism. The scheme will now be implemented from April 2025, where in the first year manufacturers will be required to sell heat pumps equivalent to 6% of their boiler sales in the UK. The Government also increased the maximum grants available to consumers under the Boiler Upgrade Scheme (BUS).

The Future Homes and Building Standard consultation closed in March, proposing that new homes built from 2025 are 'zero carbon ready' and prohibiting the installation of fossil fuel-powered heating.

In January 2024, the UK Government published the civil nuclear roadmap, which outlined plans for the biggest expansion of nuclear power for 70 years, including exploring the building of a major new power station.

The second consultation on the Review of Electricity Market Arrangements (REMA) was published in March 2024. The proposed reforms will impact the design of electricity markets and investment policies, including Contracts for Difference (CfD) and the Capacity Market (CM) schemes. Market reform can influence the siting of new assets and how they will operate.

March also saw the Government committed to supporting the building of new unabated gas power stations to ensure a safe and reliable alternative energy source during periods of high demand and low renewable generation.

The UK general election took place on the 4 July 2024. All modelling took place before the general election and reflects policy and ambition prior to the election.

3 ons.gov.uk/economy/inflationandpriceindices/articles/costoflivinginsights/energytrendsbulletin
4 ons.gov.uk/economy/inflationandpriceindices/bulletins/consumerpriceinflation/march2024
5 cornwall-insight.com/press/fierce-global-competition-could-jeopardise-investment-in-the-uks-renewable-energy-sector/
6 ey.com/en_gl/insights/energy-resources/are-the-global-winds-of-change-sending-offshore-in-a-new-direction

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Navigating Future Energy Scenarios 2024

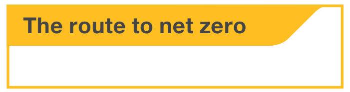
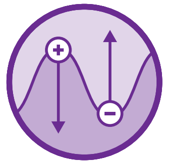
Future Energy Scenarios: ESO Pathways to Net Zero is split into three key chapters this year:

- **The Reducing Great Britain's Emissions chapter** reflects on the UK's legislated target to decarbonise by 2050.
- **The Energy Consumer chapter** covers residential, industrial, commercial and transport sectors and considers how decarbonisation affects individual consumers.
- **The Energy System chapter** explores how total Great Britain demand is met using decarbonised energy sources such as electricity, hydrogen, natural gas and bioenergy.

Flexibility is key to a net zero energy system and so this is covered in all chapters.

FES 2024 graphic elements

Within the publication, you'll see a selection of graphic elements used throughout the Reducing Great Britain's Emissions, Energy Consumer and Energy System chapters. These graphic elements all signify content of importance, which are outlined below along with an overview of their purpose.

Graphic element	Descriptor
	Insights relating directly to our net zero pathways and the Counterfactual are indicated with rings in set colours throughout the document. When two or more pathways cross over in assumptions or projections, we present combined pathway rings next to the insight.
	Our 'route to net zero' boxes summarise key measures and talking points we believe are critical to driving our key message and actions, which can be found in the Executive Summary chapter *(page 21)*.
	Technologies and actions which provide flexibility to the energy system are represented in purple.
	When a key action number is shown within a "route to net zero" or "flexibility" box, it means it directly relates to one of our actions, which can be found in the Executive Summary chapter *(page 21)*.

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Executive Summary

Introduction

We are in a period of significant change for the energy industry as a whole and the Future Energy Scenarios framework has adapted to support strategic network planning.

Our previous framework, used since 2020, presented a wide range of credible outcomes on the route to net zero. This year, our new framework seeks to explore a narrower range by identifying strategic choices that can be made on the route to net zero. This strategic evolution forms part of a wider industry overhaul to Great Britain's energy network planning, with FES underpinning the foundations of this network investment by feeding into NESO's Centralised Strategic Network Plan (CSNP), working alongside the Strategic Spatial Energy Plan (SSEP).

Hits net zero by 2050

- **Holistic Transition**
- **Electric Engagement**
- **Hydrogen Evolution**

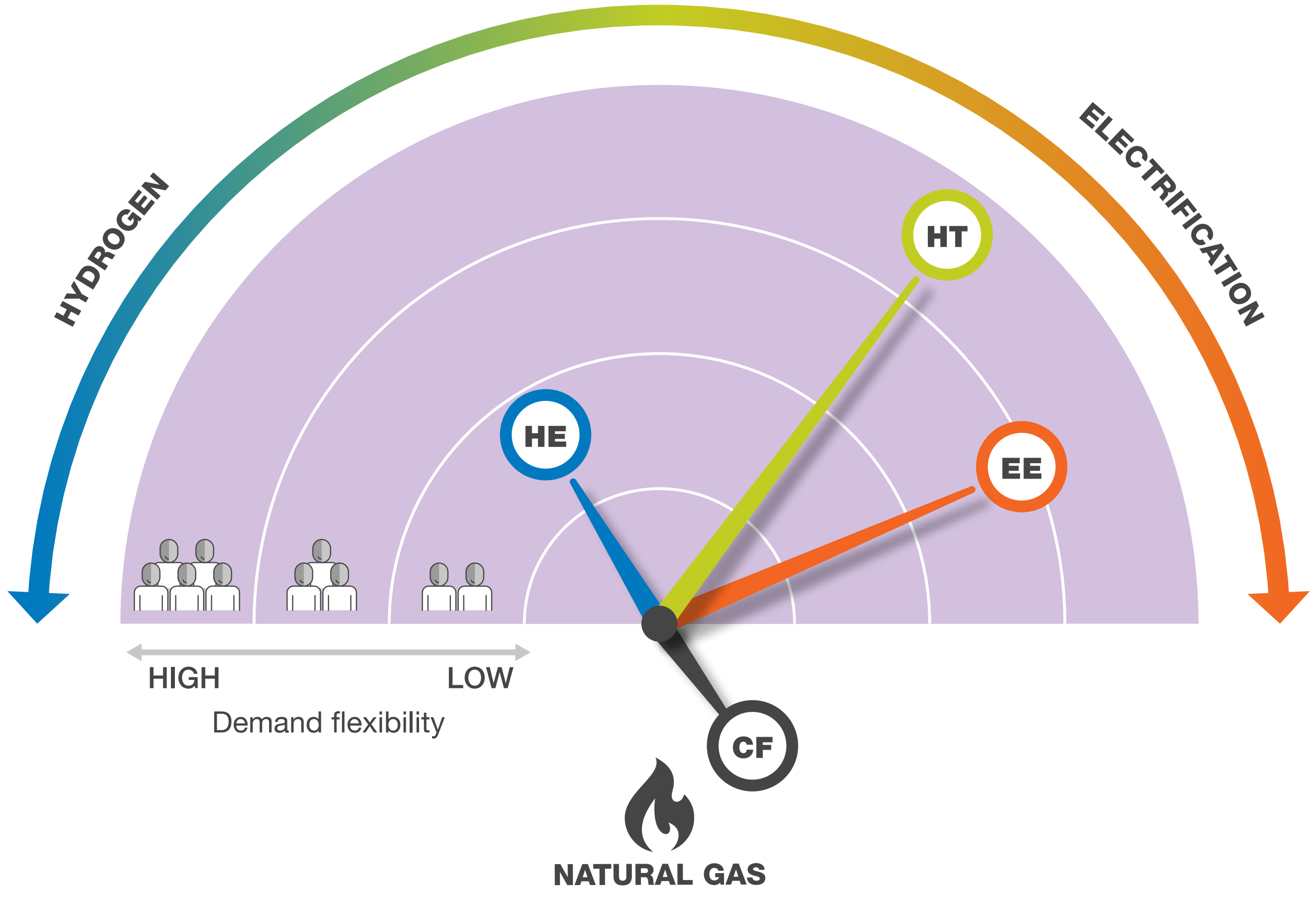
Misses net zero by 2050

- **Counterfactual**

Our new pathways – Holistic Transition, Electric Engagement and Hydrogen Evolution – explore strategic routes to net zero based on our extensive stakeholder engagement, research and analysis.

In comparison, the Counterfactual is used to understand the gap between successful tracking of the pathways versus enabling change too slowly and missing key targets.

Pathways framework 2024



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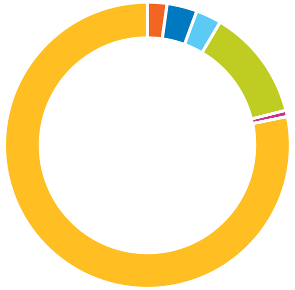
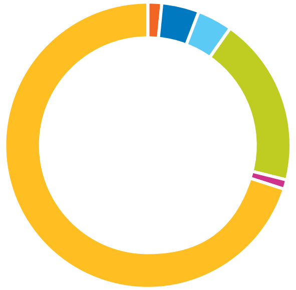
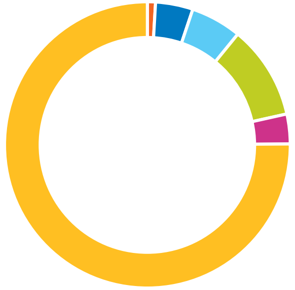
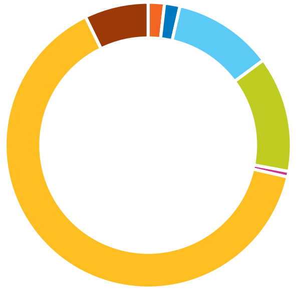
Comparing our pathways

	Holistic Transition	Electric Engagement	Hydrogen Evolution	Counterfactual
2050 energy demand	Net zero met through a mix of electrification and hydrogen, with hydrogen mainly around industrial clusters. Consumer engagement in the transition is very strong with demand shifting, with smart homes and electric vehicles providing flexibility to the grid.	Net zero met through mainly electrified demand. Consumers are highly engaged in the energy transition through smart technologies that reduce energy demand, using technologies such as electric heat pumps and electric vehicles.	Net zero met through fast progress for hydrogen in industry and heat. Many consumers will have hydrogen boilers, although energy efficiency will be key to reducing cost. There are low levels of consumer engagement. Hydrogen will be prevalent for heavy goods vehicles but electric vehicle uptake is strong.	Net zero missed, although some progress is made for decarbonisation compared to today. While home insulation improves, there is still a heavy reliance on gas across all sectors, particularly power and space heating. Electric vehicle uptake is slower than the net zero pathways, but still displaces petrol and diesel.
	 Total energy supply **1218 TWh**	 Total energy supply **1222 TWh**	 Total energy supply **1292 TWh**	 Total energy supply **1423 TWh**
2050 energy supply	Highest renewable capacity pathway with unabated gas dropping sharply to zero after 2036. Moderate levels of nuclear capacity and lowest levels of hydrogen dispatchable power present. Supply side flexibility is high, delivered through electricity storage and interconnectors.	Highest peak electricity demand requiring high nuclear and renewable capacities. Natural gas plants have lower utilisation post-2035. Supply side flexibility is high, delivered through electricity storage, interconnectors and low carbon dispatchable power.	Pathway with high levels of hydrogen dispatchable power plants leading to lower needs for renewable and nuclear capacities. Natural gas plants have lower utilisation post 2035. Hydrogen storage provides most flexibility in this pathway.	The Counterfactual sees the least renewable capacity and has heavy reliance on natural gas, which leads to net zero missed. Because of the lower needs for flexibility, lower electricity storage, interconnectors and low carbon dispatchable power are present.
				
Emissions	Negative emissions of 51 $MtCO_2e$ needed, delivered through a mix of bioenergy with carbon capture and storage for power and direct air carbon capture and storage.	Negative emissions of 51 $MtCO_2e$ needed, delivered mainly through bioenergy with carbon capture and storage for power with low levels of direct air carbon capture and storage.	Negative emissions of 51 $MtCO_2e$ needed, delivered mainly through power bioenergy with carbon capture and storage.	Negative emissions only provided through bioenergy with carbon capture and storage for power, but net zero is missed.

Storage · Carbon capture and storage biomass · Carbon capture and storage gas · Nuclear · Hydrogen · Renewable · Fossil fuel

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Key message and actions

> **Decisive action is needed within the next two years to deliver the fundamental change required for a fair, affordable, sustainable and secure net zero energy system by 2050.**

Actions:

1. Accelerate the delivery of whole system infrastructure through a strategic approach to network investment and introduction of planning reforms.
2. Deliver market reform, considering electricity, gas, hydrogen and CO_2, to ensure we have energy markets that provide for and work with a reliable and strategically planned energy system.
3. Prioritise the use of hydrogen for hard-to-electrify applications. Agree business models and kick-start delivery of the hydrogen and CO_2 transport and storage infrastructure needed for system flexibility.
4. Accelerate progress on low carbon heating including faster rollout of heat pumps irrespective of a decision on hydrogen for heat.
5. Deliver innovation and build consumer trust in affordable smart technology, enabling consumers to save on energy costs while helping with the management of Great Britain's electricity system.
6. Focus on energy efficiency improvements across all sectors to reduce overall energy demand.
7. Expedite the delivery of clean, low-cost and reliable new technologies and long-duration energy storage connected to the system by reforming the connections process.
8. Invest in supply chain and skills to deliver the low carbon technologies and infrastructure needed for net zero and enable the UK to become a world leader.

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Key comparison chart of decarbonisation milestones

Key comparison chart of demand side policies

This chart contains a selection of recent policy ambitions in relation to net zero and energy security and highlights how they compare to the different pathways. The chart also shows non policy-related items that are key decarbonisation milestones.

Note that energy demand will be affected by policy on the supply side which is set out in the comparison chart on the following page. It is critical that policy considers the whole energy system and not supply and demand in isolation.

Please note analysis for FES 2024 commenced before the publication of several key policy documents and the UK general election and reflects policy targets and ambitions at the time of analysis.

		2023	2025	2030	2035	2040	2045	By 2050	Maximum potential by 2050	Maximum potential pathway
Transport	Sales of petrol and diesel cars and vans banned	1.6m petrol, diesel and hybrid cars and vans sold			HT EE HE	CF			39m battery electric cars and vans	HE
	Zero tailpipe emissions for all new heavy goods vehicles	<1% of heavy goods vehicles sold				HT EE HE	CF		Zero diesel heavy goods vehicles still on the road	HT EE HE
Heating	600,000 heat pumps installed per year (by 2028)	Approximately 100,000		HT EE HE		CF			1.5m per year	EE
	4 in 5 homes not using natural gas boiler as primary heat source	1 in 5					HT EE HE		100%	HT EE HE
Natural gas	Gas grid connection for new homes ends	80%	HT EE HE	CF					0%	HT EE HE
Industry	Annual industrial hydrogen demand over 10 TWh	<0.5 TWh		HT HE		EE			78 TWh	HE

In developing the pathways we balance current ambitions, progress towards targets, stakeholder feedback and what we have modelled for an optimal pathway. Policy assumptions vary across the pathways in line with the pathway narrative. More information can be found in our "Future Energy Scenarios: Pathway Assumptions 2024[1]" document.

HT Holistic Transition
EE Electric Engagement
HE Hydrogen Evolution
CF Counterfactual
Government policy

1 nationalgrideso.com/future-energy/future-energy-scenarios-fes/fes-documents

FES 2024 / Executive Summary / Key comparison chart of decarbonisation milestones 22

Key comparison chart of decarbonisation milestones

Key comparison chart of supply side policies

This chart contains a selection of recent policy ambitions in relation to net zero and energy security and highlights how they compare to the different pathways. The chart also shows non policy-related items that are key decarbonisation milestones.

Note that energy system will be affected by policy on the demand side which is set out in the comparison chart on the previous page. It is critical that policy considers the whole energy system and not supply and demand in isolation.

Please note analysis for FES 2024 commenced before the publication of several key policy documents and the UK general election and reflects policy targets and ambitions at the time of analysis.

		2023	2025	2030	2035	2040	2045	By 2050	Maximum potential by 2050	Maximum potential pathway
Emissions	Meets 2050 net zero target	422 $MtCO_2e$						HT EE HE (Government policy)	Net zero by 2050	HT
	Meets Fifth Carbon Budget			HT EE HE CF						
	Meets Sixth Carbon Budget				HT EE HE (Government policy)					
Electricity generation	50 GW of offshore wind	15 GW		HT (Government policy)	EE HE CF				101 GW	HT
	5 GW floating offshore wind	0 GW			HT EE HE	CF			20 GW in HT 19 GW in EE and HE	HT EE HE
	70 GW of solar	15 GW			(Government policy)	HT	EE	HE	108 GW	HT
	No unabated natural gas-fired generation capacity, subject to security of supply	36 GW			(Government policy)	HT	EE	HE	HT reaches this target in 2036	HT
	24 GW nuclear generation capacity	6.1 GW						(Government policy)	22 GW	EE

In developing the pathways we balance current ambitions, progress towards targets, stakeholder feedback and what we have modelled for an optimal pathway. Policy assumptions vary across the pathways in line with the pathway narrative. More information can be found in our "Future Energy Scenarios: Pathway Assumptions 2024[2]" document.

HT Holistic Transition
EE Electric Engagement
HE Hydrogen Evolution
CF Counterfactual
Government policy

2 nationalgrideso.com/future-energy/future-energy-scenarios-fes/fes-documents

FES 2024 / Executive Summary / Key comparison chart of decarbonisation milestones 23

Key comparison chart of decarbonisation milestones

Key comparison chart of supply side policies (continued)

		2023	2025	2030	2035	2040	2045	By 2050	Maximum potential by 2050	Maximum potential pathway
Hydrogen	10 GW low carbon hydrogen production capacity in operation or construction	<1 GW		HE	HT	EE			75 GW	HE
	5 GW hydrogen production from electrolysis	<1 GW			HT HE	EE			49 GW	HE
	2 GW of low carbon hydrogen production capacity in operation or construction	<1 GW		HT EE HE	CF				75 GW	HE
Natural gas	40% reduction in gas consumption			Government policy	HT EE	HE			85% reduction	EE
Bioenergy	Biomass supply consistent with Climate Change Committee Sixth Carbon Budget - not directly modelled									
Energy storage	100 GWh of non-battery electrical storage	2.75 GW / 28 GWh				HT			118 GWh in HT	HT
	30 GWh of battery electrical storage	4.7 GW / 5.8 GWh		HT EE HE					65 GWh in HT	HT
Interconnectors	18 GW capacity	8.4 GW		Government policy	HT EE				25 GW in HT	HT

HT Holistic Transition
EE Electric Engagement
HE Hydrogen Evolution
CF Counterfactual
Government policy

FES 2024 / Executive Summary / Key comparison chart of decarbonisation milestones 24

Emissions reductions

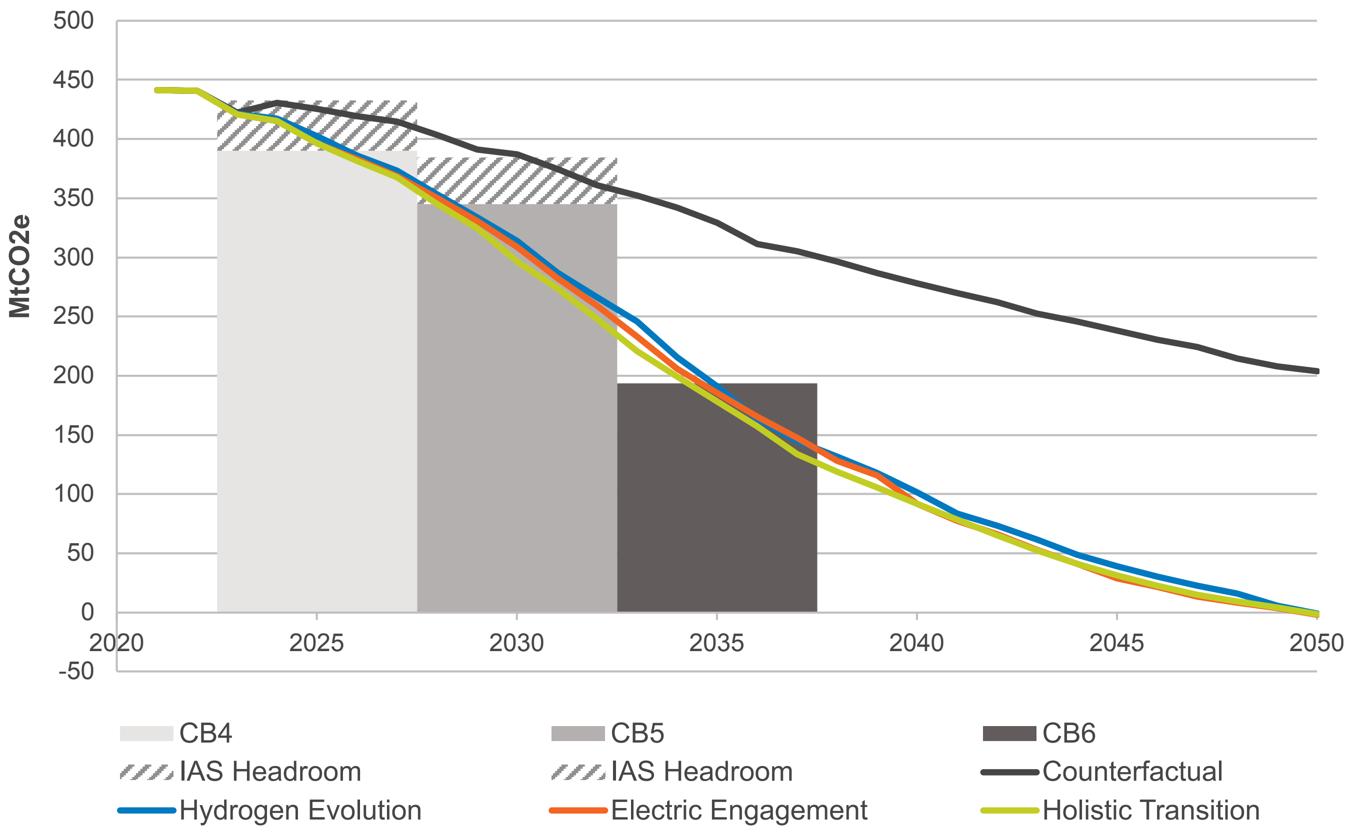
We must go further and faster to deliver the emissions reductions needed for the Sixth Carbon Budget on the route to net zero. Our pathways show ambitious strategic routes to net zero and without decisive action within the next two years there is a risk of emissions remaining high, particularly in the heat sector.

All net zero pathways achieve the Sixth Carbon Budget, although there is limited headroom, reinforcing the challenge of achieving this. Holistic Transition has the largest margin of 79 $MtCO_2e$ over the five year Sixth Carbon Budget period. Electric Engagement has a margin of 31 $MtCO_2e$, whilst the margin in Hydrogen Evolution is 7 $MtCO_2e$.

All pathways achieve net zero in 2050, with net emissions of -0.9 $MtCO_2e$ to -1.9 $MtCO_2e$. This is not a significant margin, highlighting the importance of continued, focused decarbonisation efforts over the next 26 years.

The **Counterfactual** does not meet net zero and instead has close to just over 200 $MtCO_2e$ of residual annual emissions in 2050. This is due to either slow or lack of decarbonisation across many sectors. The Sixth Carbon Budget is missed by a significant margin.

NZ.03: Net greenhouse gas emissions and carbon budgets



IAS stands for international aviation and shipping

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Key statistics

	2023	2030				2035				2050			
Emissions		HT	EE	HE	CF	HT	EE	HE	CF	HT	EE	HE	CF
Annual average carbon intensity of electricity (g CO_2/kWh)	133	41	73	74	134	-17	-11	-9	69	-28	-36	-36	21
Net annual emissions (MtCO_2e)	422	297	309	314	387	178	185	191	329	-1	-2	-1	204
Electricity													
Annual demand (TWh)[1]	285	334	328	332	311	419	425	422	351	667	700	671	533
Electricity demand for heat (TWh)	40	42	44	44	42	51	57	53	43	108	114	107	83
Peak demand (GW)[2]	58	62	65	64	64	76	81	76	70	109	119	104	102
Total installed capacity (GW)[3]	116	219	205	191	166	289	264	244	206	411	386	343	285
Wind and solar capacity (GW)	44	121	106	94	71	189	156	141	113	249	225	197	152
Interconnector capacity (GW)	8	12	12	12	12	24	19	17	14	25	22	17	16
Total storage capacity (GW)[4]	7	34	29	26	22	48	38	30	27	83	66	50	34
Total storage volume (GWh)[5]	34	130	92	86	63	172	112	105	87	269	258	208	132
Maximum vehicle-to-grid capacity (GW)[6]	0	2	1	0	0	18	10	1	0	65	40	19	8
Natural Gas													
Annual demand (TWh)[7]	872	642	649	724	790	433	478	545	666	138	127	303	636
1-in-20 peak demand (GWh/day)	5082	3811	4327	4726	5352	2786	3289	3786	4933	1047	1136	1791	4593
Residential demand (TWh)[8]	292	266	266	288	307	200	199	215	291	0	0	0	188
Imports (TWh)	494	430	446	510	586	308	360	418	540	113	105	279	581
Hydrogen													
Annual demand (TWh)	0	32	6	36	1	64	38	134	4	182	138	393	24
Residential hydrogen demand for heat (TWh)	0	0	0	0	0	0	0	12	0	15	0	77	0
CCS enabled hydrogen production (TWh)[9]	0	26	4	42	0	38	25	82	0	60	38	177	8
Electrolytic hydrogen production (TWh)[10]	0	12	5	14	1	25	16	46	4	116	95	161	17
Bioresources													
Bioresource demand (TWh)	170	151	139	149	102	167	163	176	86	191	205	225	91

1. Customer demand plus on-grid electrolysis meeting Great Britain hydrogen demand only, plus losses, equivalent to GBFES System Demand Total in 'ED1' of data workbook
2. Refer to data workbook for further information on winter average cold spell peak demand
3. Includes all networked generation as well as total interconnector and storage capacity (including vehicle-to-grid available at winter peak)
4. Includes vehicle-to-grid capacity available at winter peak
5. Excludes vehicle-to-grid
6. Less capacity will be available during peak 5-6pm due to vehicle usage
7. Includes shrinkage, exports, biomethane and natural gas for methane reformation
8. Residential demand made up of biomethane and natural gas
9. Carbon capture and storage enabled hydrogen is created using natural gas as an input, with carbon capture and storage
10. Electrolytic hydrogen is created via electrolysis using zero carbon electricity (this figure does not include hydrogen produced directly from nuclear or bioenergy)

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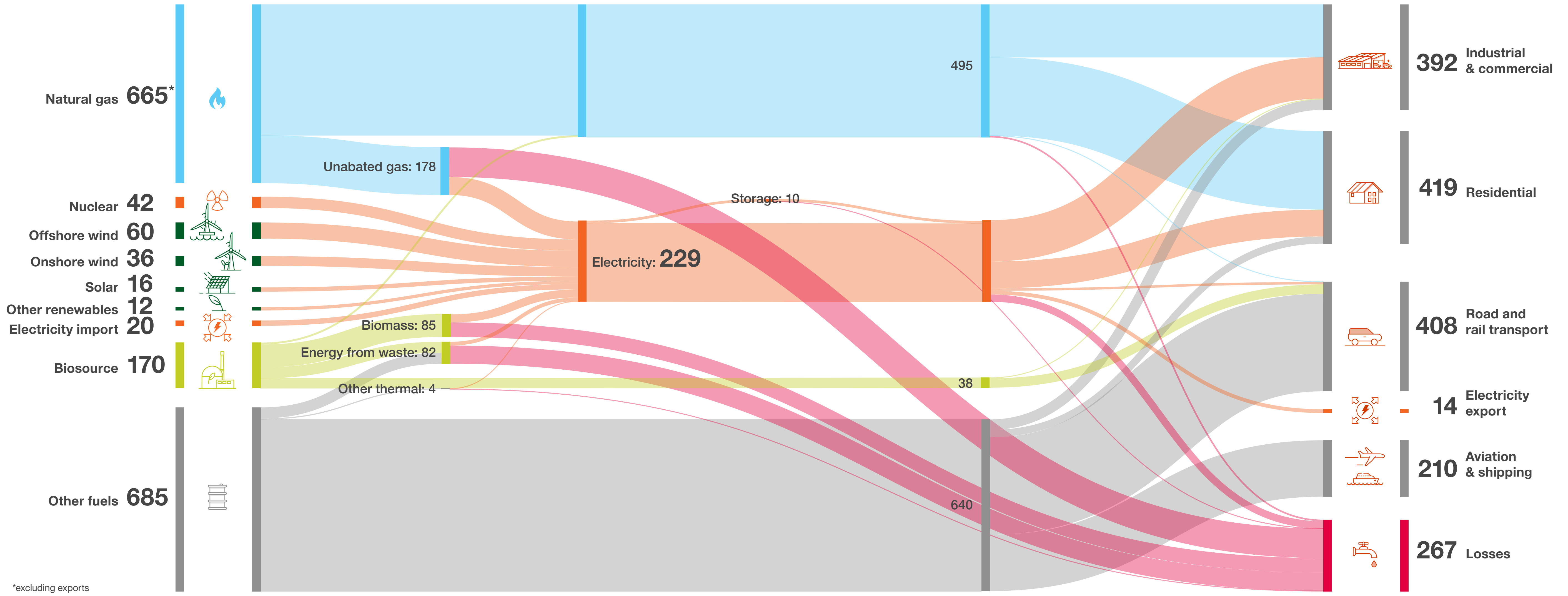
Energy supply and demand

2023

Interactions between different fuels are low, demonstrating limited whole system thinking or cross-sector decarbonisation. Fossil fuels make up 79% of total energy supply. Petroleum supplies over 90% of road transport demand and 100% of aviation and shipping demand.

Total energy supply
1706 TWh



*excluding exports

Please note that TWh figures are rounded to the nearest number.

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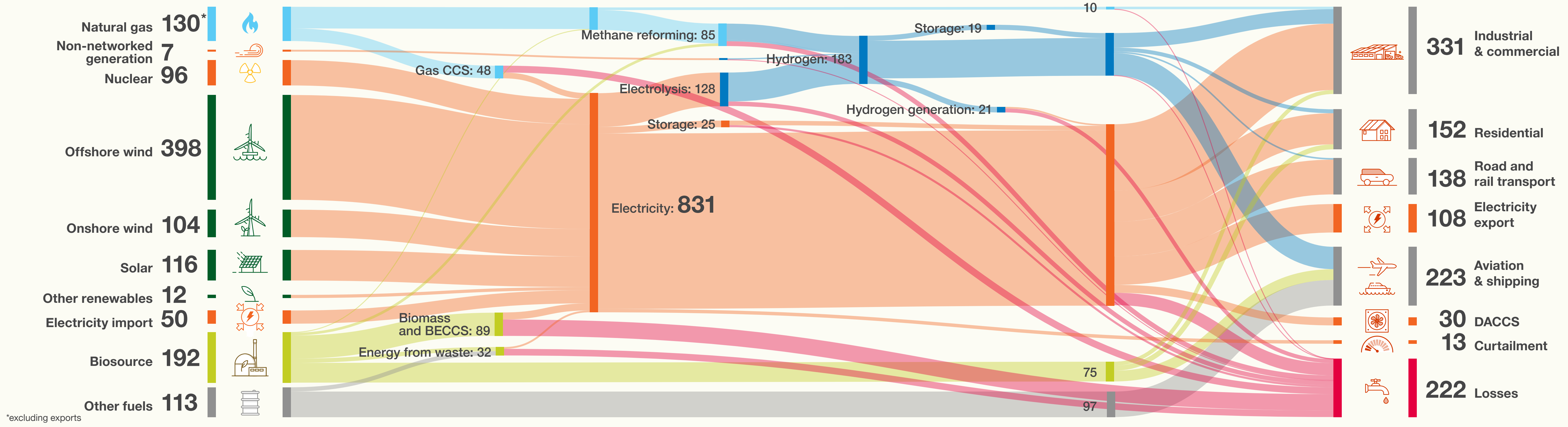
Energy supply and demand in 2050

Holistic Transition

Reliance on fossil fuels has significantly reduced, with nearly all the remaining gas used for power and hydrogen production being abated through carbon capture and storage (CCS). Overall energy demand falls by 488 TWh from 2023 driven by efficiency improvements and electrification. Electricity and hydrogen work together to supply 60% and 19% of the 2050 energy demand respectively.

Total energy supply
1218 TWh



Please note that TWh figures are rounded to the nearest number.

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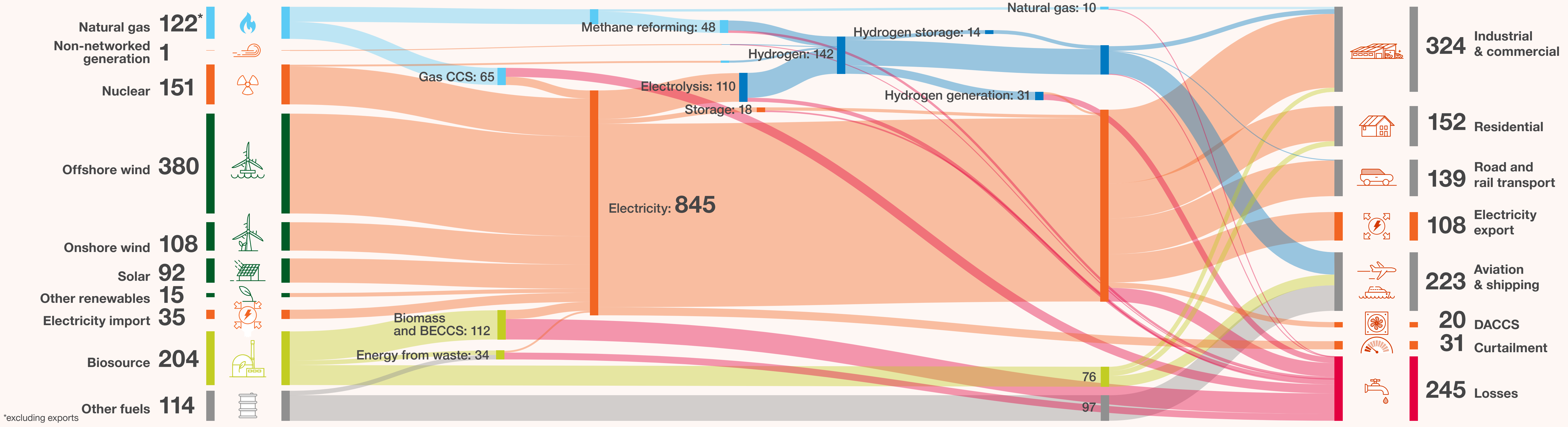
Energy supply and demand in 2050

Electric Engagement

Electricity supplies 66% of overall energy demand in 2050. Electricity generated increases by 616 TWh but overall energy demand falls by 484 TWh compared to today. This is driven by consumer engagement, insulation and efficiency gained through electrification. Hydrogen provides 19% of the overall energy needed for industry, aviation and shipping.

Total energy supply
1222 TWh



Please note that TWh figures are rounded to the nearest number.

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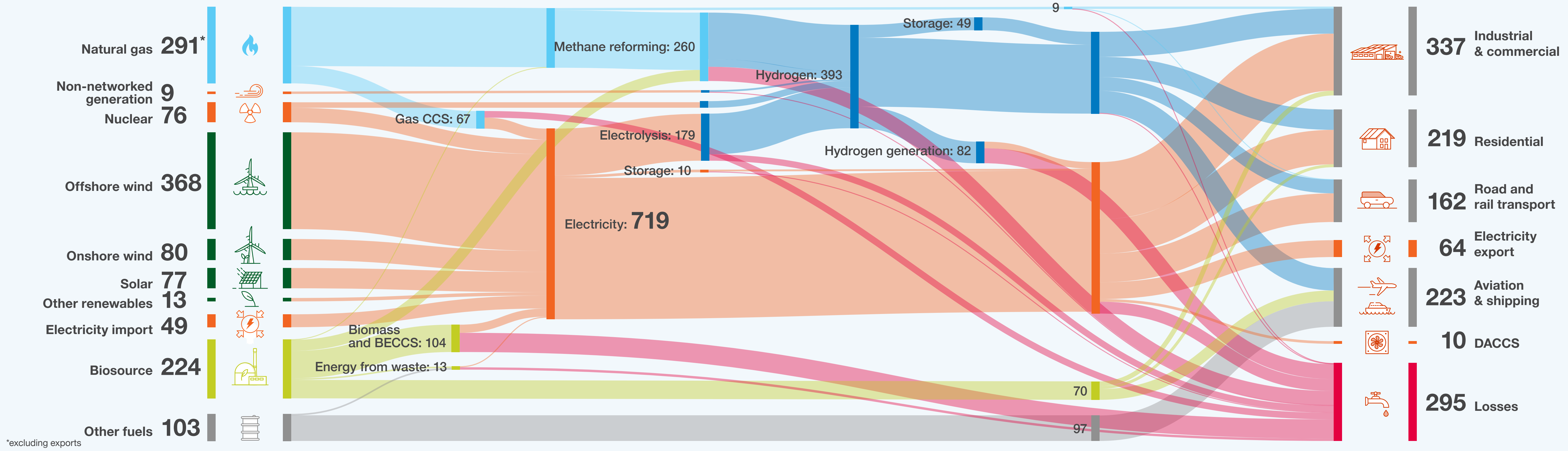
Energy supply and demand in 2050

Hydrogen Evolution

Hydrogen supplies 30% of overall energy needed in 2050 used across all sectors. Overall energy demand drops by 414 TWh driven primarily by the remaining demand that is electrified. Natural gas is still used for electricity and hydrogen production in 2050 but it is abated through CCS.

Total energy supply
1292 TWh



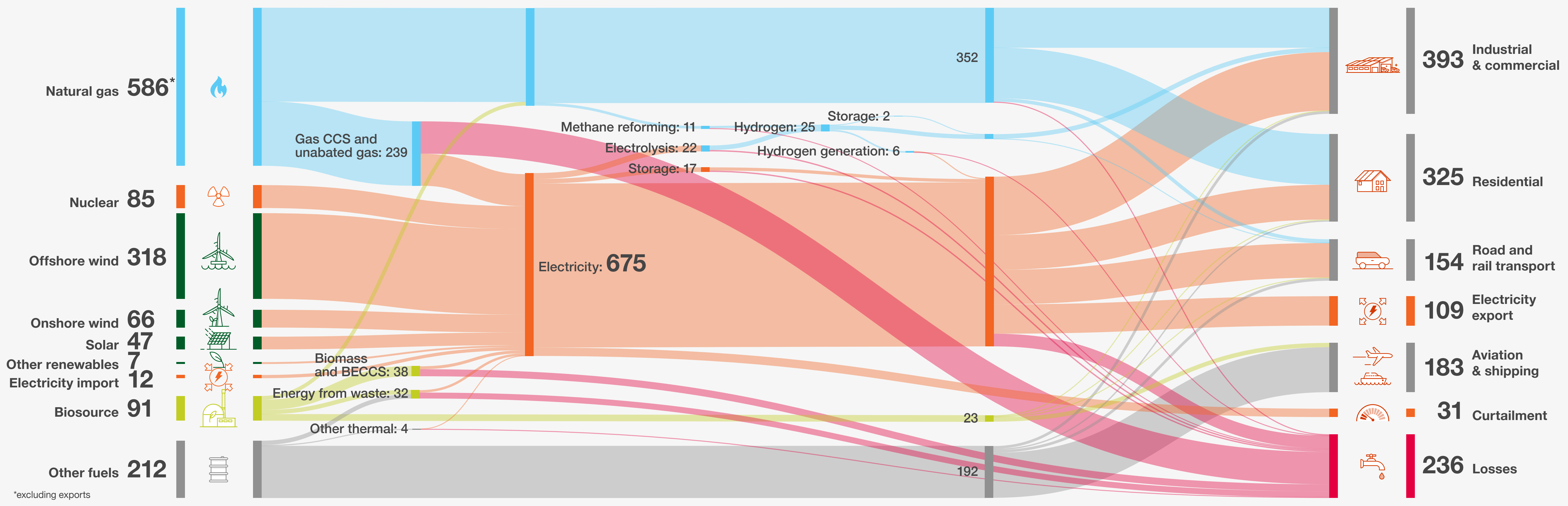
Please note that TWh figures are rounded to the nearest number.

Energy supply and demand in 2050

Counterfactual

Heavy reliance on fossil fuel remains, supplying 56% of energy needed across all sectors, predominantly supplied by natural gas. Hydrogen use is limited due to the continued use of natural gas. Road transport sees the most decarbonisation with 85% of demand met by low carbon fuels.

Total energy supply
1423 TWh



Please note that TWh figures are rounded to the nearest number.

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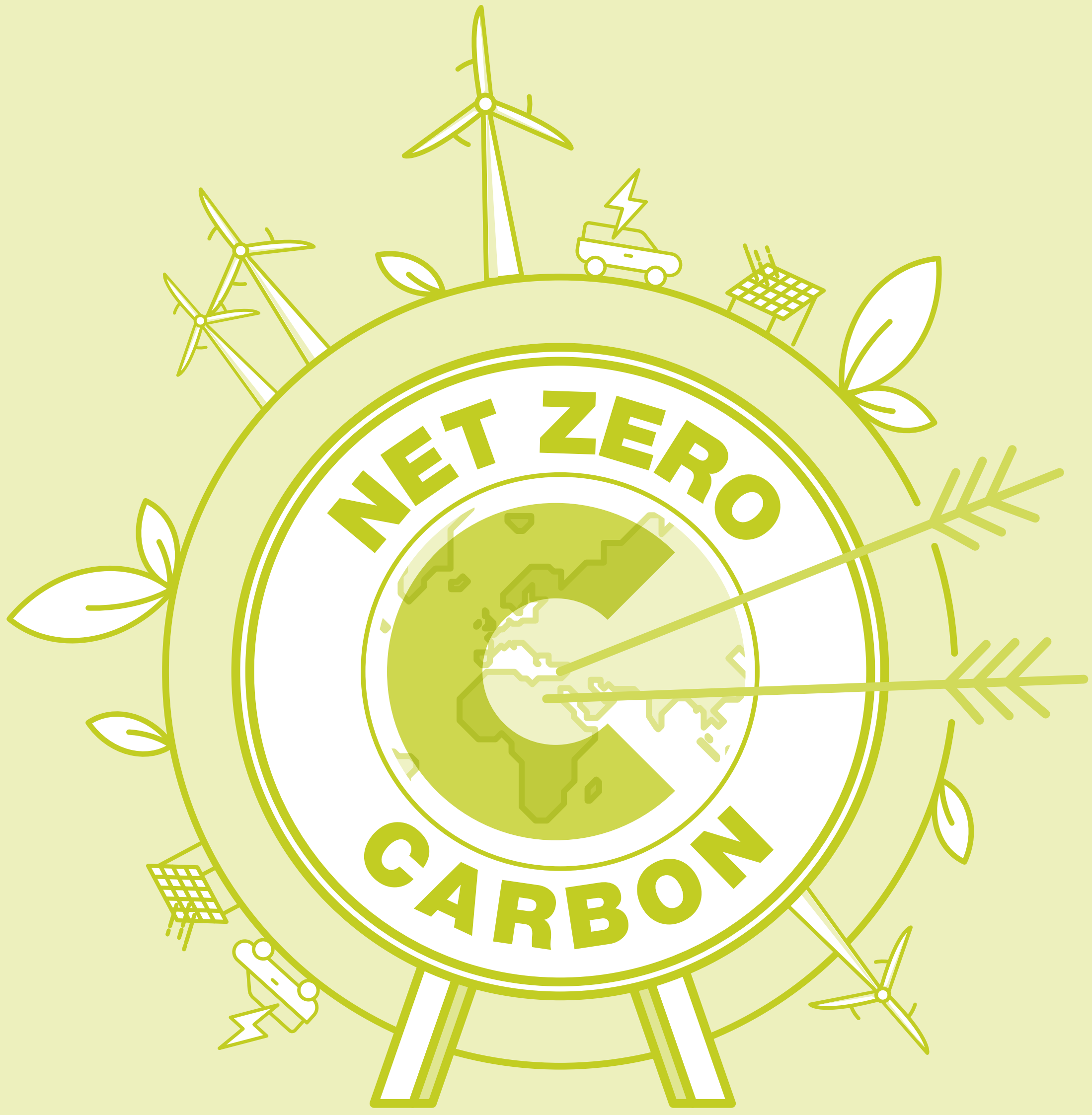
Reducing Great Britain's Emissions



Introduction

Great Britain has made significant progress in reducing carbon emissions. Since 1990, territorial greenhouse gas emissions have halved, with renewable energy now accounting for more than 40% of our electricity mix[1]. However, progress must be accelerated to reach net zero by 2050.

Operating a low carbon energy system will undoubtedly bring many challenges. The phasing out of fossil fuels necessitates significant investment in industry and infrastructure; moving to a weather-dependent electricity system demands innovative new technologies and markets. Ensuring security of supply and a fair transition will require strategic thinking across the whole system. The target is bold, but one that can be achieved if progress is swift and coordinated.

We have a once-in-a-lifetime opportunity to build an energy system for the future that is fair, affordable, sustainable and secure.

Figure NZ.01: Annual emissions by sector from 2019 to 2022 in relation to 1990 levels

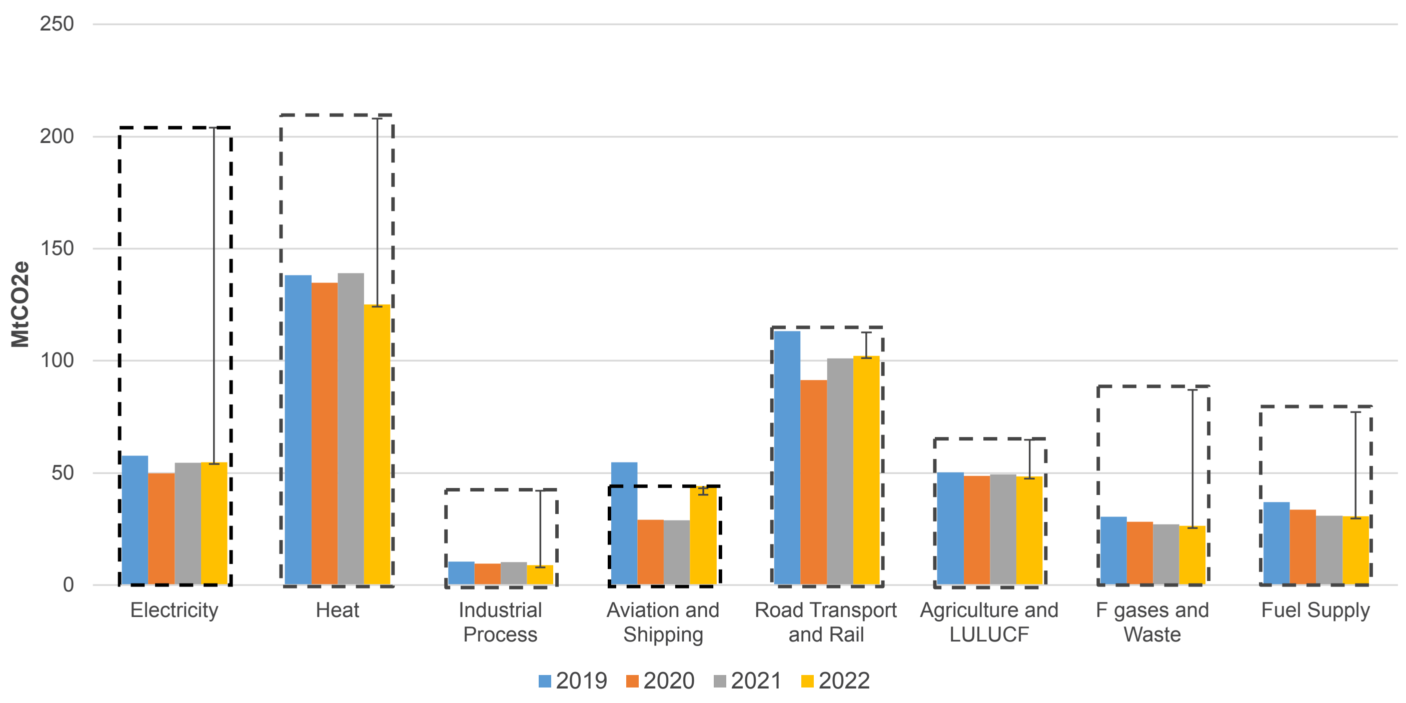


Figure NZ.01 shows progress from 2019 to 2022 against 1990 levels. The dashed boxes show 1990 emissions.

1 gov.uk/government/news/uk-first-major-economy-to-halve-emissions

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Introduction

Great Britain has the fastest decarbonising electricity grid in the world, with emissions reducing by almost 75% since 1990. This has driven the bulk of emissions reductions to date[2].

Heat accounts for the highest proportion of remaining emissions across all sectors, at 125 $MtCO_2e$ or 28% of a total of 441 $MtCO_2e$. Progress on fuel switching is key to reducing this figure.

The reduction in industrial emissions since 1990 is driven primarily by reduced fuel consumption by business and industry.

Aviation has seen a 50% increase in emissions since 1990[3]. During the COVID-19 pandemic, aviation emissions more than halved, from 37 $MtCO_2e$ to 14 $MtCO_2e$ due to restrictions on travel for business and leisure. Emissions rose back to 28 $MtCO_2e$ in 2022, as restrictions around the world were lifted.

Shipping has seen around a 40% reduction in emissions compared to 1990 levels. This is due to reduced UK marine fuel sales, caused largely by reduced shipping journeys and freight tonnages. The COVID-19 pandemic had a limited impact on shipping emissions, as the movement of goods around the world continued.

Road and rail emissions have decreased by only 10% since 1990. Petrol and diesel cars were the largest contributors to road and rail emissions in 2021.

Agriculture and land use, land-use change and forestry (LULUCF) has seen a 25% reduction in emissions since 1990. This is due to a combination of factors, such as increased forested areas, reduced livestock numbers and changes to farming practices.

Decarbonising heat and transport, the highest emitting sectors, will have the most significant impact on net zero emissions. Alongside these efforts, the delivery of a net zero power system will also be critical.

2 assets.publishing.service.gov.uk/media/660445fce8c442001a2203d0/uk-greenhouse-gas-emissions-provisional-figures-statistical-summary-2023.pdf
3 Aviation emissions in both 2020 and 2021 fell below the 1990 figure due to the travel restrictions in place at the time.

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Carbon budgets and net zero

Carbon budgets

The Climate Change Act requires the Government to set legally-binding Carbon Budgets which act as stepping stones towards the UK's 2050 net zero target. A Carbon Budget is a cap on the amount of greenhouse gases emitted over a five-year period. Budgets must be set at least 12 years in advance, with the Climate Change Committee (CCC) advising on the appropriate level of each carbon budget.

We have used the CCC's Balanced Pathway from the Sixth Carbon Budget for FES 2024, adjusted to reflect the latest recorded emissions and emissions methodology for sectors not directly modelled in FES (agriculture, aviation, shipping, LULUCF and waste).

The UK has met the first three carbon budgets and is currently in the Fourth Carbon Budget period[4]. The Sixth Carbon Budget (2033-2037) will be the first net zero compliant carbon budget. This budget will not be met without urgent and decisive action to increase the pace of decarbonisation across all sectors.

All net zero pathways require negative emissions technologies, despite the rapid and heavy decarbonisation that is already modelled. These technologies must be used to offset emissions in sectors where there is no clear, credible path for decarbonisation.

Reduction in emissions between carbon budgets

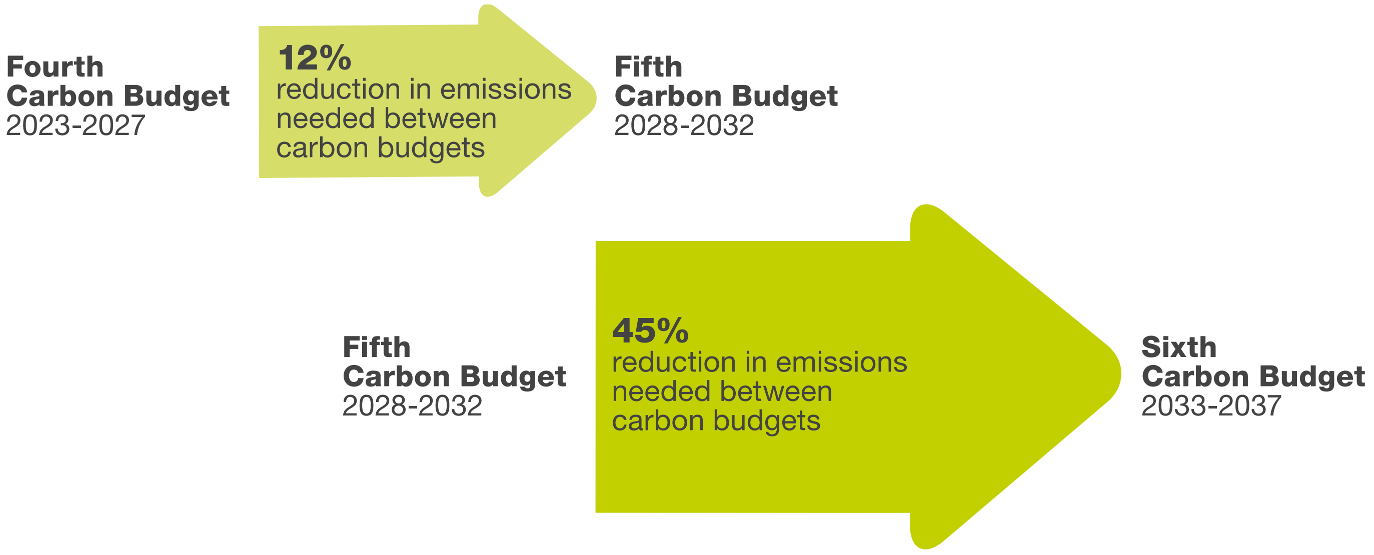
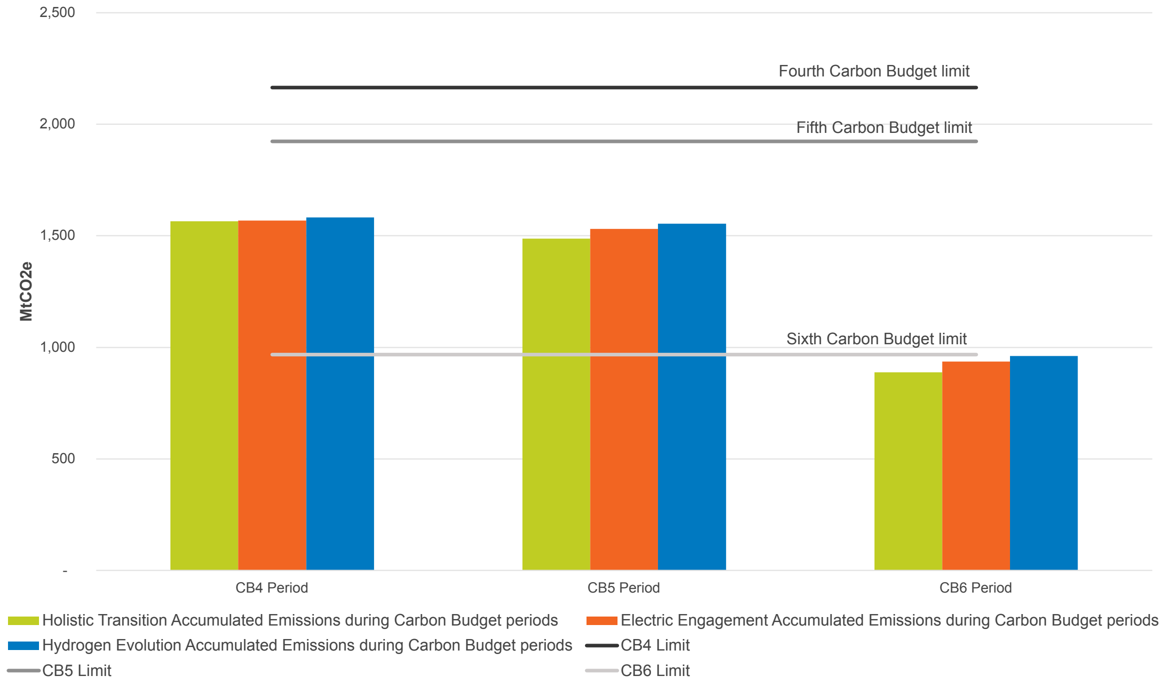


Figure NZ.02: Accumulated emissions for carbon budget period



4 gov.uk/guidance/carbon-budgets

FES 2024 / Reducing Great Britain's Emissions / Carbon budgets and net zero 35

Carbon budgets and net zero

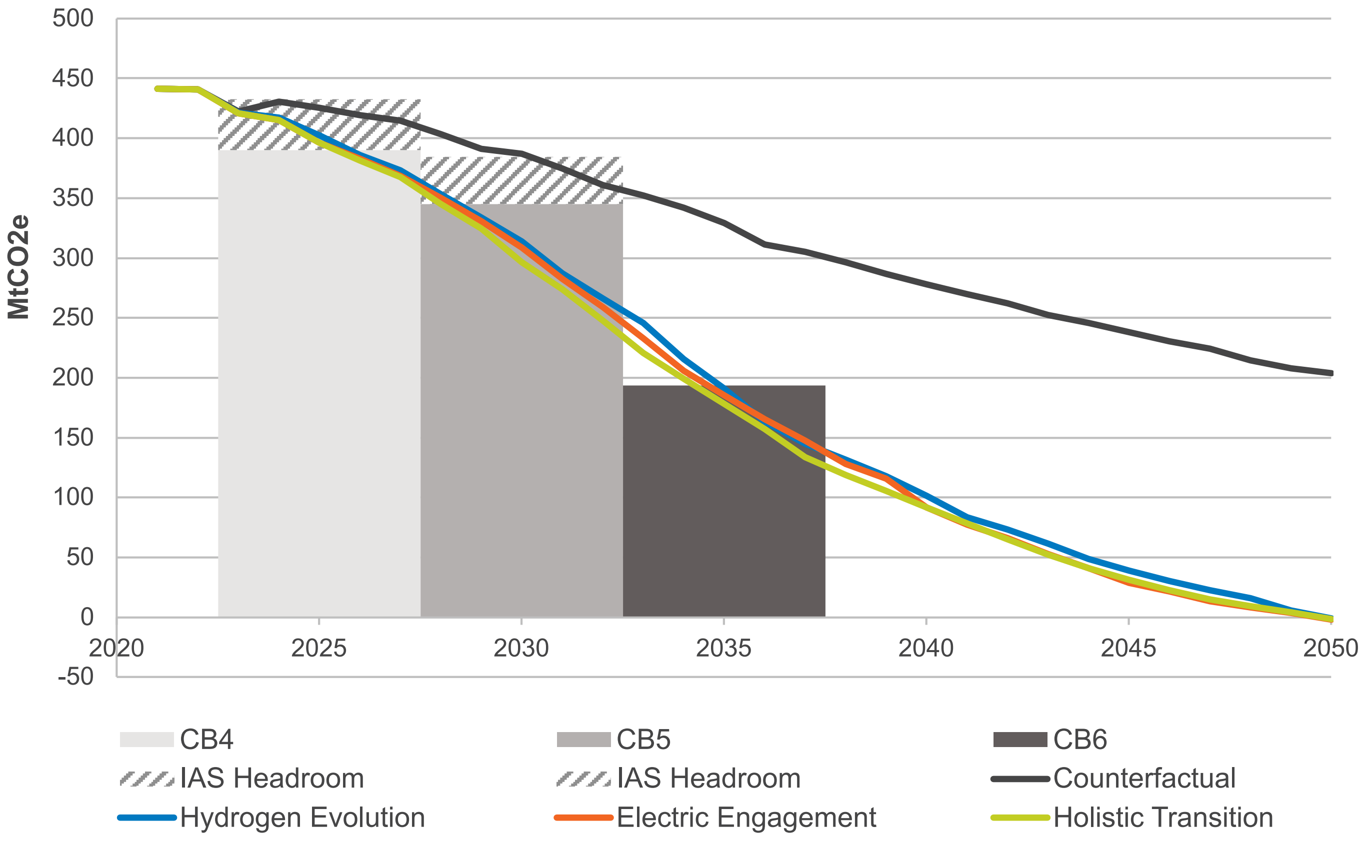
All net zero pathways meet net zero by 2050. They also achieve the Sixth Carbon Budget (2033 to 2037), although there is limited headroom which reinforces the challenge of achieving this. Holistic Transition has the largest margin of 79 $MtCO_2e$ over the five year carbon budget period. Electric Engagement has a margin of 31 $MtCO_2e$, with the margin in Hydrogen Evolution 7 $MtCO_2e$.

The **Counterfactual** does not meet net zero and instead has just over 200 $MtCO_2e$ of residual annual emissions in 2050. This is due to either slow or lack of decarbonisation across many sectors. The Sixth Carbon Budget is missed by a significant margin.

During the Fifth Carbon Budget period, the 2030 Nationally Determined Contribution (NDC) target sets out a 68% reduction in emissions against 1990 levels. This is met in Holistic Transition.

This target is not shown on NZ.03 as it excludes International Aviation and Shipping.

Figure NZ.03: Net greenhouse gas emissions and carbon budgets



*IAS: International Aviation and Shipping

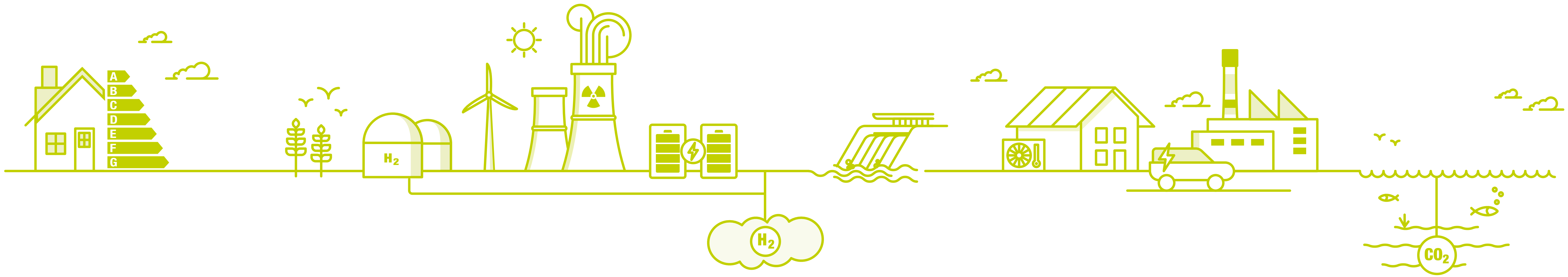
FES 2024 / Reducing Great Britain's Emissions / Carbon budgets and net zero 36

Carbon budgets and net zero

Reducing emissions to net zero

While progress has been made in reducing emissions, the actions that have taken us this far will not be enough to achieve carbon budgets and reach net zero. It's time to move further and faster.

The steps below are critical in the bid to reduce emissions. They must be delivered together, in parallel, at pace.



Demand reduction
Key Actions 5 & 6

Low carbon energy production
Key Actions 1, 2, 3 & 7

Low carbon flexibility and storage
Key Actions 1, 2, 3 & 7

Fuel switching
Key Actions 3 & 4

Carbon removals
Key Actions 2, 3 & 8

Key Action 8

FES 2024 / Reducing Great Britain's Emissions / Carbon budgets and net zero 37

Steps to net zero

Demand reduction

Demand reduction measures include energy efficiency improvements and changes in consumer behaviour. These have a tangible impact on net emissions, as less energy input is needed to meet the required energy demand. Shifting demand away from peak times can also reduce emissions by avoiding additional high carbon generation. More information on this is in the Energy Consumer chapter *(page 71)*.

All net zero pathways see demand reduction in residential heating due to improved insulation of households. Improved insulation measures and the associated emissions savings occur in parallel with fuel switching to low carbon heating systems, with fuel switching a driver for some insulation measures.

Holistic Transition and **Electric Engagement** see changing consumer behaviour reducing the average household indoor temperature. This measure is around half of the reduction seen during the energy crisis.

Holistic Transition and Electric Engagement have 80 and 82 TWh residential thermal demand reduction by 2035 respectively, when the pathways have 19 million gas boilers still in use. Early deployment of energy efficiency measures can make a significant contribution to achieving the Sixth Carbon Budget.

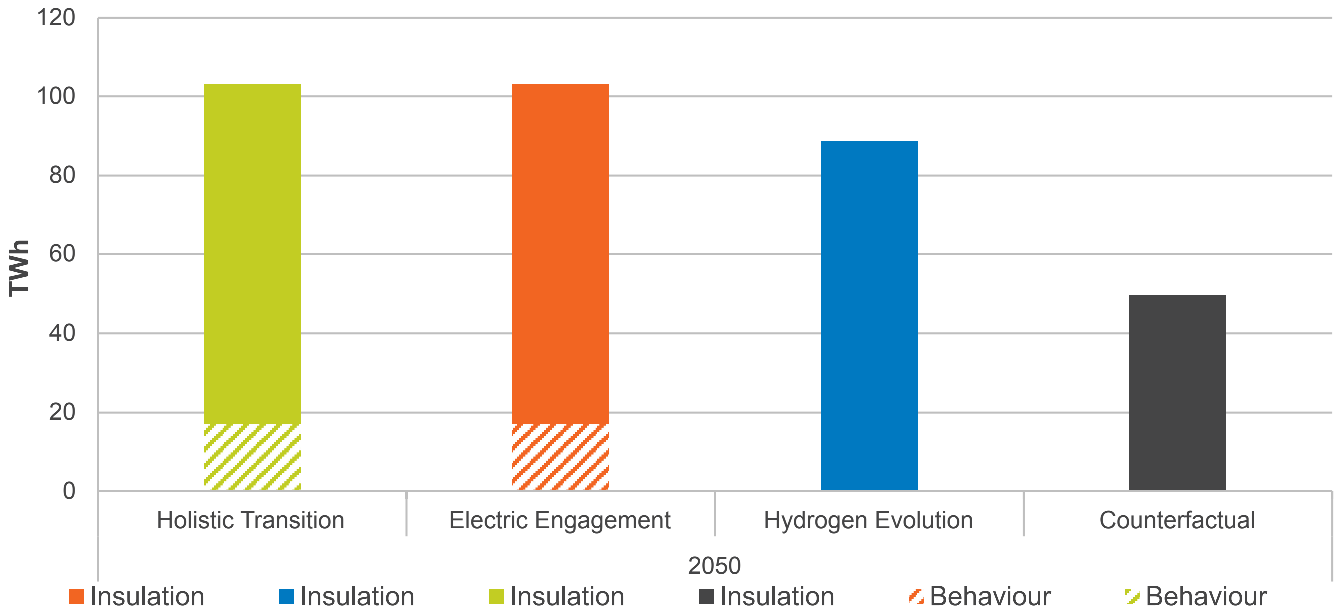
The route to net zero

Focusing on energy efficiency improvements across sectors will reduce energy demand and emissions.

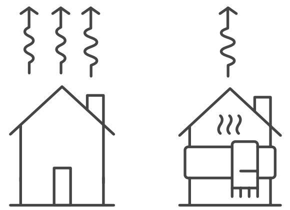
Key Action 6

Residential energy savings and emissions reductions must be delivered through raising minimum efficiency standards for buildings and appliances, as well as building on The Future Homes and Buildings Standard.

Figure NZ.04: Breakdown of residential thermal demand savings in 2050



If all homes in Holistic Transition remained on gas in 2050 but implemented the same insulation and behavioural changes assumed in the pathway, emissions from heating would fall 39% against current levels.



FES 2024 / Reducing Great Britain's Emissions / Steps to net zero 38

Low carbon energy production

A decarbonised power sector represents a critical milestone in the decarbonisation of the whole energy system. It can enable full decarbonisation of sectors such as transport and heat (through the adoption of electric vehicles and heat pumps) and can also hold the key to unlocking other energy vectors, such as hydrogen production.

Our pathway modelling considers net zero to be the point at which emissions to atmosphere are equal to emissions removed. Low levels of unabated gas generation are compatible with a net zero power system alongside negative emissions.

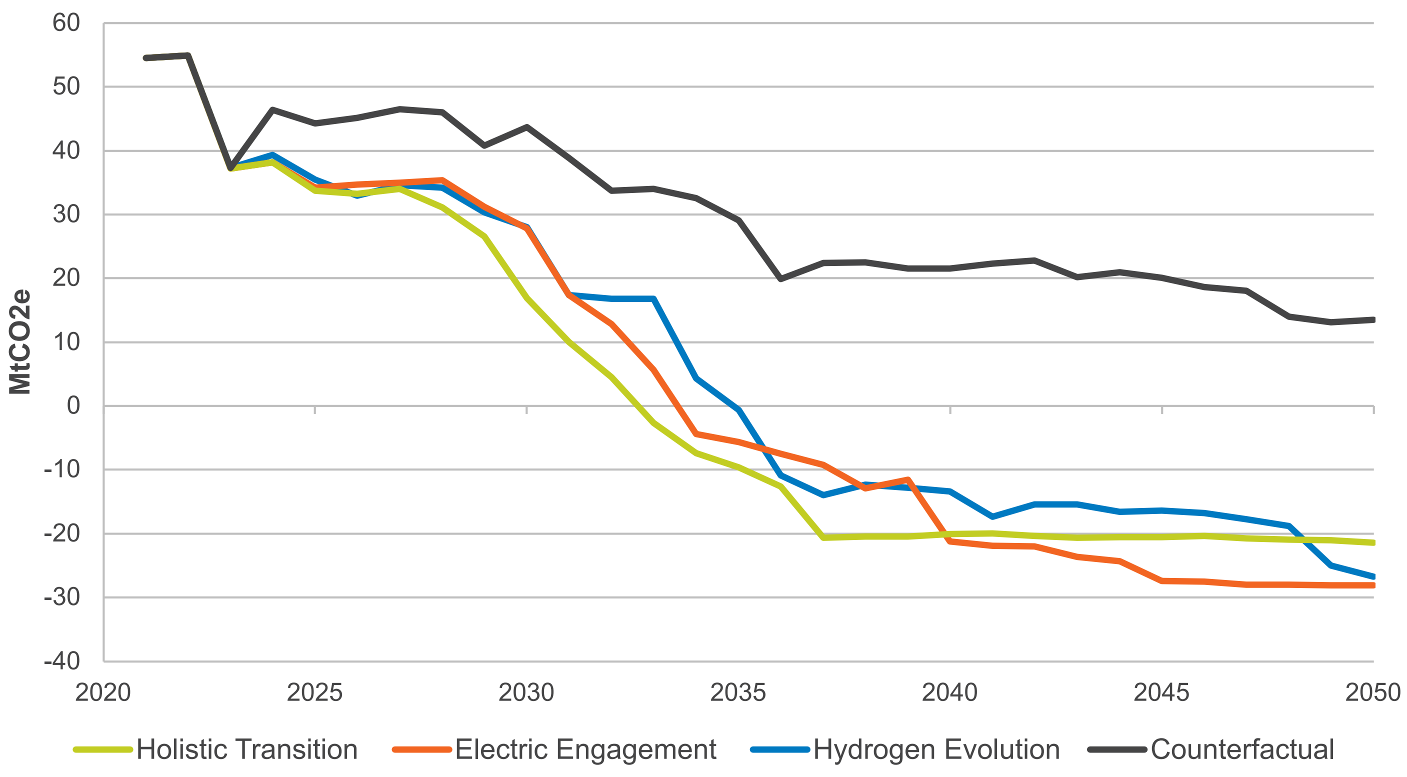
It is possible to go further and faster in the decarbonisation of Great Britain's power sector.

All net zero pathways achieve a decarbonised power sector by 2035 at the latest. Holistic Transition and Electric Engagement achieve this in 2033 and 2034 respectively. This is driven by high levels of wind and solar uptake, reduced use of unabated gas and initial deployments of bioenergy with carbon capture and storage (BECCS). Negative emissions with power BECCS from 2030 onwards are essential to achieving net zero power.

Towards 2050, the power sector acts as a net source of negative emissions due to the use of power BECCS. This offsets hard-to-abate emissions from elsewhere in the economy. Electric Engagement has the most carbon removal from power BECCS in 2050, at 33 $MtCO_2e$ per year. Hydrogen Evolution achieves net zero power in 2035.

The **Counterfactual** does not achieve a decarbonised power sector, with continued net emissions of 13 $MtCO_2e$ per year in 2050. This is due to continued use of unabated gas, lower levels of renewables and low utilisation of power BECCS.

Figure NZ.05: Power generation emissions out to 2050



Low carbon energy production

The route to net zero

Achieving a net zero power system requires rapid acceleration in the deployment of low carbon generation and flexible technologies.

Key Actions 7&8

Substantial growth in capacity is required across all pathways to facilitate the electrification of heat, transport and other sectors in line with Government targets.

Reducing delivery times of new infrastructure is critical to the delivery of a net zero power system.

Key Actions 1&8

Delivery of optimal whole system infrastructure can be accelerated through implementation of strategic network investment, alongside planning reforms and investment in supply chain and skills.

A net zero power system must be underpinned by improved market design.

Key Action 2

There is a need to incentivise assets to locate and dispatch where they can minimise whole system costs. Market reform should consider the benefits of cross-vector interactions across the whole energy system.

Negative emissions are required in the power sector to offset emissions from hard-to-decarbonise energy uses.

Key Actions 2&3

Robust emissions accounting standards are needed to ensure both investor and public confidence in a negative emissions market. Further demonstration of innovative emissions reduction technologies is required to reduce uncertainties over technology and commercial readiness.

The operational impact of a net zero power system is manageable.

As part of our effort to make the grid ready to operate with 100% zero carbon electricity by 2025, we are already delivering frequency services. Our stability and voltage pathfinders reduce reliance on dispatchable generation for critical transmission system services and we can already maintain our system restoration capability without warming or running fossil fuel generation.

Technology specific recommendations are made in the The Energy System chapter *(page 86)*.

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Low carbon flexibility

Flexibility

We need low carbon flexibility to operate a net zero energy system. This means switching from unabated gas to low carbon fuels and technologies such as those shown on chart NZ.06. This, alongside electricity storage, CO_2 and hydrogen storage, can help reduce emissions. More information on supply side flexibility is in the Energy System chapter *(page 86)*.

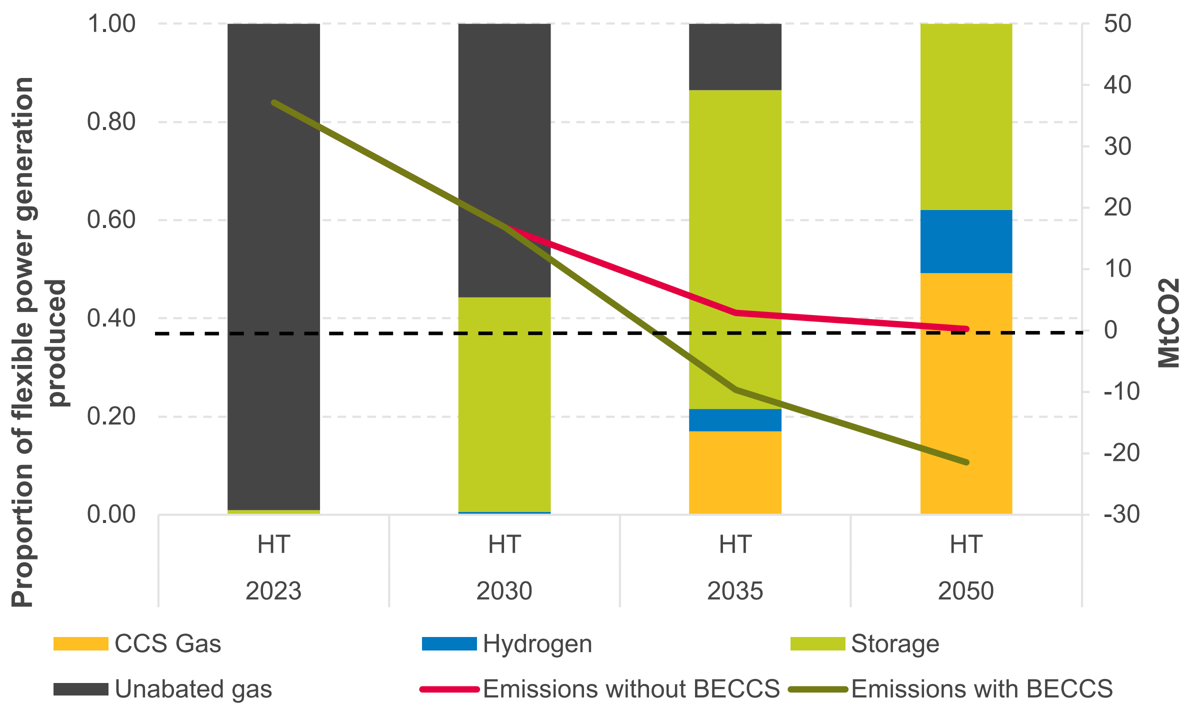
Holistic Transition like all our net zero pathways sees the role of natural gas evolving and it will still be needed to ensure secure and reliable power delivery. Low carbon dispatchable power (in the form of either gas carbon capture and storage (CCS) or hydrogen generation) as well as large scale electricity storage replace the flexibility provided by natural gas today, leading to lower emissions in future years. A small amount of natural gas remains to ensure a secure and reliable power system. We also consider aggregated smaller-scale flexibility via battery storage, which becomes increasingly important as we move towards a net zero system.

The route to net zero

Low carbon flexible energy sources and storage are vital to provide the adequacy needed for a reliable energy system. Key Action 2

Changing the policy, regulatory and market framework, particularly for long-duration storage, will support the business case for electricity storage projects and bring forward the levels of energy storage required. Business models for hydrogen transport and hydrogen storage must be agreed to kick-start delivery of the necessary infrastructure.

Figure NZ.06: Flexible power generation and emissions out to 2050 for Holistic Transition



The chart above shows energy produced from flexible generation sources and associated emissions out to 2050, with and without BECCS. Interconnectors are not included as associated emissions are not considered within Great Britain.

Fuel switching

All our pathways to net zero require fuel switching from carbon intensive fuels (such as natural gas or petrol) to low carbon alternatives (such as electrification or hydrogen). Fuel switching is required across all areas of the economy and is particularly important for decarbonising heat and transport. Electrification is an important fuel switching option across all sectors as is the production of hydrogen with electrolysis. Fuel switching will come with different challenges and opportunities in each sector, including the technological readiness of options, the rate at which they can be installed and the wider system benefits and trade-offs. An example of the emissions impact of fuel switching for road transport is shown in Figure NZ.07.

Holistic Transition sees road transport emissions more than halve by 2035, from 96 $MtCO_2e$ in 2023 to 42 $MtCO_2e$ in 2035. This is largely due to fuel switching from petrol and diesel to electric-powered vehicles.

Road transport reaches zero emissions in 2050. The vast majority of decarbonisation is from electric vehicles, with small quantities of hydrogen vehicles. Between now and 2042, road transport emissions fall to less than 10% of current values (9 $MtCO_2e$, compared to 96 $MtCO_2e$ at present).

Fuel consumption for road transport declines by almost 70% from just over 400 TWh in 2023, to just over 125 TWh in 2050. This is due to significant efficiency improvements that arise from fuel switching.

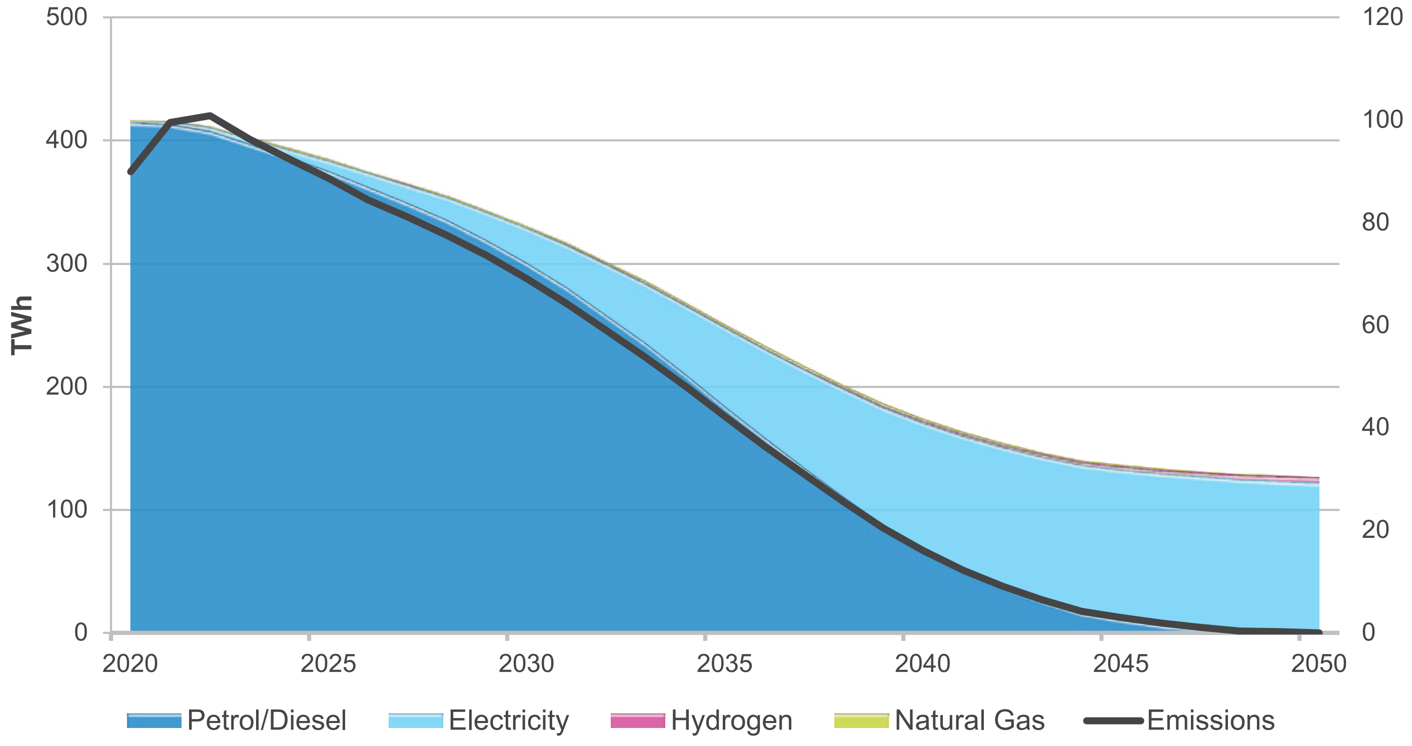
The route to net zero

Fuel switching is essential for net zero and will require whole system coordination to be successful.

Key Actions 1,3&4

Coordination is required to make sure end users in different sectors of the economy are incentivised to switch and that suitable alternative low carbon fuels are available.

Figure NZ.07: Estimated vehicles fuel consumption in Great Britain and associated emissions in Holistic Transition



Carbon capture and storage capacity

All pathways require the development of CCS capacity to achieve net zero. CCS is used across the decarbonisation of power (low carbon dispatchable power), industry, hydrogen production (gas reformation) and negative emissions technologies. The broad range of sector use for CCS storage potential will bring deployment challenges as different sectors begin to make use of these networks in different locations, at different times and to store different relative amounts of CO_2. Our pathways suggest a need for up to 100 million tonnes of CO_2 per year ($MtCO_2$/yr) of CCS capacity by 2050, against an estimated total UK geological CCS capacity potential of over 70 billion tonnes[5]. To contextualise the scale of this future network, UK domestic crude oil production peaked at 137 million tonnes per year in the 1980s and 1990s[6].

All net zero pathways see at least 77 $MtCO_2$/yr of CO_2 capacity in 2050 as essential for net zero. This begins to come online from 2030 and all pathways see between 42-47 $MtCO_2$/yr of capacity in 2035. The Government has highlighted the potential need for 50 $MtCO_2$/yr capacity by 2035[7].

Hydrogen Evolution has the greatest need for CCS capacity, at 100 $MtCO_2$/yr in 2050. This is driven primarily by hydrogen production through methane reformation with CCS, accounting for 28 $MtCO_2$/yr of network use, compared to 6 and 9 $MtCO_2$/yr in Electric Engagement and Holistic Transition respectively.

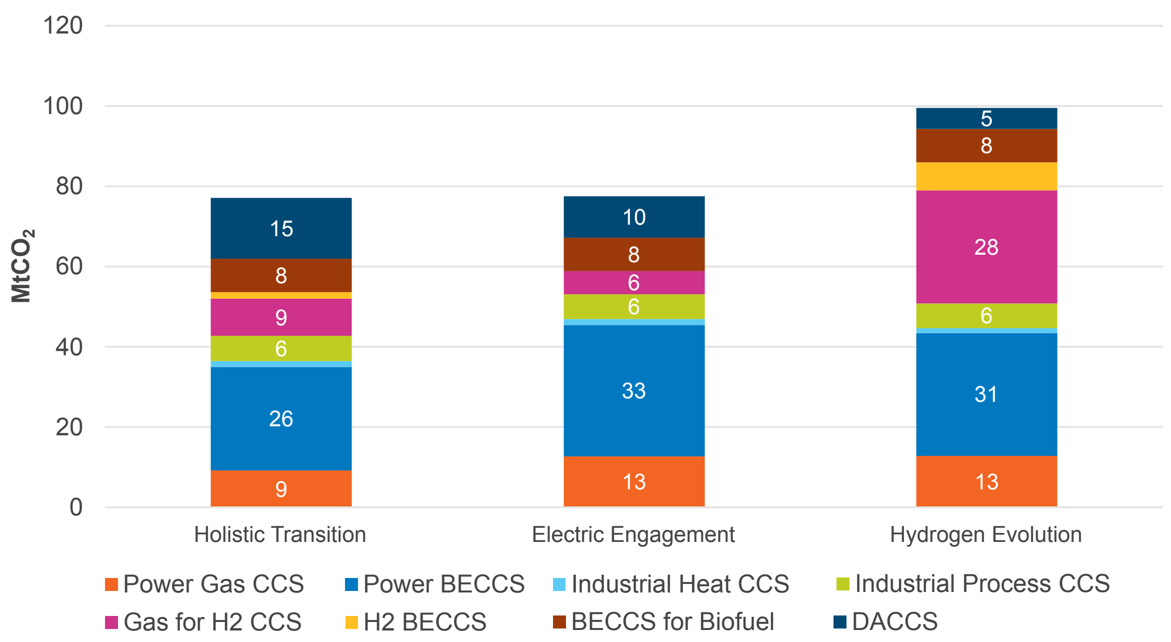
The route to net zero

The development of carbon capture and storage capacity must proceed now if we are to achieve net zero.

Key Actions 1&2

CCS capacity is essential in our pathways and must be available from 2030 onwards to continue decarbonisation across a variety of sectors. Coordination is needed to make sure the timing, location, scale and operation of capacity are suitable for all users and their needs.

Figure NZ.08: Carbon captured per year with CCS in 2050



77-100 $MtCO_2$/yr is equivalent to 18-23% of total UK emissions in 2022

5 bgs.ac.uk/geology-projects/carbon-capture-and-storage/co2-storage-capacity-estimation
6 gov.uk/government/statistical-data-sets/crude-oil-and-petroleum-production-imports-and-exports
7 gov.uk/government/publications/carbon-capture-usage-and-storage-a-vision-to-establish-a-competitive-market

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Carbon removal

Negative emissions technologies (NETs) are essential across all our net zero pathways. However, further demonstration of innovative emissions reduction technologies is required to reduce uncertainties over technology and commercial readiness. Robust emissions accounting standards are also needed to ensure both investor and public confidence in a negative emissions market.

To enable large-scale negative emissions technologies, CCS networks need to be deployed at scale. CCS networks can be used across multiple technologies and sectors and play a vital role in all pathways. Without this large-scale deployment of CCS, we will not meet net zero by 2050. Reaching net zero will rely upon negative emissions, low carbon dispatchable power and the production of low carbon hydrogen.

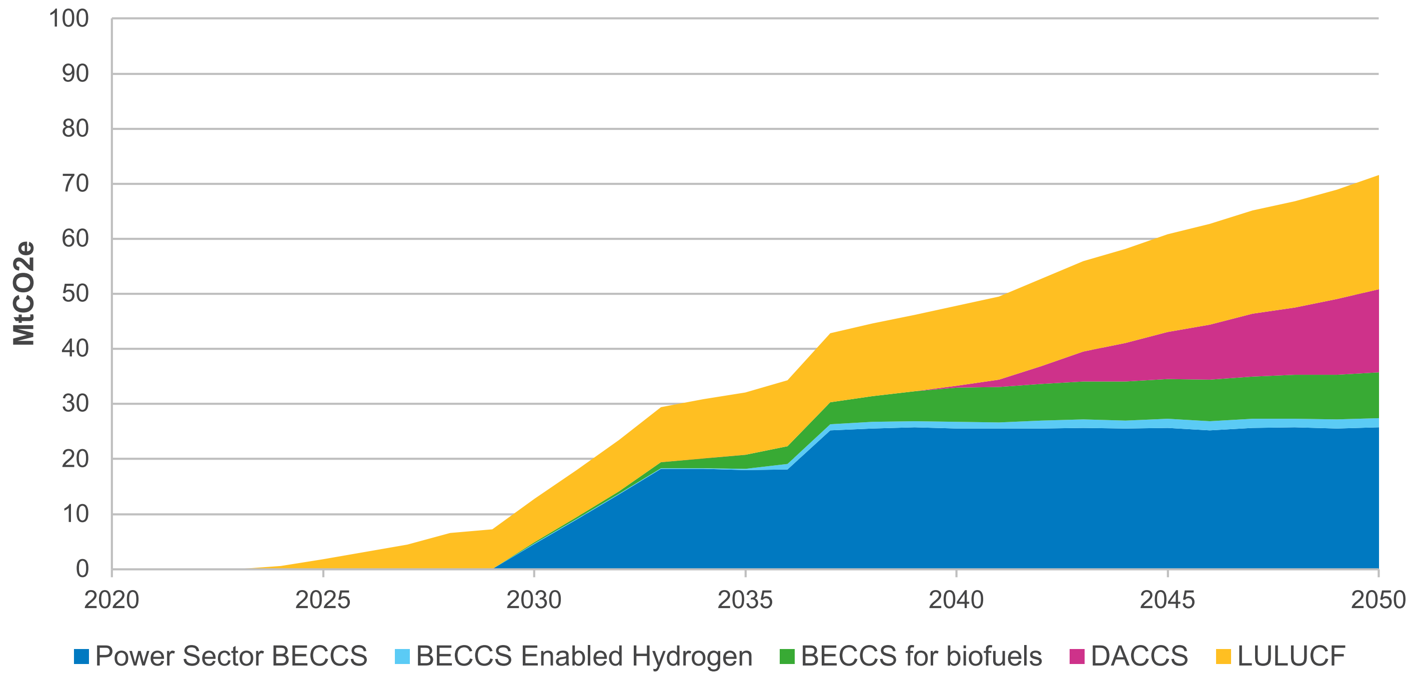
All net zero pathways need negative emissions. Without negative emissions technologies and approaches, our pathways would have around 70 $MtCO_2e$/yr emissions in 2050, equivalent to 16% of the UK's 423 $MtCO_2e$/yr emissions in 2023.

BECCS delivers 33-44 $MtCO_2e$ of removal across the pathways. Power BECCS is seen as the most viable large-scale removal option, given that over 4 GW of UK biomass power generation was built or converted from 2005-2020. The pathways see up to 4.7 GW of power BECCS capacity by 2050.

Direct air carbon capture and storage (DACCS) delivers 5-15 $MtCO_2e$ of removal across the pathways. DACCS is deployed in 2040 but there is potential for this to be brought forward.

The **Counterfactual** sees emissions remaining close to 200 $MtCO_2e$/yr in 2050. An extremely high deployment of negative emissions technologies, far beyond what appears credible, would not be able to counteract slow or no decarbonisation.

Figure NZ.09: Holistic Transition negative emissions with land use, land-use change and forestry



Carbon removal

Figure NZ.10: Electric Engagement negative emissions with land use, land-use change and forestry

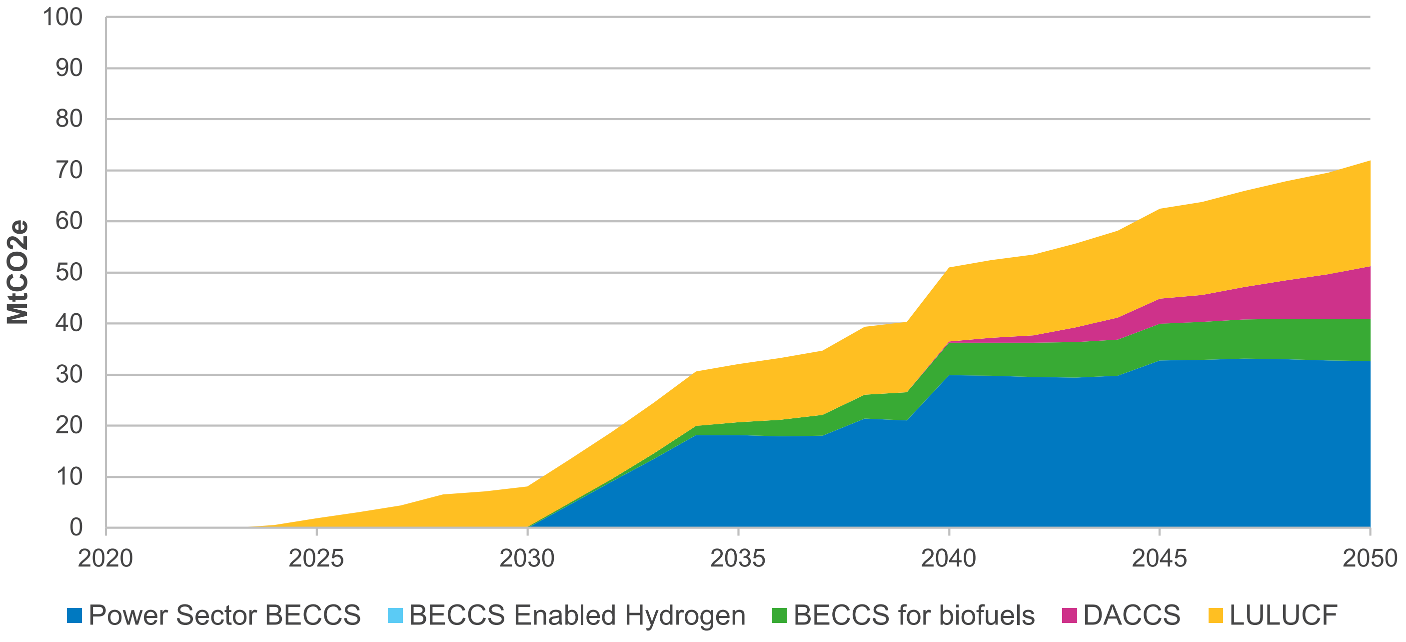
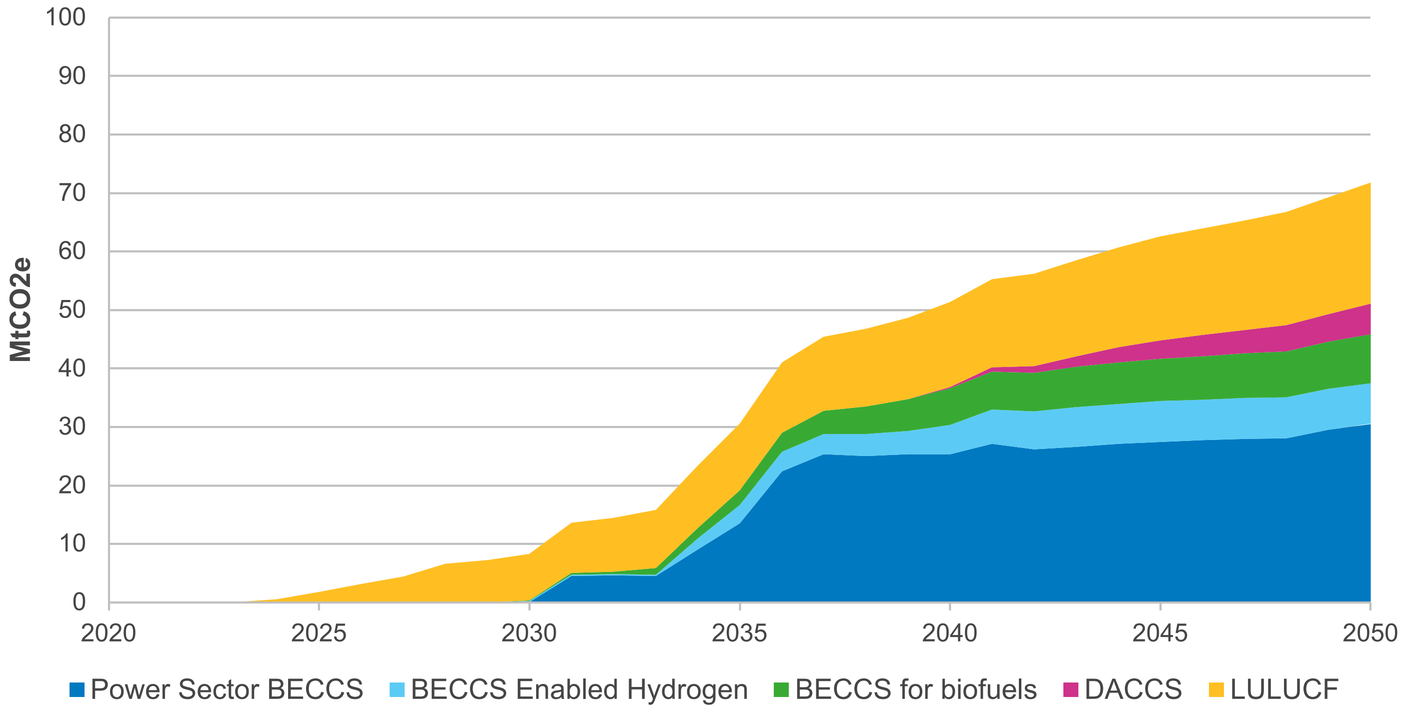
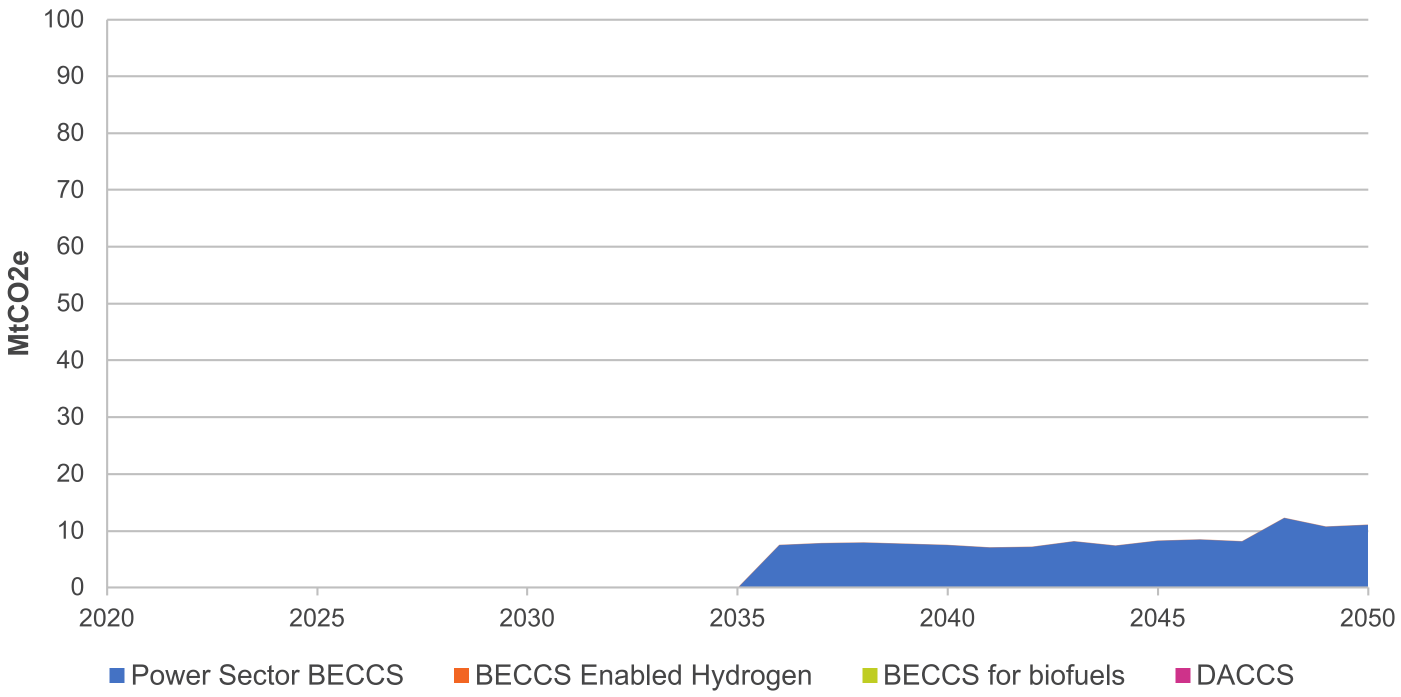


Figure NZ.11: Hydrogen Evolution negative emissions with land use, land-use change and forestry



Carbon removal

Figure NZ.12: Counterfactual negative emissions with land use, land-use change and forestry



Calculating emissions for the pathways

The emissions in our pathways focus on territorial emissions within the borders of the UK, including industrial processes, transport, heat, residential and commercial energy use and energy production. Emissions from other sectors are taken from the Climate Change Committee's Sixth Carbon Budget, updated to reflect latest recorded sector emissions. We follow official carbon accounting rules within our modelling.

Carbon capture, utilisation and storage and carbon capture and storage

Throughout our pathways, we have assumed that captured carbon is always permanently geologically stored from an emissions standpoint.

It is possible to utilise some captured CO_2 in products and store the remainder. This is covered under the broader term carbon capture, utilisation and storage (CCUS). CO_2 utilisation may impact net emissions. Captured CO_2 used in a carbonated drink would quickly be released back into the atmosphere, while CO_2 used in construction materials may be stored for the life of the building (decades).

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Carbon removal

Greenhouse gas removal methods can be broadly classed into two categories.

The first is engineered solutions or negative emissions technologies. This includes BECCS, DACCS or emerging approaches such as enhanced rock weathering or biochar. The second category includes nature-based solutions such as afforestation, soil carbon sequestration and more general approaches around increasing the carbon stored in LULUCF.

Direct air carbon capture and storage

DACCS captures CO_2 directly from atmospheric air before pumping it to permanent storage reservoirs. DACCS is an energy-intensive process requiring both electricity and heat. The heat requirement can be supplied from waste heat sources, such as industrial waste heat. Alternatively, other DACCS technologies in development, such as electrochemical DACCS, work in a similar way to a fuel cell and do not require heat, therefore reducing overall energy demand. Significant activity around DACCS deployment is under way in the USA. Notably, there may be commercial deployment of DACCS in the USA, capturing millions of tonnes of CO_2 per year by the late 2020s. The Government also has an ongoing DACCS and Greenhouse Gas Removals Demonstration competition[8]. The carbon market is a driver of the economic viability of DACCS but, due to the current cost of carbon, there is a disparity between today's value of carbon and what is needed to make the technology viable.

Flexibility

DACCS facilities can be operated flexibly and, if located in areas with high renewable supply and low demand, could play a role in managing network constraints and reducing balancing costs.

This may be beneficial for DACCS, where capture units cycle through a capture mode followed by a solvent or sorbent regeneration step where a significant energy input is required. Other technologies with a high electrical demand could play a similar flexibility role, such as large-scale electrolysers for hydrogen production.

8 gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition

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Bioenergy with carbon capture and storage

BECCS captures CO_2 emissions from bioenergy facilities and stores the carbon underground, leading to a net removal of carbon from the atmosphere. BECCS facilities could produce key energy vectors, such as electricity, hydrogen or other liquid or gaseous fuels.

Carbon accounting in BECCS supply chains must be transparent if BECCS is to be widely accepted as a solution for net zero and clear and strict criteria for the qualification of emissions removal projects must be implemented based on this. Future deployment of BECCS will rely on both scaling up domestically grown biomass feedstock and increasing imported biomass feedstock. As global demand for biomass increases, consideration must be given to the continued amount of biomass imports available for Great Britain.

Land use, land-use change and forestry

LULUCF relates to emissions arising from direct human-induced land use, land-use change and forestry activities.

Carbon is captured both above ground in plants and below ground in soil and organic matter. Increasing the total amount of carbon would see a net removal of carbon from the atmosphere. A net increase in the carbon captured by LULUCF can be achieved through methods such as afforestation or peatland restoration.

Current challenges include monitoring, reporting and verification of carbon stock changes over time. Our LULUCF removals are taken from the CCC's Balanced Pathway. Assuming higher levels of removals from this sector, such as additional afforestation, may take removals beyond credible amounts. Additionally, removals are not necessarily permanent: land use changes could be reversed again, forests may be affected by disease, fires or the effects of climate change. Engineered removal methods such as DACCS and BECCS offer permanent geological storage of CO_2.

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Steps to net zero

The route to net zero

Acceleration of business models and commercial scale-up of negative emissions technologies are needed to reduce uncertainty.

Power BECCS, hydrogen BECCS and DACCS are at varying levels of technological and commercial readiness. These, and other emerging negative emissions technologies, require continued development to ensure they can be deployed.

Negative emissions technologies are required for net zero but should not replace other low carbon technologies or approaches.

NETs are used in addition to credible low carbon technologies and approaches to achieve net zero. They should not be used in place of efforts to avoid emissions to atmosphere.

Acceleration of business models and robust emissions accounting standards are necessary to ensure investor and public confidence in a negative emissions market.

Clear and strict criteria for emissions removal projects must be implemented based on transparency of supply chain emissions.

Large-scale deployment of CCS is needed within the next 10 years.

Key Actions 1&2

The development of CCS networks will underpin many decarbonisation technologies and efforts, including electricity generation and the production and use of hydrogen for fuel switching. Delivery of industrial clusters will be key to this.

The UK has a large amount of depleted oil and gas reservoirs. There is an opportunity to import CO_2 from Europe, particularly North West Europe which lacks access to such reservoirs.

Key Action 8

Continued investment and international collaboration and regulation would be needed to develop this. Great Britain is a world leader in both technology development and knowledge exports and has an extensive offshore engineering skill base. This could be leveraged to expand our offshore CO_2 storage and pipeline infrastructure. Innovation and development of negative emissions technologies can bring additional opportunities in this space.

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Emerging technologies

There are a variety of other emerging negative emissions technologies and approaches rapidly evolving in the carbon removals sector. Their use at scale would depend upon validation of their carbon removal ability and an understanding of their potential broader impacts, such as on the environment.

If you know of a new and innovative technology that could be considered in the modelling of our pathways, please contact fes@nationalgrideso.com.

Biochar

Biochar is produced when biomass is heated in the absence of oxygen, in a process known as pyrolysis. This produces a carbon-rich solid (biochar) alongside co-products of bio-oil and syngas. Biochar can be used as a soil amendment for agriculture and is also proposed as a long-term stable store of carbon. Programmes are under way to validate the performance of biochar as a store of carbon.

Bio-oil injection

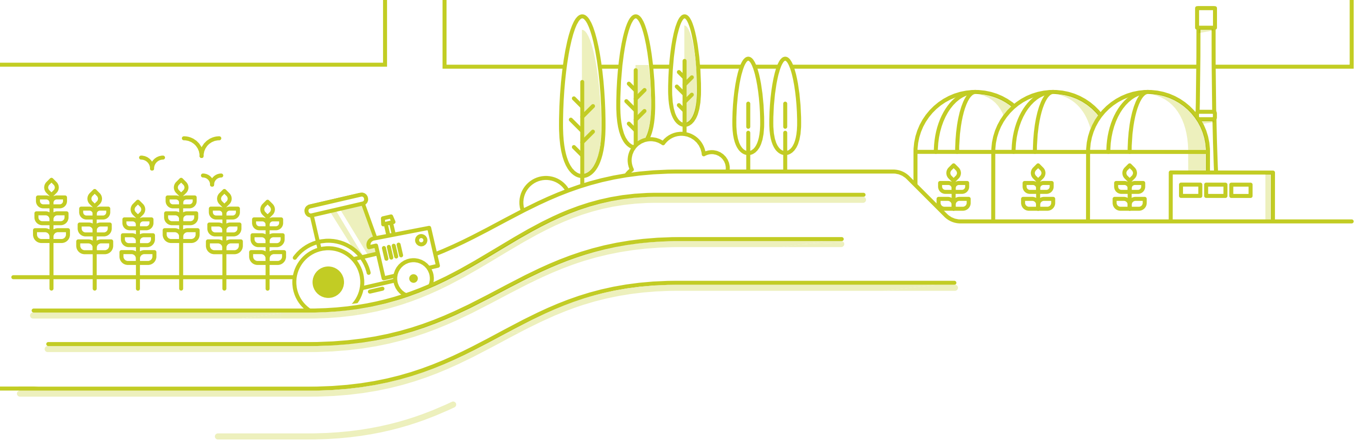
Alongside the production of biochar, bio-oil is produced as a co-product. Bio-oil can be permanently stored in underground storage wells, similar to the long-term storage of fossil oil or waste liquids and slurries. This approach has been piloted at scale in the USA. A similar concept also under development is biomass slurry injection, where a liquid slurry is created with waste biomass and injected into underground storage wells.

Biomass burying/storage

Biomass of various types can be turned into dense blocks and stored in an environment under which it will not decompose further.

Enhanced weathering and ocean alkalinity enhancement

Minerals that will react with CO_2 in the air or increase uptake of CO_2 into marine systems are milled to a powder and spread over land or in water.



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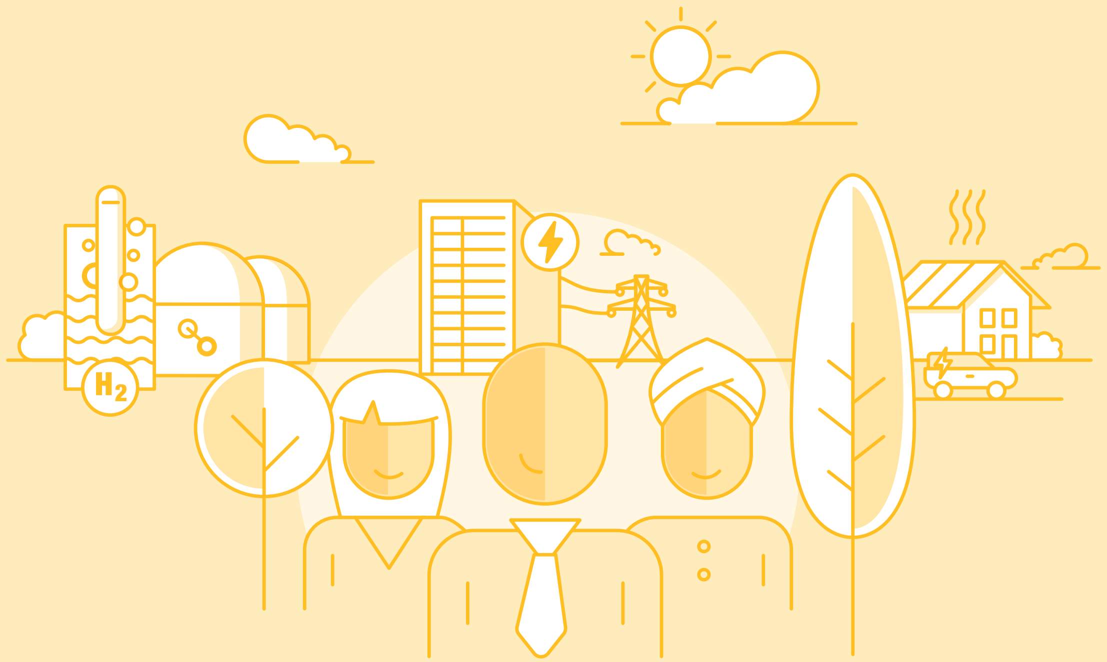
The Energy Consumer



Introduction

Consumers are the heart of our energy system and the transition to clean energy sources must be fair and affordable for all. This will require engagement in low carbon technology adoption and supporting them to fully optimise energy efficiency measures.

Demand in this chapter represents the energy directly used solely by consumers. This includes, for example, residential consumers and their homes and cars, large-scale industrial manufacturing sites and commercial consumers operating shops and offices.

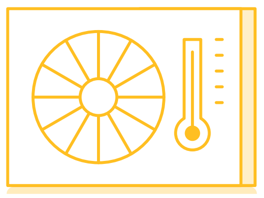
People around Great Britain continue to struggle with energy costs, with a reported 6 million UK households in fuel poverty as of 1 April 2024[1]. The ongoing cost of living crisis is having a direct impact on how UK households consume energy and their lifestyle choices. Consumers have a major role to play in enabling the energy system of the future, but care needs to be taken to ensure the transition doesn't leave anyone behind.

Consumers need to be provided with advice and financial support to help them adopt low carbon technologies and energy efficiency measures. Empowering them to understand how to use their appliances most efficiently, with the added benefit of good operating practices on our network, will lower the cost of decarbonisation by helping to reduce network investment and increase utilisation of renewables. This can be achieved through the adoption of smart home devices or by actively shifting demand in line with signals from flexibility services.

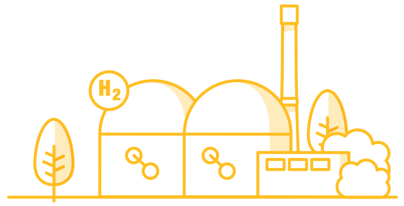
Alongside increased interaction with the energy system, consumers could benefit from lower energy costs through the adoption of smart, low carbon technologies, better operating practices and optimising usage through time-of-use tariffs (TOUTs) with off-peak charging rates. However, many of these technologies still have high upfront costs, which is a barrier to uptake.

There is an urgent need to foster consumer trust in energy markets and emerging technologies and services, and to ensure these services are as inclusive as possible. Ensuring there is independent, comparable and simple advice and information on products and services can encourage adoption of low carbon technologies, support consumers to realise cost savings and enable system operators to maximise system operation benefits. Long-term engagement plans must clearly present evidence of realised cost and emissions savings and robust data privacy and security measures will be critical to building consumer confidence to maximise engagement.

Further action is needed to enable mass consumer participation in the energy transition, but this undertaking can't be considered in isolation from the cost of living crisis. Ongoing targeted support is required to prevent impacting groups of consumers disproportionately that may be impacted by the transition to net zero.



Net zero pathways see 0.8-1.0 million heat pumps installed per year in 2030.



Hydrogen Evolution has over 40 TWh of hydrogen demand for industry in 2035.

Smart charging and vehicle-to-grid reduce peak demand by 49 GW in Holistic Transition in 2050.

Data centres add up to 62 TWh of electricity demand in 2050.

1 National Energy Action

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Total consumer energy demand

Total consumer energy demand falls in all pathways driven by the rollout of improvements in energy efficiency measures and electrification. This reduction in demand has a range of impacts, most significantly on natural gas demand, with all net zero pathways reaching close to zero unabated natural gas use by 2050.

There is a variation in the use of hydrogen across the pathways, with Electric Engagement seeing only 16 TWh within industry, whereas Hydrogen Evolution sees 78 TWh from consumer demands (excluding power), with a national hydrogen network supplying all sectors. Holistic Transition has a more mixed outlook, with hydrogen networks local to industrial clusters.

Figure EC.01: Annual consumer demand in Holistic Transition by fuel and sector

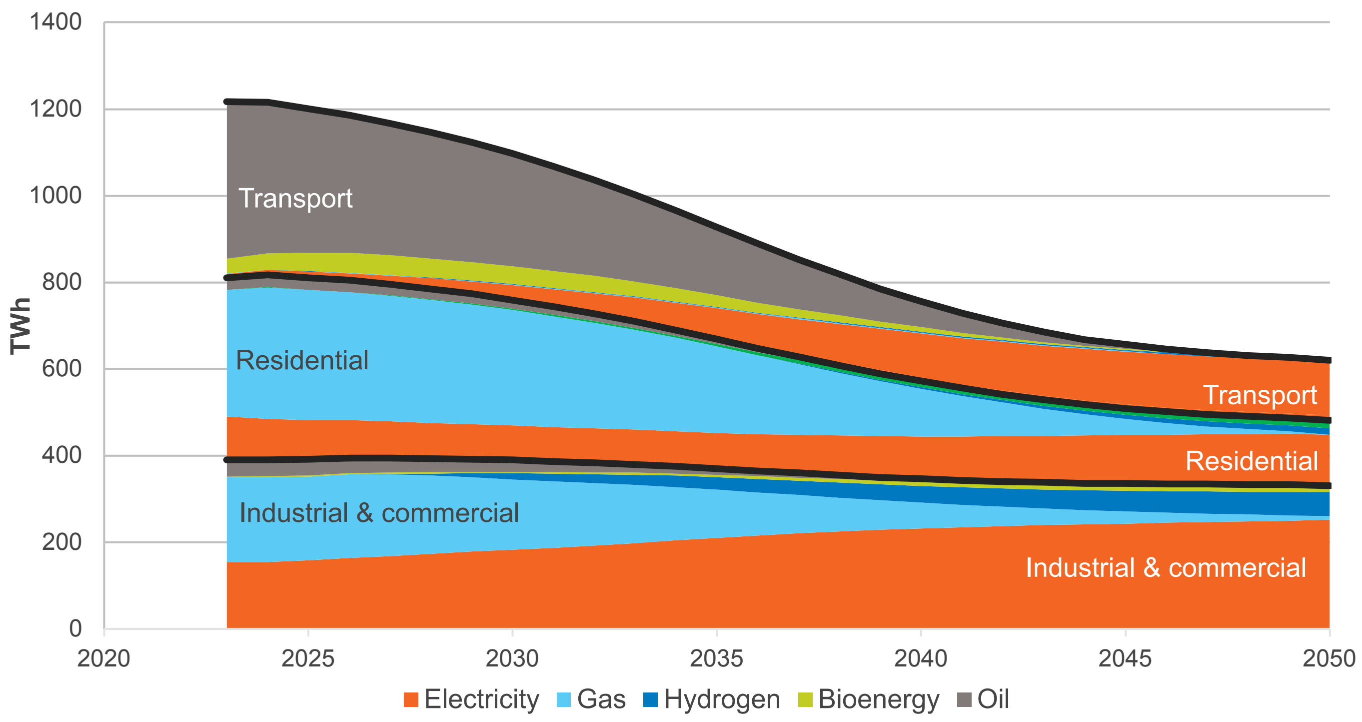
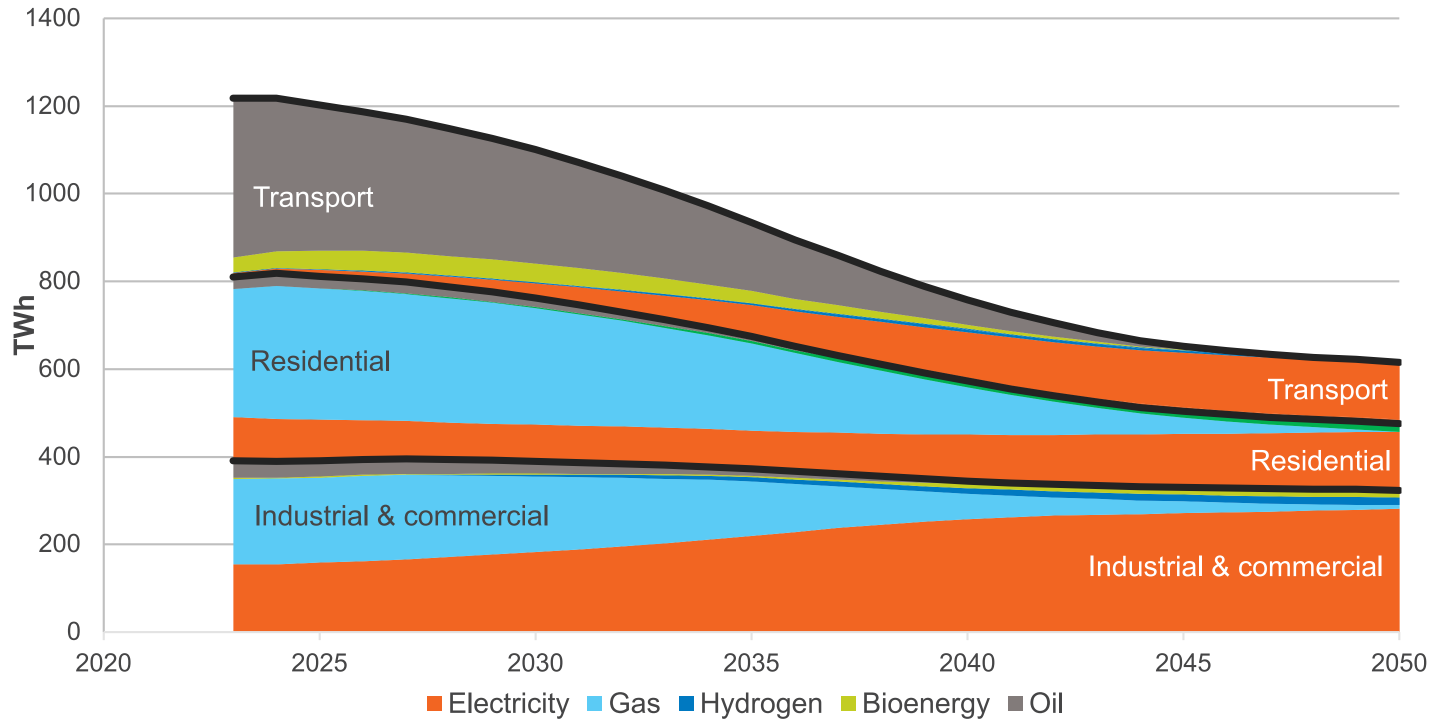


Figure EC.02: Annual consumer demand in Electric Engagement by fuel and sector



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Total consumer energy demand

The greater the level of electrification within a pathway, the lower the overall consumer annual energy demand. Across the pathways, reduction in energy demand is most prominent in the heat and transport sectors due to heat pumps being over triple the efficiency of gas boilers and battery electric vehicles (BEVs) being over double the efficiency of petrol cars. All transport demand is captured in the transport section of this chapter *(page 57)*.

The Counterfactual has a slower transition away from fossil fuels, mainly to electrification because of negligible hydrogen uptake outside of the industrial sector. The transport sector is the only sector to make significant progress with an 85% use of low carbon fuels in the Counterfactual in 2050, although at a slower pace than the pathways.

Figure EC.03: Annual consumer demand in Hydrogen Evolution by fuel and sector

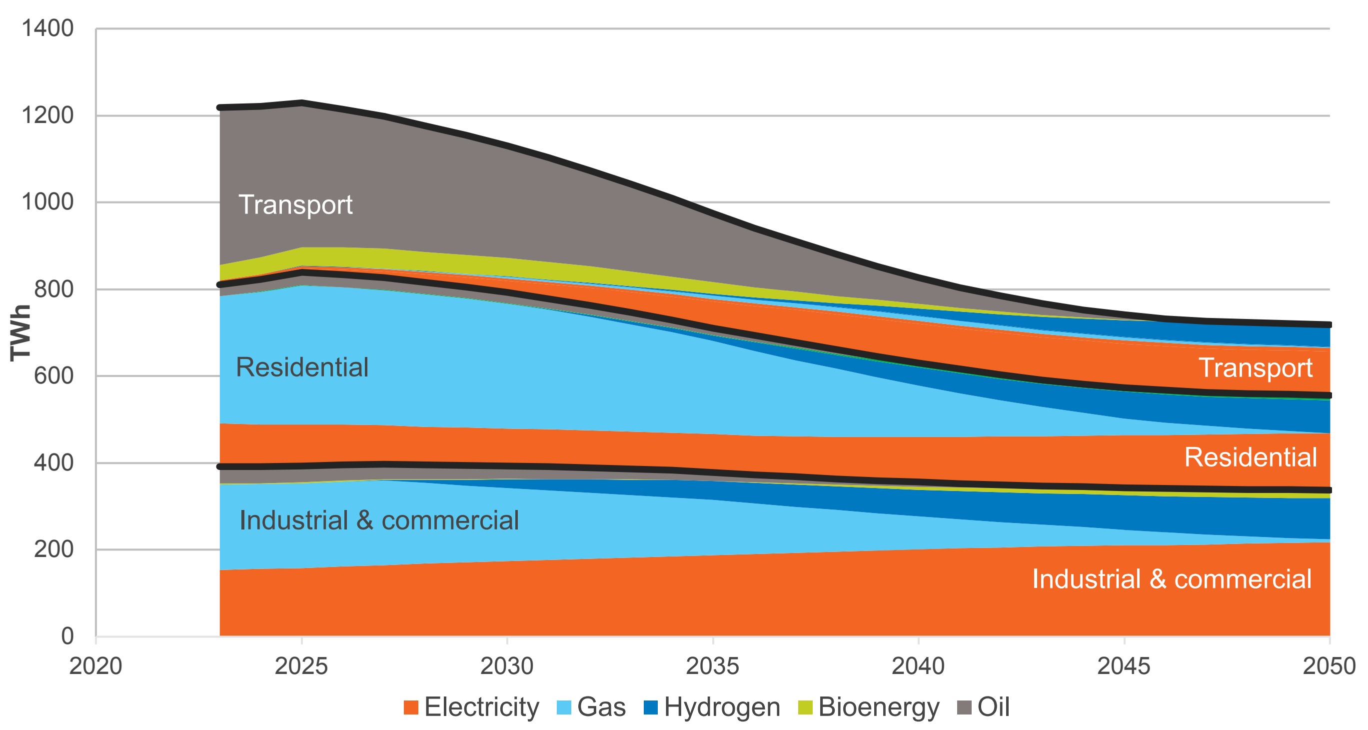
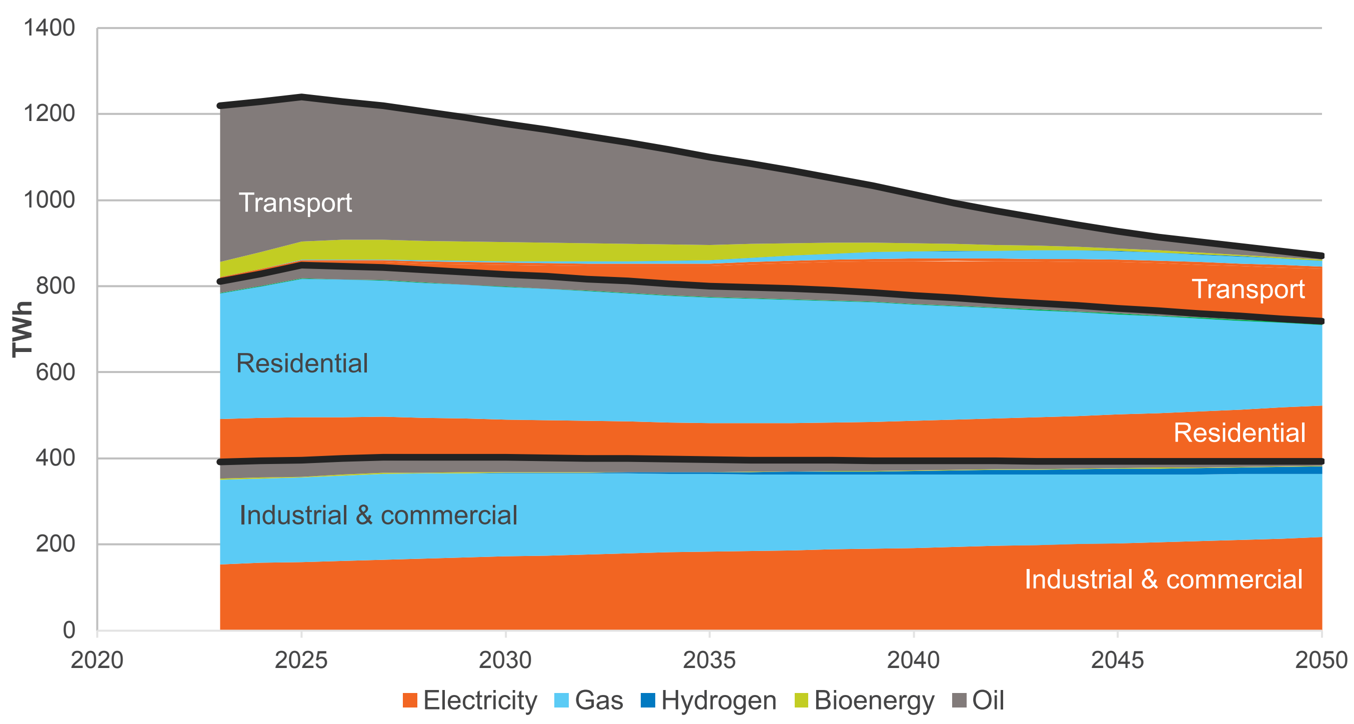


Figure EC.04: Annual consumer demand in the Counterfactual by fuel and sector



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Consumer flexibility

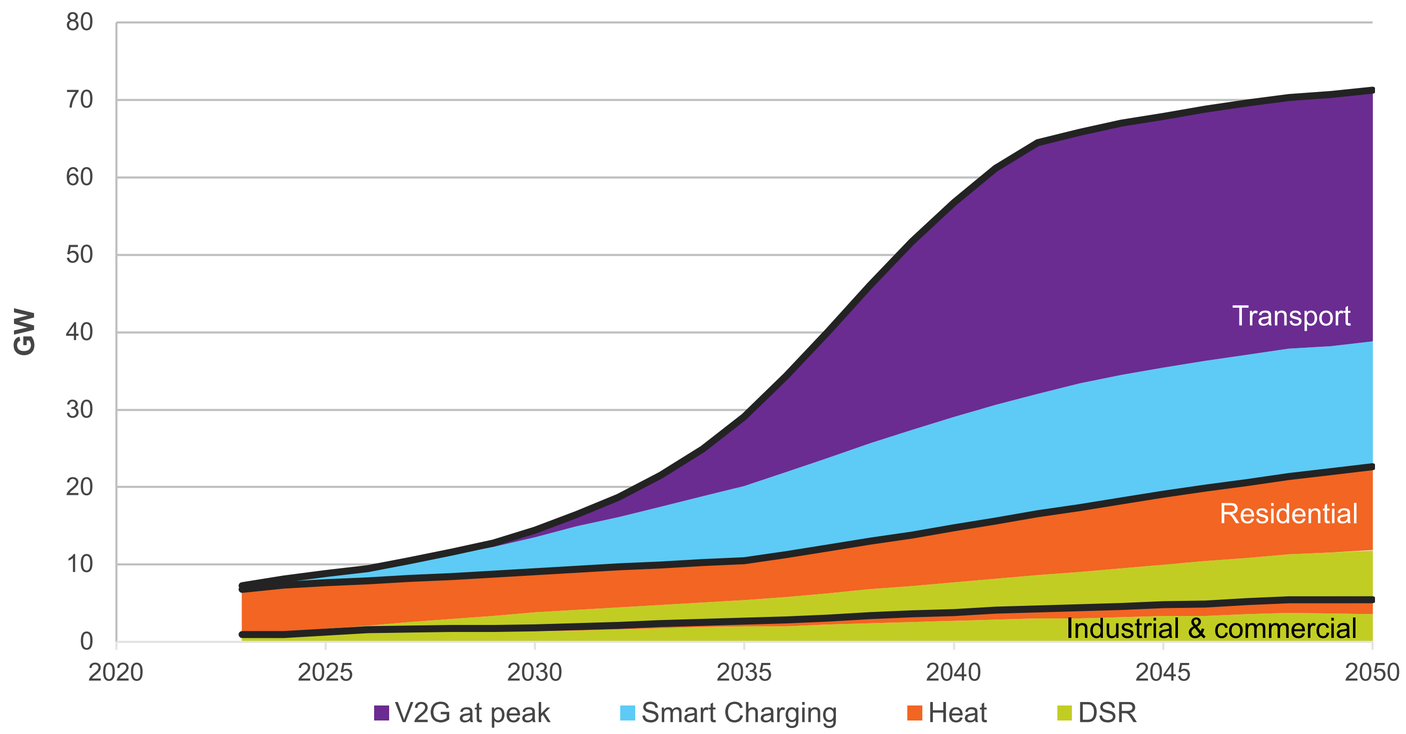
Flexibility

The Average Cold Spell (ACS) peak electricity demand is linked to the cost of the electricity system from a supply capacity and infrastructure perspective. For more information on this, please see the Energy System chapter *(page 86)*. Flexibility from consumers is key to reducing peak electricity demand, particularly as more sectors electrify. As we move away from dispatchable electricity supply, consumers can also support by turning up their demand to use surplus generation or to avoid high cost or carbon-intensive generation.

The National Grid Electricity System Operator (ESO) Demand Flexibility Service (DFS) promotes consumer engagement in shifting demand. More than 2.4 million households signed up for Winter 23/24 DFS[2], compared to 1.6 million in Winter 22/23. These statistics show a positive increase in consumer engagement and it is vital that flexibility services are widely accessible. The increasing selection of TOUTs, including some dedicated towards specific technologies such as BEVs and heat pumps, encourage longer-term engagement by offering consumers the opportunity to save money by shifting demand.

Evening peak demand flexibility in **Holistic Transition** is supported by all sectors. Smart charging of BEVs and use of thermal storage for heating demand offer large amounts of flexibility. Demand side response (DSR) in residential appliances and industrial and commercial processes support system flexibility. BEVs using vehicle-to-grid (V2G) functionality have the potential to reduce demand by 32 GW in Holistic Transition by 2050, the largest of any consumer flexibility technology.

Figure EC.05: Consumer flexibility in Holistic Transition at peak by sector



2 National Grid ESO: Demand Flexibility Service Overview of Winter 23/24 and What's Next

Key comparison chart of decarbonisation milestones

Key comparison chart

This chart contains a selection of recent policy ambitions in relation to net zero and energy security and highlights how they compare to the different pathways. The chart also shows non policy-related items that are key decarbonisation milestones.

Note that energy demand will be affected by policy on the supply side which is set out in the comparison chart in the Energy System chapter *(page 96)*. It is critical that policy considers the whole energy system and not supply and demand in isolation.

Please note analysis for FES 2024 commenced before the publication of several key policy documents and the UK general election and reflects policy targets and ambitions at the time of analysis.

		2023	2025	2030	2035	2040	2045	By 2050	Maximum potential by 2050	Maximum potential pathway
Transport	Sales of petrol and diesel cars and vans banned	1.6m petrol, diesel and hybrid cars and vans sold			HT EE HE	CF			39m battery electric cars and vans	HE
	Zero tailpipe emissions for all new heavy goods vehicles	<1% of heavy goods vehicles sold				HT EE HE	CF		Zero diesel heavy goods vehicles still on the road	HT EE HE
Heating	600,000 heat pumps installed per year (by 2028)	Approximately 100,000		HT EE HE		CF			1.5m per year	EE
	4 in 5 homes not using natural gas boiler as primary heat source	1 in 5					HT EE HE		100%	HT EE HE
Natural gas	Gas grid connection for new homes ends	80%	HT EE HE	CF					0%	HT EE HE
Industry	Annual industrial hydrogen demand over 10 TWh	<0.5 TWh		HT HE		EE			78 TWh	HE

HT Holistic Transition
EE Electric Engagement
HE Hydrogen Evolution
CF Counterfactual
Government policy

In developing the pathways we balance current ambitions, progress towards targets, stakeholder feedback and what we have modelled for an optimal pathway. Policy assumptions vary across the pathways in line with the pathway narrative. More information can be found in our "Future Energy Scenarios: Pathway Assumptions 2024[3]" document.

3 nationalgrideso.com/future-energy/future-energy-scenarios-fes/fes-documents

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Battery electric vehicles

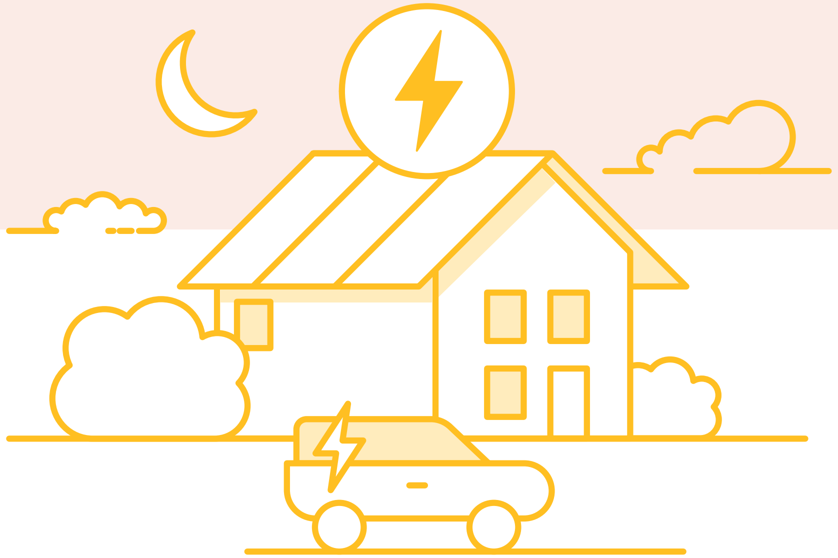
The private and commercial car market is strengthening but sales remain 18% lower than pre-pandemic levels. Sales of BEVs continue to rise as the technology becomes more commonplace in society and barriers to uptake decrease, such as growth in the second-hand BEV market. However, despite an increase in sales in 2023, battery electric cars' share of the market idled at 17% due to an increase in petrol car sales throughout 2023[4].

The UK Government's Zero Emission Vehicle (ZEV) mandate provides much needed clarity for automotive and energy industries. Through the ZEV mandate, 80% of new cars and 70% of new vans sold in Great Britain will be zero emissions by 2030, increasing to 100% by 2035, guaranteeing year-on-year market growth. While following this mandate will be challenging, it is essential to meet the Sixth Carbon Budget.

The Local Electric Vehicle Infrastructure (LEVI) Fund and Electric Vehicle Chargepoint Grant for Households with On-Street Parking offers cross-pavement solutions to help increase charging accessibility, while giving consumers easier access to smart charging and associated smart tariffs. These schemes, and future equivalents, can help make the transition to BEVs more accessible, but Great Britain's public charging network will also need to be bolstered across the country.

To build on the sustainability benefits of BEVs, more work is required to provide information up front to help empower consumers to make informed decisions on all aspects of their next vehicle, based on their mileage and lifestyle requirements. In recent years, consumers have shown a growing preference for larger utility sized vehicles, whereas smaller vehicles and battery sizes typically offer improved energy efficiencies and have lower associated embodied emissions. Increasing the recycling and second-hand use of batteries is required to improve the sustainability of BEVs by decreasing the overall amount of rare earth materials needed.

As more consumers transition to low carbon fuels for transportation, the operating costs of the fossil fuel market will be shared across a reduced number of users over time – these increased costs on the market need to be managed considerately for consumers who are unable to consider alternative private transportation options.



4 SMMT vehicle data - car registrations

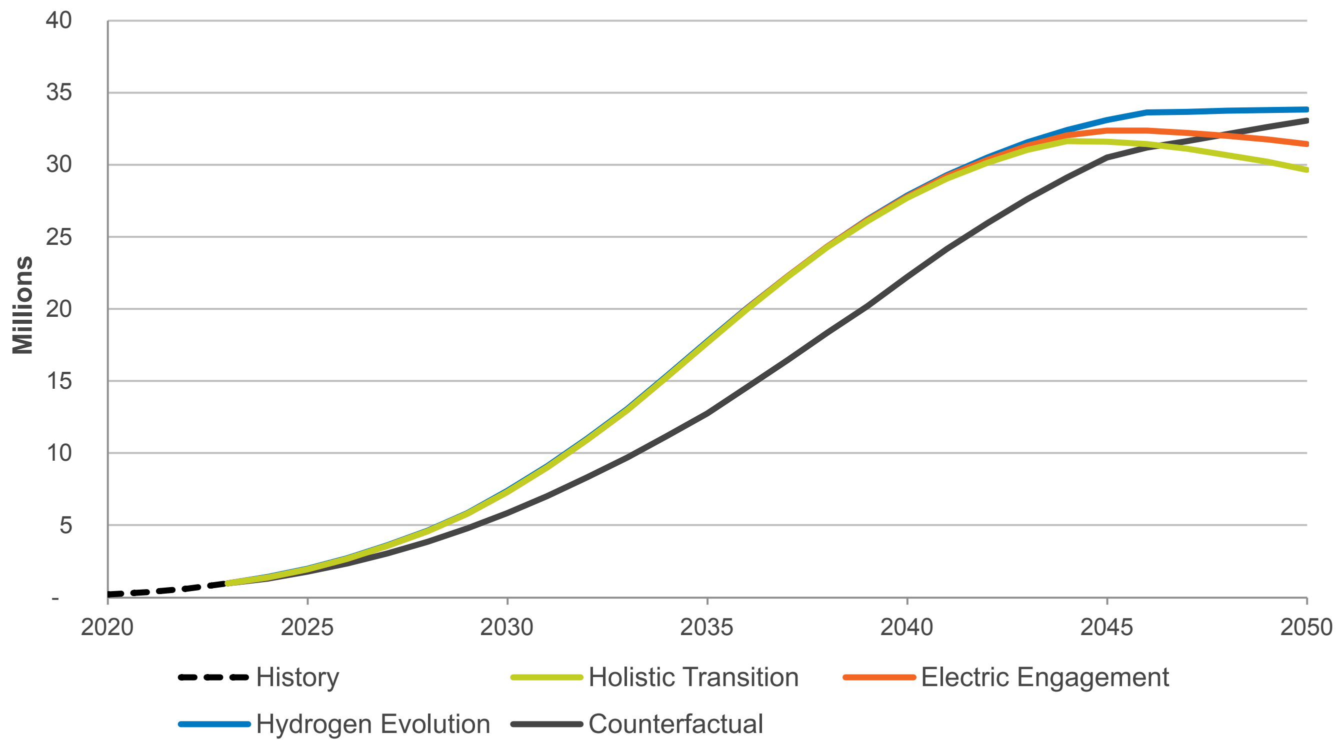
Battery electric cars in our pathways

All net zero pathways follow the targets of the ZEV mandate, as BEV cars provide potential to accelerate the decarbonisation of the industry. Deviation from the mandate would require increased action in other sectors to make hitting targets within the Sixth Carbon Budget feasible.

The pathways begin to diverge in the 2040s, accounting for an increase in shared autonomous vehicle (AV) usage which reduces car ownership at varying levels across the three net zero pathways. Holistic Transition features the most AV usage, reducing the number of BEV cars on the road by 2m from 2044 to 2050.

The **Counterfactual** has a slower BEV car uptake than the UK Government's ZEV mandate, with BEVs only reaching 100% of new car sales by 2040 (five years after the net zero pathways), and fails to meet the Sixth Carbon Budget.

Figure EC.06: Battery electric cars on the road



Other battery electric vehicles in our pathways

Other BEVs are also increasing in popularity and smaller BEV motorcycles and scooters are now at price parity with internal combustion engine (ICE) equivalents. Zero tailpipe emission bus registrations have increased to approximately 60% of the market in 2023.

Progression in the development of battery electric heavy goods vehicles (HGVs) has already begun, with some vehicles now able to cover the distances between drivers' mandatory breaks. This technology enhancement will give haulage companies more options when considering their low carbon fleet in the future.

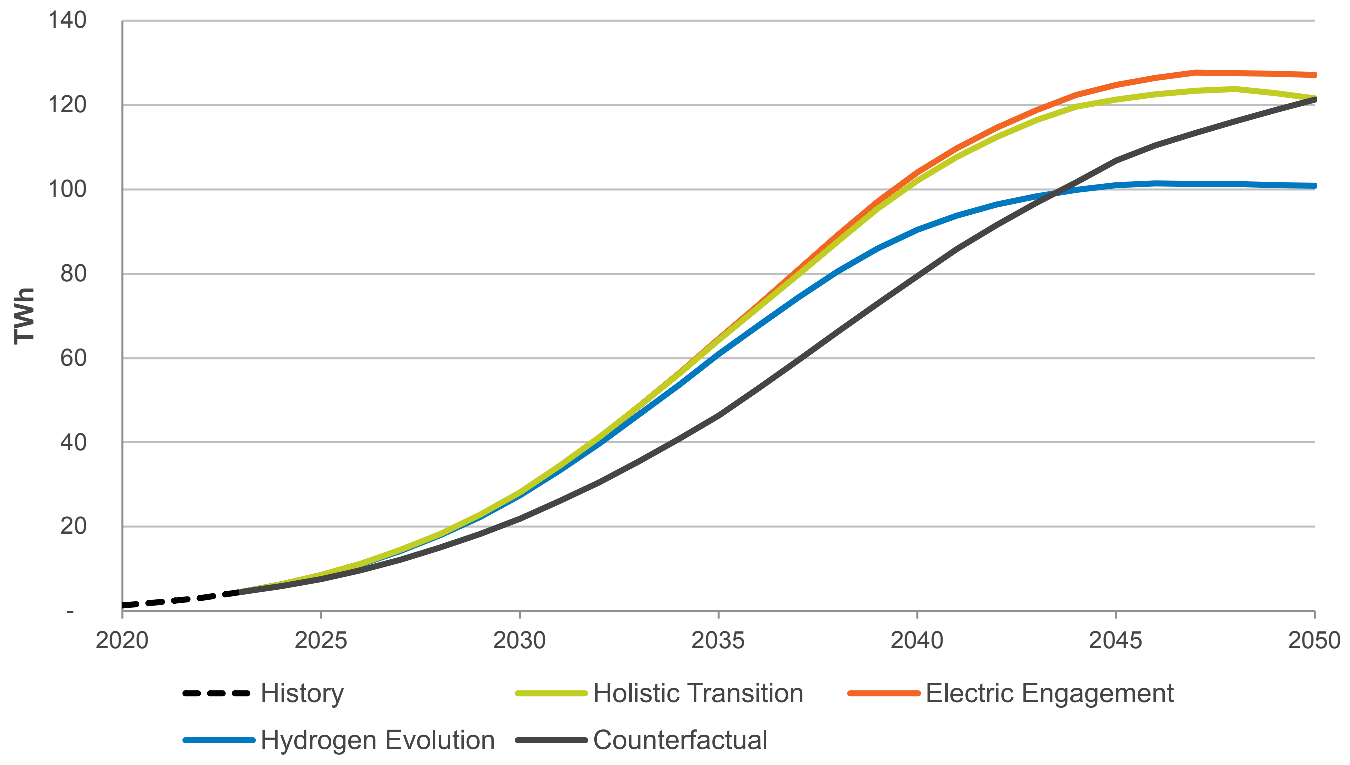
All net zero pathways follow the ZEV mandate for vans. Buses and coaches are predominately electrified in all net zero pathways by 2050, with hydrogen vehicles still in use for longer journeys.

Motorcycles are heavily electrified in all net zero pathways and meet an ICE ban date in 2030 for small motorcycles and scooters and 2035 for larger motorcycles.

Holistic Transition and **Electric Engagement** see high levels of electric HGV uptake, starting with lighter vehicles as the technology develops and gradually becoming more competitive in the heavier HGV market. The electrification of road transport sees a 122 TWh increase in electricity demands in 2050 in Holistic Transition, and 127 TWh increase in 2050 in Electric Engagement.

Hydrogen Evolution mainly sees the electrification of lighter HGVs, with the requirement for larger vehicles (approximately half of all HGVs) forecast to be met by fuel cell electric vehicles (FCEVs).

Figure EC.07: Electricity demand for road transport



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The route to net zero

Public charge points in Great Britain increased by 45% in 2023[5], but more investment is required to keep pace with the growth of battery electric vehicles.

Investment in public charge points needs to be geographically targeted to give consumers without access to off-street parking or cross-pavement systems more opportunity to consider a BEV as their primary mode of transport.

Widespread distribution of rapid charge points across the country will help consumers overcome range anxiety when travelling cross-country. Increased consumer confidence in public charger access will also improve consumer acceptance of smaller battery capacity BEVs, which coincides with a lower purchase price.

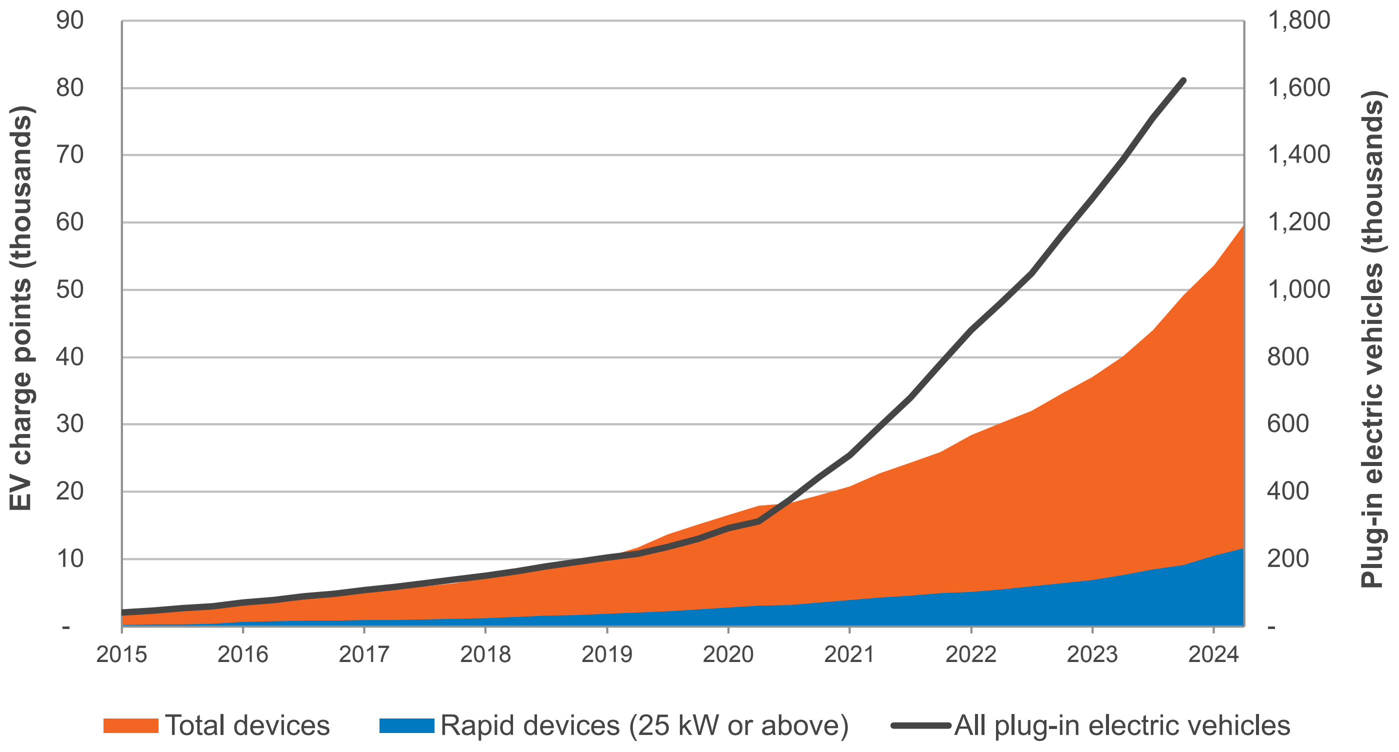
Charging infrastructure can be limited by electrical connection delays, particularly for larger charging hubs, HGV depots and service stations. The Rapid Charging Fund (RCF) scheme could allow faster infrastructure growth of high-power recharging on major routes. There is ongoing work across the transmission and distribution connections processes that seeks to speed up these connections.

As with the Zero Emission Vehicle mandate for cars and vans, similar policies for other vehicles will provide certainty in investment and the supply chain, further decarbonising road transport.

Key Action 8

The introduction of clear long-term policies will provide greater certainty and confidence around decarbonisation of other vehicles such as buses, coaches, HGVs and motorcycles.

Figure EC.08: Electric vehicle public charge points installed in the UK



Source: Gov. UK vehicle licensing statistics data tables

5 gov.uk/government/statistics/electric-vehicle-public-charging-infrastructure-statistics-april-2024

Smart charging

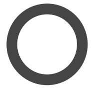
Flexibility

Smart charging can help balance the grid when demand is high and make use of surplus energy during periods of excess supply, while providing financial benefits to consumers. This cooperative consumer engagement practice has the power to reduce peak demand and, when combined with accurate locational wholesale prices, also has the potential to reduce constraints on the network as well as maximise renewable energy usage.

Often combined with lower off-peak charging tariffs, smart charging offers financial benefits and will become more autonomous as the technology develops, making the process more valuable and convenient for consumers. More recently, charging point operators have started offering off-peak rates and smart charging functionality for some public charge points, reducing costs and the burden on our electricity network. ESO is assessing the implications of EV demand shifting and now allows 300 MW of flexible aggregated assets to joint the balancing mechanism[6].

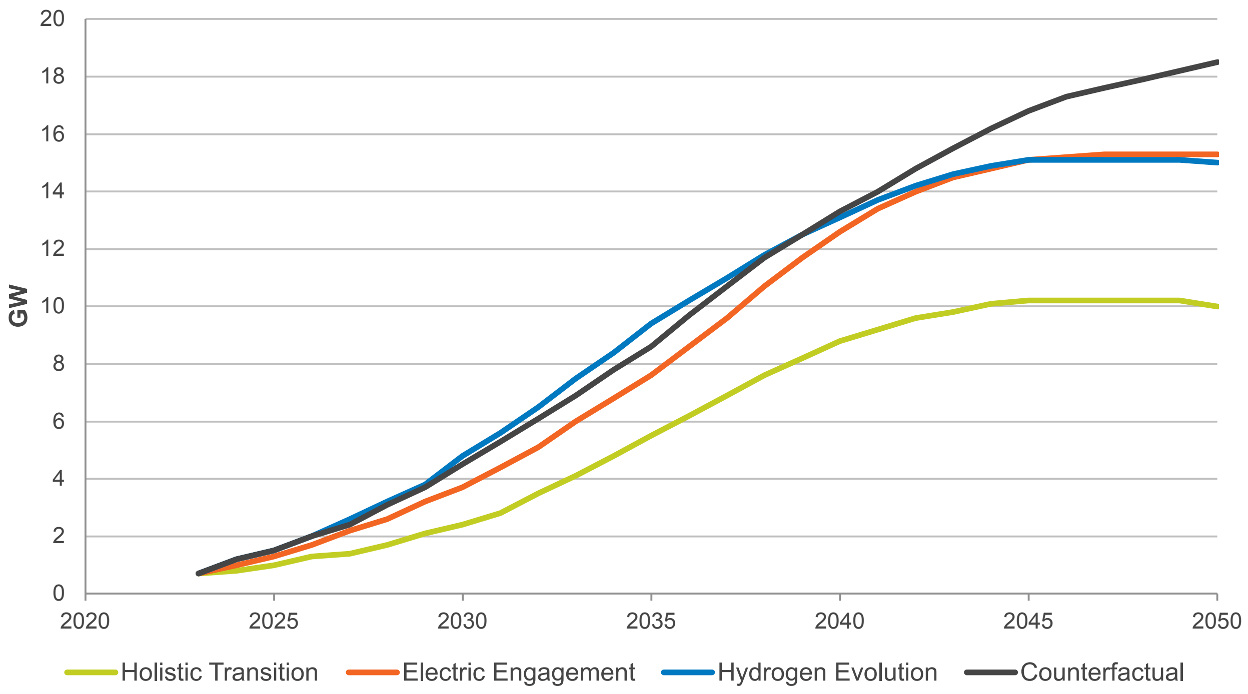
All **net zero pathways** feature varying levels of smart charging engagement but also feature the same number of battery electric cars on the road until the 2040s, aligning with the ZEV mandate. By 2050, peak demand from transport ranges from 10-15 GW across the pathways.

Holistic Transition has the highest level of engagement with smart charging, reducing peak demand in this pathway by 7 GW in 2045 compared to the Counterfactual, despite featuring similar numbers of battery electric cars on the road in both pathways.



The **Counterfactual** sees the lowest level of consumer engagement with smart charging, with late adopters of electric vehicles (EVs) participating in smart charging less frequently than that of early users.

Figure EC.09: Peak demand from road transport with smart charging (excluding vehicle-to-grid)



6 nationalgrideso.com/news/eso-make-change-allowing-300mw-flexible-assets-balancing-mechanism

The route to net zero

Key Action 5

Empowering consumers with information on the financial and whole system benefits of demand shifting flexible services is key to achieving high levels of engagement, helping to reduce household bills and the cost of battery electric vehicle ownership.

To increase participation, smart charging needs to become effortless for consumers, featuring autonomous functionality. TOUTs also need to be promoted until they are the mainstream solution. Price signals to encourage charging during times of excess generation need to be carefully managed, particularly with consumers who aren't yet engaging in autonomous smart charging, to ensure local electrical network limitations aren't reached.

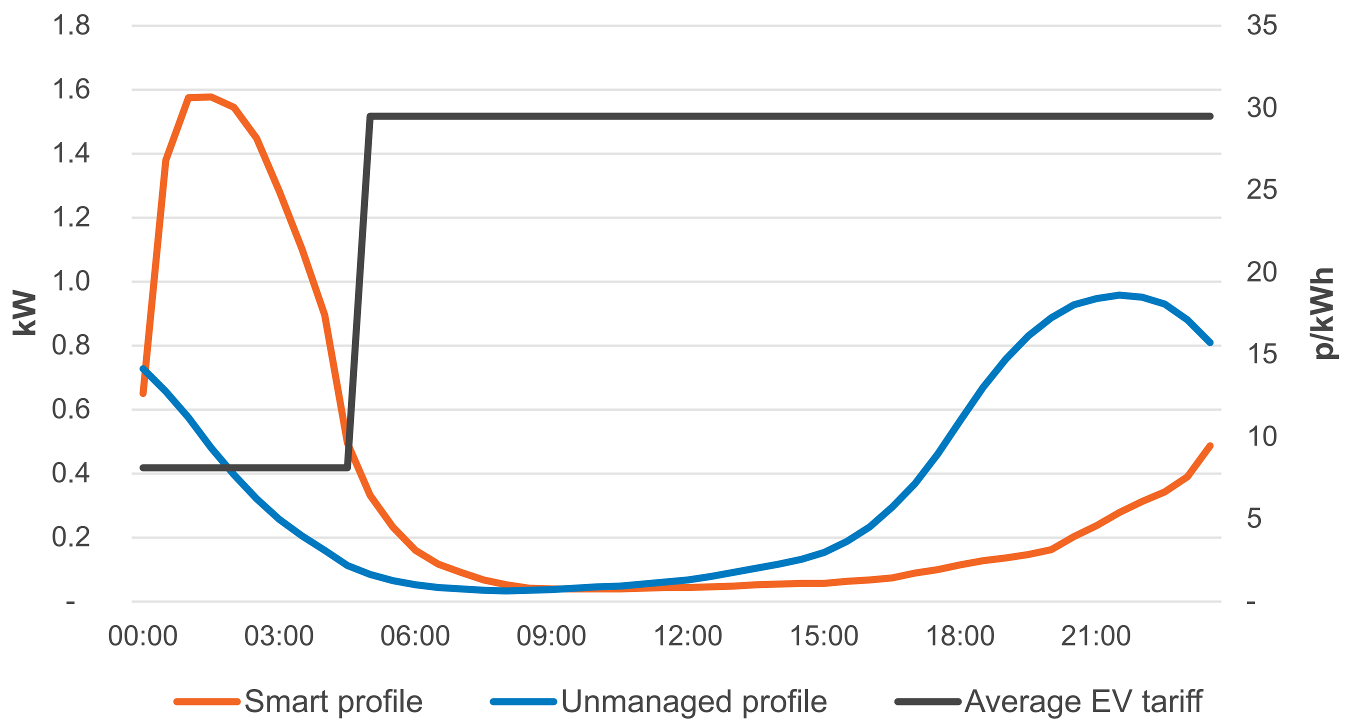
Consumers need to be rewarded for turning down demand at peak times and turning up demand when there is excess generation. These price signals need to consider local network constraints.

Competitive, nationwide off-peak charging rates for public and kerbside charge points are needed to help increase the affordability of battery electric vehicles for those without off-street parking. This will expose consumers to better charging rates and assist in demand flexibility.

Councils need to invest in residential kerbside charging solutions and encourage good public charging practices to guarantee there is ample infrastructure to satisfy local residents' requirements, and ensure those without off-street parking are not left behind in the transition to low emissions vehicles.

Continued improvement, in awareness and understanding of the off-peak public charging process and public smart charging availability, is required for consumers to realise the potential to reduce their energy bills.

Figure EC.10: Average demand on the network from unmanaged and smart charging profiles



Sources:
EV charging profiles - ev.energy,
Average EV tariff[7] - Money Saving Expert

7 moneysavingexpert.com/utilities/ev-energy-tariffs/#allevs

Vehicle-to-grid

Flexibility

V2G has the potential to balance supply and demand at times of network strain over and above smart charging, while reducing the requirement for fossil-fuelled peaking plants. Trials have helped develop V2G to better integrate with market signals. As public awareness of the impact of V2G on BEV battery degradation increases and the technology is gradually incorporated into more car warranties, barriers to uptake will decrease. Encouragingly, some car manufacturers are now including V2G in warranty terms.

In all pathways, V2G technology is adopted at varying rates to support the grid, offsetting household demand in the first instance. In Holistic Transition, V2G offers up to 32 GW capacity at peak times, a significant proportion of the overall demand at 109 GW.

The route to net zero

Communication campaigns will help showcase the system value of consumers engaging in vehicle-to-grid.

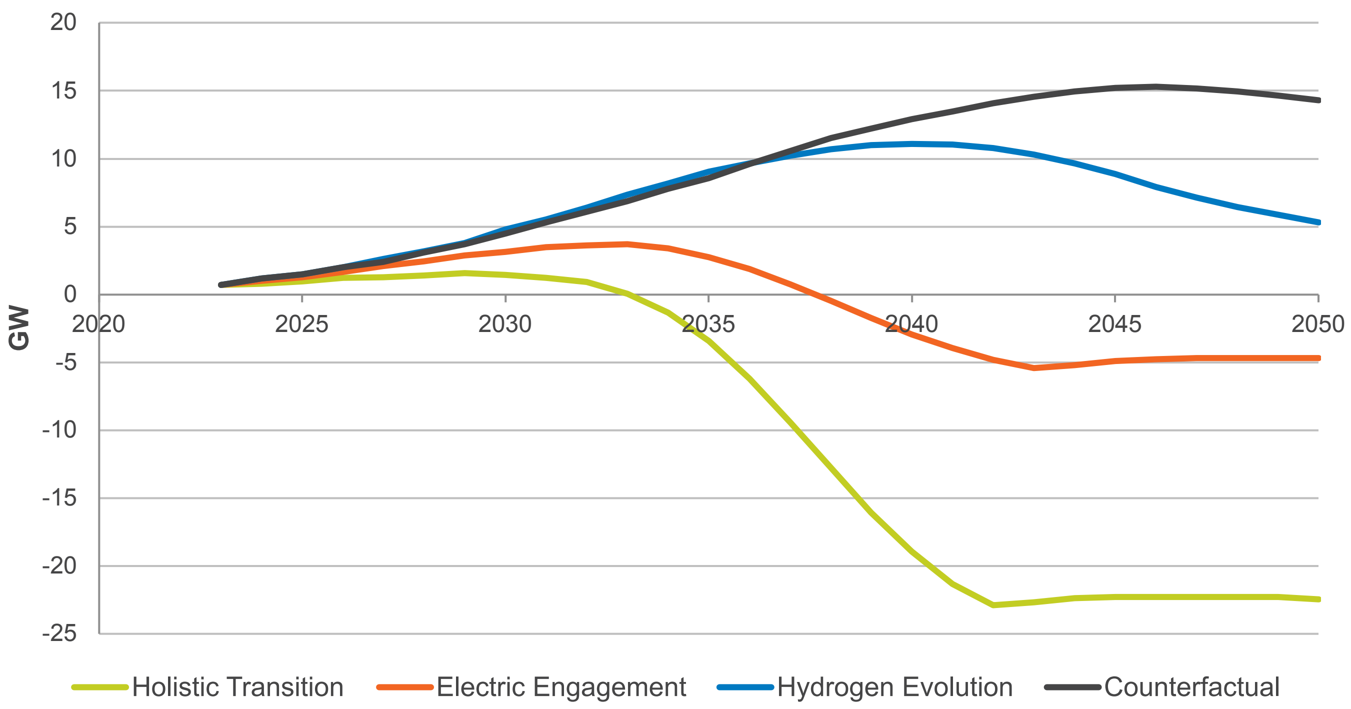
Key Action 5

More new vehicles need to have V2G functionality to empower consumers to engage with the process. UK Government and car manufacturers need to showcase the value of engaging in V2G, to help reduce whole energy system costs and reassure that there is no significant impact on a vehicle with good operating practices.

Financial support for access to vehicle-to-grid charging is needed to help consumers participate at scale.

Reductions can be achieved through economies of scale for V2G chargers or integration of on-board invertors, helping to avoid a potential barrier to uptake for consumers transitioning to a BEV.

Figure EC.11: Peak demand from road transport with smart charging and vehicle-to-grid



Hydrogen in road transport

Hydrogen buses are currently operating at low volumes around Great Britain, helping to develop the technology, but, for cars, there are far more BEVs than hydrogen FCEVs models available and vehicles on the road today. Fuel cell cars currently have higher capital costs than battery electric cars and far fewer refuelling locations, driving consumers who are looking for a low emission vehicle towards a BEV.

The use of hydrogen is most likely to grow in heavier commercial vehicles that require a long range and fast refuelling. If hydrogen transport is to increase, it's important Great Britain has a sufficient hydrogen refuelling infrastructure for domestic and European HGVs to support international industry.

All net zero pathways see low levels of hydrogen buses and coaches on the roads out to 2050, with BEVs dominating due to their lower operational costs.

Hydrogen Evolution features the largest hydrogen demand in road transport, with 93% of road transport hydrogen demand coming from HGVs by 2050. This creates 51 TWh of hydrogen demand from transport in the pathway, 49 TWh more than in Electric Engagement. This equates to a 26 TWh electricity saving in Hydrogen Evolution, due to higher efficiencies in electric vehicles (EVs) than hydrogen vehicles.

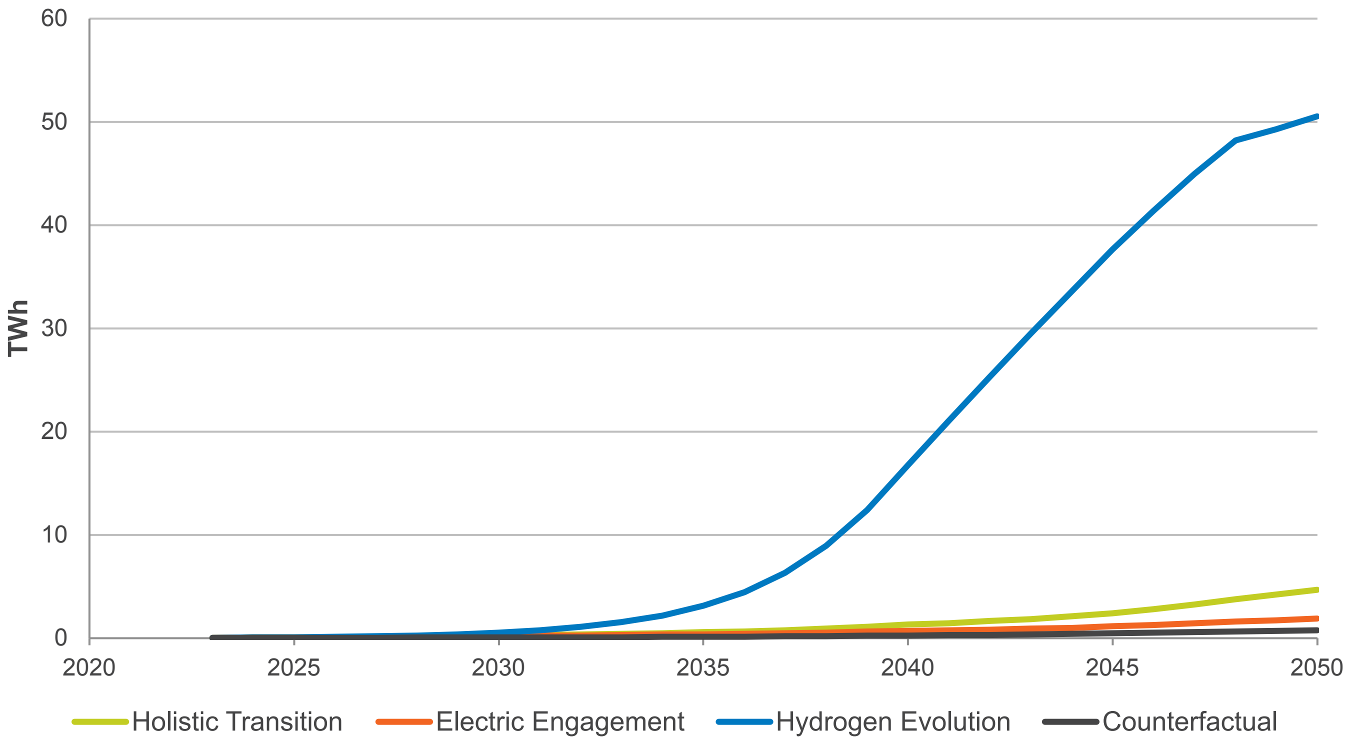
The route to net zero

If there is a desire to grow hydrogen use in transport, strategically located hydrogen refill stations on major transport routes will be required.

Key Action 1

Opportunities may arise with hydrogen refuelling stations at industrial clusters and shipping ports where there will be other hydrogen demands.

Figure EC.12: Low carbon hydrogen demand for road transport



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Residential

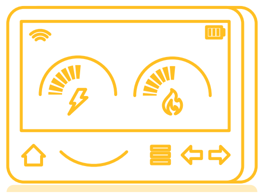
Appliances

Energy efficiency improvements in lighting and appliances have driven down demand in the short term. Banning the purchase of lower-efficiency incandescent and fluorescent light bulbs, a switch that offers a 75–85% efficiency gain, has been effective in the rollout of light emitting diode (LED) lights. This continues to reduce electricity demand in the short term.

Efficiency improvements from appliances such as fridges and freezers have also aided demand reduction in the near term, and improved labelling for appliances has positively empowered consumers with information on the most efficient models available.

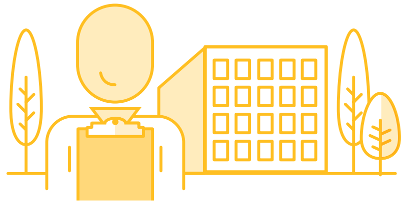
The number of residential air conditioning units across Great Britain may increase in response to our warmer climate driven by climate change, but widespread adoption of air conditioning units risks increasing electricity power demand spikes. Instead, designing homes to be more durable against overheating and information on passive cooling best practice, such as using fans and drawing curtains during heatwaves, will help reduce consumers' desire to install air conditioning units.

As household gas use reduces with the transition to low carbon heating alternatives, residential cooking will predominately become more electrified. This would require households to purchase new appliances to avoid maintaining a gas standing charge solely for cooking.



The Demand Flexibility Service delivered over 500 MWh demand reduction on 29 November 2023.

Residential and commercial demand side response in Holistic Transition achieves 10 GW peak demand reduction in 2050.



Improved building standards and behavioural change reduce thermal demand by 103 TWh in Electric Engagement in 2050.

Air conditioning demand maintains a similar level to present day in Holistic Transition and grows by 9 TWh in the Counterfactual in 2050.

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Residential

All net zero pathways have a fast rollout of LED light bulbs in the 2020s. Other appliances also trend towards increasing efficiencies over time.

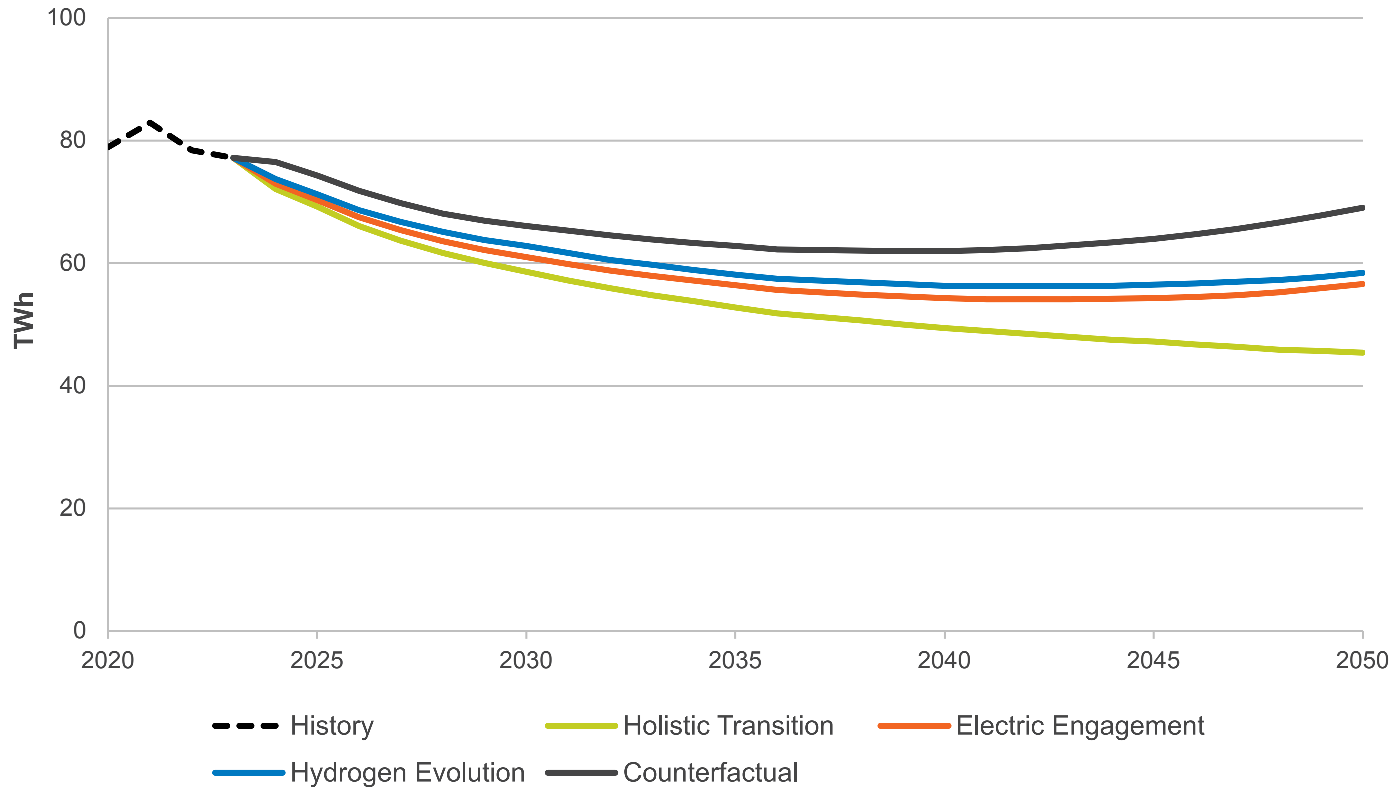
Holistic Transition forecasts the adoption of the highest efficiency light bulbs, with the average bulb installed in 2039 the same as today's most efficient bulb. The number of air conditioning units also remains the same as present day, coupled with high implementation of passive cooling. The combination of measures results in appliance and lighting demands decreasing from 77 TWh today down to 45 TWh in 2050 in Holistic Transition.

Electric Engagement has central projections on appliance and light efficiency improvements, but the growth in air conditioning units increases electricity demand in the long term.

Hydrogen Evolution has an increase in air conditioning units in the long term. A low level of hydrogen is used for cooking.

The **Counterfactual** has the lowest improvement in appliance efficiencies and the largest increase in air conditioning units. This is in line with the limited reduction in residential gas boilers, and gas cooking remains in use in 2050. The Counterfactual sees a 69 TWh demand from appliances and lighting in 2050.

Figure EC.13: Residential electricity demand for appliances



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The route to net zero

Key Actions 2&5

The Market-wide Half-Hourly Settlement will reduce system costs, encourage time-of-use tariffs and facilitate smart charging.

The introduction of the Market-wide Half-Hourly Settlement (MHHS), planned for delivery in December 2026, will make the electricity settlement process more accurate by capturing consumers' usage on a more regular basis. This can benefit consumers indirectly through flexible charging tariffs, and act as a driver for the adoption of more flexibility services alongside the increased use of electricity aggregators.

This should be supplemented with the continuation of a dual approach to improve market signals and strengthen incentives for energy suppliers to support efficient investment, alongside broadening information and awareness on the cost-saving opportunities for consumers who shift their key appliance usage to off-peak hours.

Key Action 6

Raising the minimum efficiency standards for appliances over time drives down demand.

Similar to the progress made with light bulbs, a higher minimum standard for new appliances provides long-term benefits to reduce energy demand.

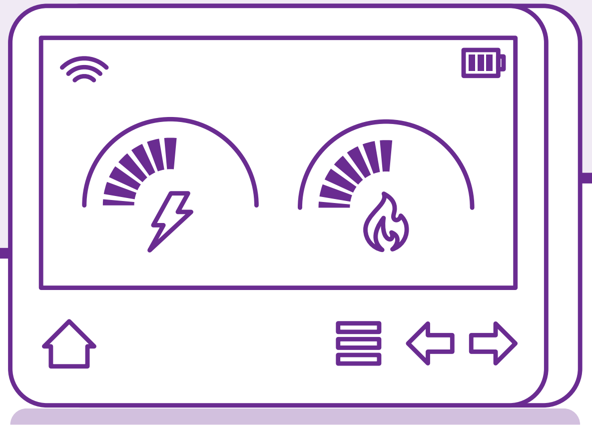
Flexibility

Key Action 5

Demand side response opportunities

In adopting BEVs, consumers will become more familiar with smart charging functionalities and TOUTs, which have the potential to drive DSR engagement with appliances in the same way.

Smart appliances and home energy management systems have the potential to optimise appliance demand times automatically, using in-built timers to coordinate with price signals to deliver financial benefits for consumers. These technologies need to be affordable and have consumers' trust to drive mass adoption.



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Heat

Decarbonisation of heat remains one of the biggest challenges in reaching net zero. Every household on fossil fuel boilers will need to be part of the transition by switching to a low carbon alternative. Incentives are critical to driving mass residential fuel switching and unlocking the system benefits, but further action is needed to hit targets within the Sixth Carbon Budget. The current rate of low carbon heating sales is not fast enough.

Installation costs of low carbon heating systems are currently higher than gas alternatives, but as more installers specialise in new technologies, installation costs should reduce. In what is typically a ‘distress purchase’, consumers should feel empowered on the low carbon heating options available to help prepare for such a purchase well ahead of time.

Not all technologies will suit every household. Heat pumps are a highly efficient option where there is sufficient space. In denser areas, heat networks should be the first consideration as district heating is viable in areas with high heat densities. Shared ground loop heat pumps also offer novel solutions for households with limited external space.

The cost and perceived hassle of change contribute to reduced consumer willingness to adopt new technology. Alternatives with lower disruptive installation and purchase cost may be preferable, such as hydrogen boilers or direct electrical heating. These systems have lower efficiencies and higher operating costs, but, when combined with storage, they can also offer whole energy system benefits.

All net zero pathways follow similar electricity demand in the short term from similar heat pump uptakes. The range in electricity demand up to 2035 is influenced by the range in heat pump efficiency projections.

A phase-out on the installation of new gas boilers in 2035 is required to make sure Sixth Carbon Budget targets are met. This also prevents the decommissioning of any gas boilers installed after this point and potentially before the unit’s end of life, in order to achieve the 2050 net zero target. Holistic Transition and Electric Engagement see fast decarbonisation of heat compared to historic trends. These are only slightly faster than Hydrogen Evolution, which has the slowest rate while still achieving emissions targets.

All pathways see a range of low carbon heating technologies but have varied access to hydrogen. To ensure a sufficient pace of heat decarbonisation, all pathways to net zero require supportive policies for all technologies.

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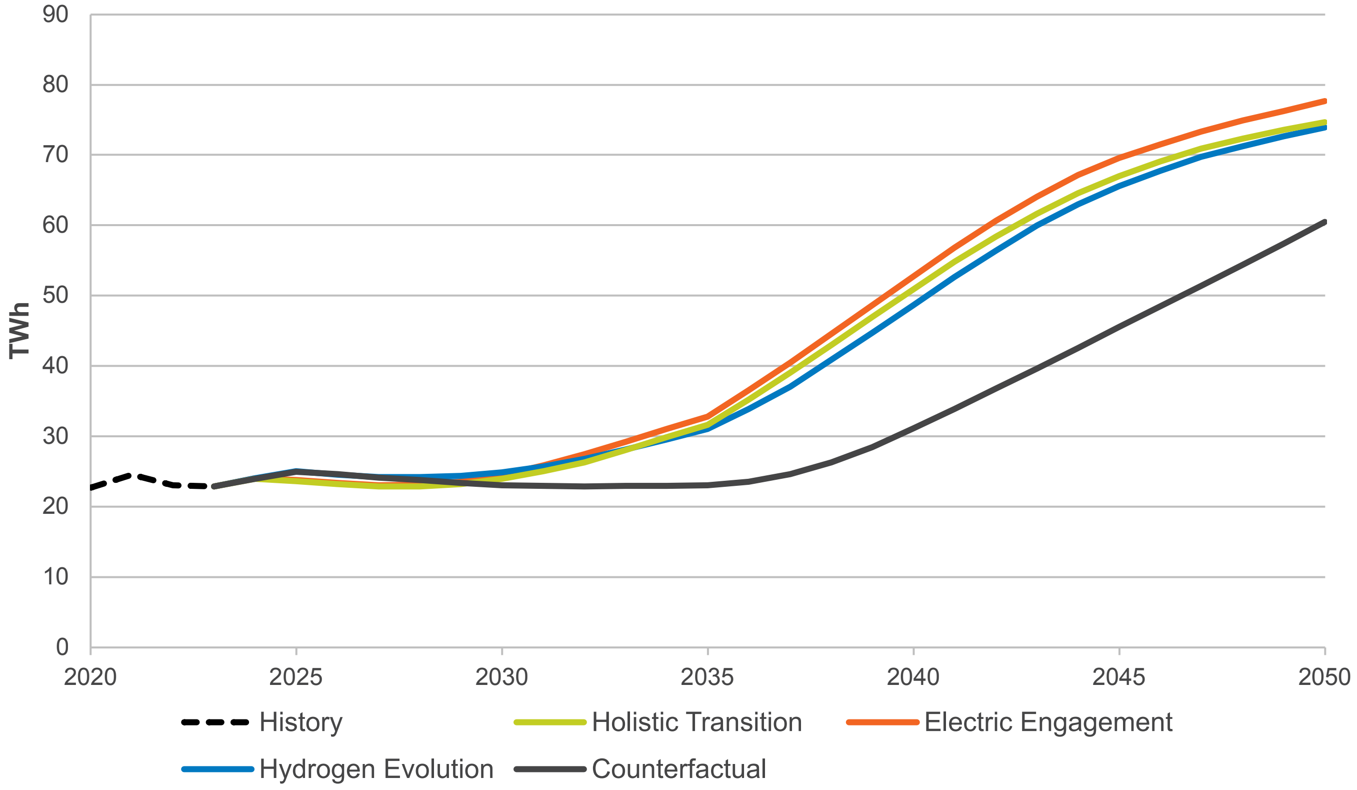
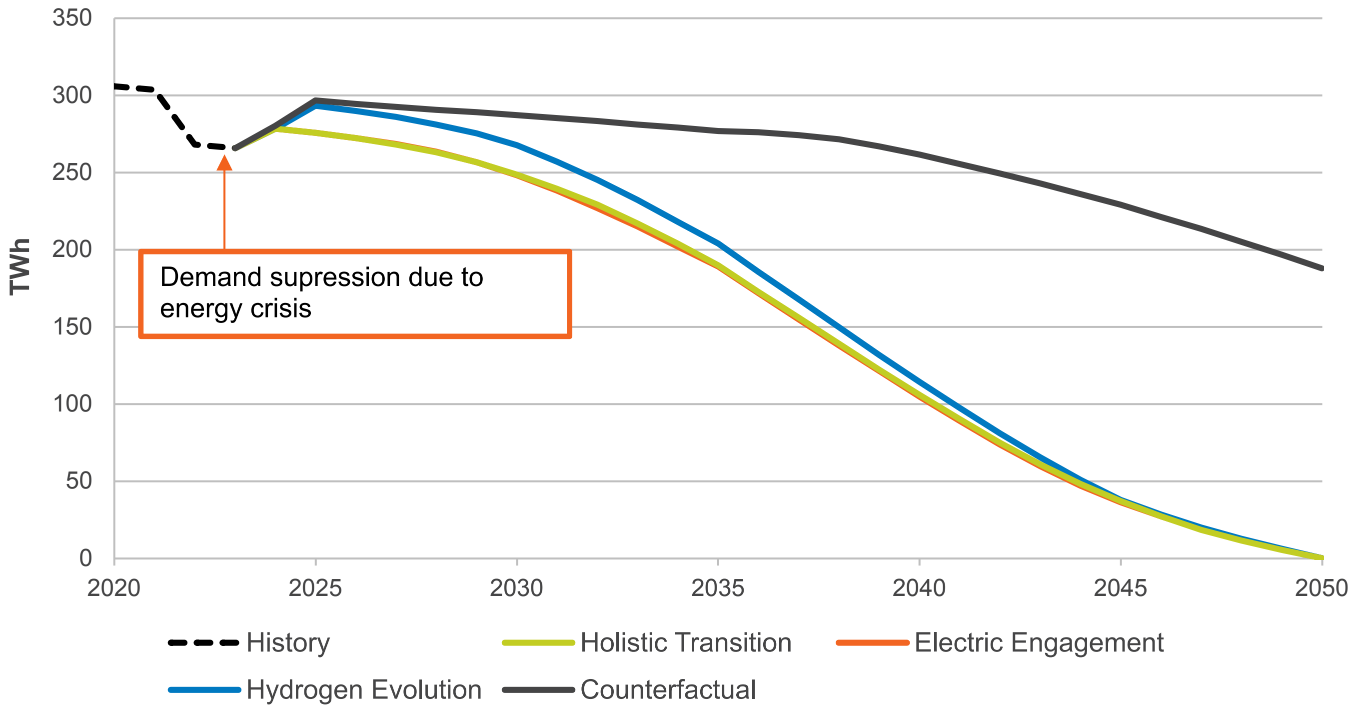
Figure EC.14: Residential annual electricity demand for heat



Holistic Transition has higher projections of heat pump efficiency improvements as defined by the seasonal coefficient of performance (SCOP), achieving SCOP 3.8 for air source heat pumps in 2035 compared to today's average of SCOP 2.8. This pathway sees hydrogen for residential heat around industrial clusters.

Please note the scale difference across these two charts.

Figure EC.15: Residential annual gas demand for heat



Electric Engagement features no hydrogen for residential heat along with the same high projection of heat pump efficiencies as Holistic Transition – this means Electric Engagement has the highest electricity demand (78 TWh) in 2050.

Hydrogen Evolution features higher household temperatures, leading to higher gas demand in the short term. Wider geographical access and significant policy support for hydrogen means increased hydrogen uptake and fewer heat pump installations with associated efficiency improvements, resulting in 5% or 4 TWh lower electricity demand for heat than in Electric Engagement.

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The route to net zero

Regional clarity on the use of hydrogen for heat must be provided as soon as possible. This will deliver clarity for investment in all technology types and provide time to develop infrastructure that can facilitate the necessary rollout to meet carbon budgets.

Key Action 3

If a decision is taken to support hydrogen for domestic heat, a rapid deployment of upgrading the gas transmission and distribution network and sufficient development in geological hydrogen storage for heating are necessary to facilitate the scale of rollout required by 2035. The future role of Regional Energy Strategic Planner (RESP) can improve regional plans for energy use.

Flexibility

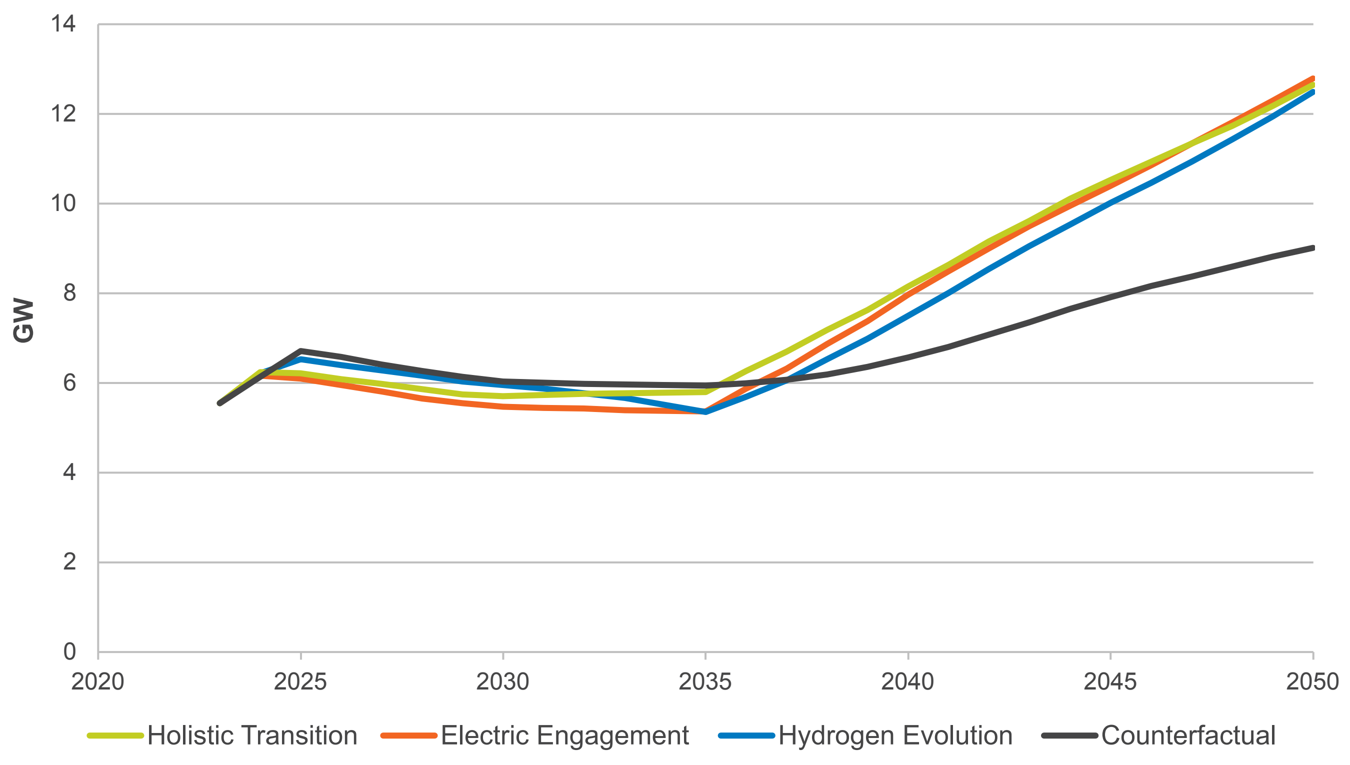
Demand side response opportunities

Running heat pumps constantly at low heat leads to higher efficiencies and shifts more demand to off-peak times. Evening peak demand can also be reduced by pre-heating the house.

Heating hot water cylinders or other thermal storage at off-peak times is a 'no regret' action for consumers on a multi-rate tariff, as these consumers can save money and help reduce evening peak demand.

District heat networks use thermal storage to meet peak heat demand. Installing slightly higher-capacity thermal stores can provide flexibility to the grid, giving the ability to turn down electrical demand.

Figure EC.16: Flexibility from electrified heating



Energy efficiency

Energy efficiency brings significant benefits regardless of the heating technology. Further rollout of efficiency measures is needed to reduce national heating demand, energy demand and fuel poverty.

Our research calculates that the average indoor household temperature sits at 20.1°C, with a range to account for consumers' varying preferences, equating to 80% of consumers sitting within 15.9 to 24.1°C. Reducing thermal demand broadens household heating options while reducing required investment, allowing consumers to opt for smaller-capacity heat systems.

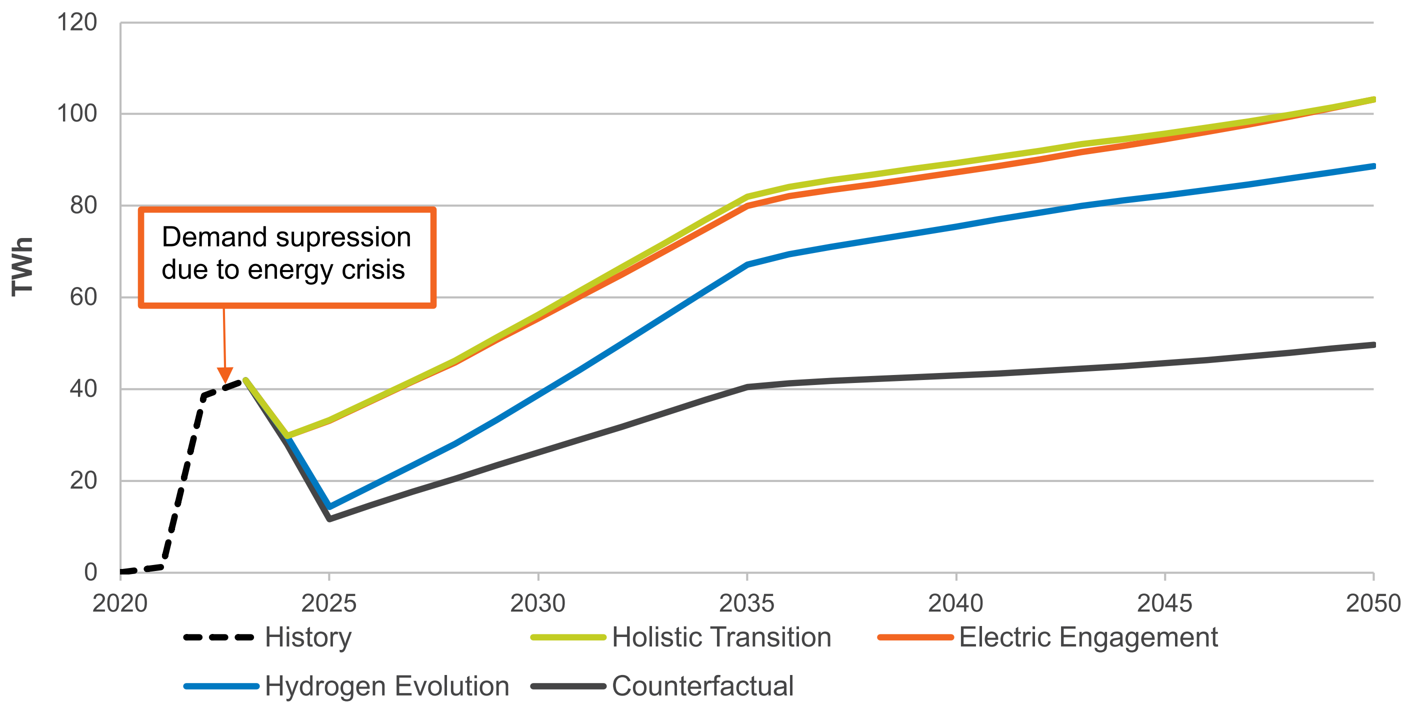
Holistic Transition and **Electric Engagement** assume that high levels of consumer engagement lead to climate-conscious consumers willing to make changes to help reduce energy demand, including reducing the average temperature of homes from today's values.

These pathways both have an average 0.5°C reduction in household temperature to 19.6°C (featuring a range to recognise personal requirements). A reduction in temperature is particularly beneficial for heat pumps, as it reduces thermal demand and allows lower flow temperatures, which improves heat pump efficiencies.

Hydrogen Evolution assumes average household temperatures remain the same as current temperatures at 20.1°C. Energy efficiency incentives follow those implemented in Holistic Transition and Electric Engagement. Higher operating costs of hydrogen boilers lead to increased value of energy efficiency measures for consumers.

The **Counterfactual** assumes average household temperatures do not change and only considers energy efficiency incentives that have already been proposed.

Figure EC.17: Residential thermal demand savings from insulation improvements and behavioural change



The route to net zero

Building on The Future Homes and Buildings Standard together with increasing minimum efficiency standards will drive thermal efficiencies in households.

Key Action 6

The Future Homes and Buildings Standard will increase the energy efficiency standards for new builds from 2025. A gradual increase in minimum performance standards for rented properties could also drive cost reductions for tenants.

Widespread energy efficiency incentives are, in part, required to plan a build-up of supply chain and experience – from long-term, government-backed incentives to green financing opportunities for businesses and consumers. Accelerated training and effective communications between installers and customers can also support building the supply chain.

To increase the effectiveness of initial measures, higher levels of support needs to be targeted for consumers living in properties with the lowest levels of insulation who need it most.

Incentives will reduce the financial payback time of energy efficiency measures for consumers and act as a long-term investment for Great Britain to reduce future energy demand.

Flexibility

Demand side response opportunities

Buildings with improved thermal properties also have the potential to reduce peak demand. As buildings become more efficient, they retain heat for longer and so their ability to shift thermal demand increases.

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Heat pumps

Heat pumps are a highly efficient way of heating a home by using heat from an ambient source (like outside air ground or water) and are already a popular and effective heating choice across several countries.

While some reports suggest heat pumps will be the optimal low carbon solution for residential homes, they present several installation considerations including building surveys, space requirements and upfront costs. A certain level of home insulation is also beneficial to make sure heat pump technology is effective. Positively, developments in alternatives to hot water cylinders are reducing internal space requirements, which will overcome the space barrier for some households.

Further work is needed to address the survey and planning lead times to assess the suitability for a heat pump, recognising that households often need to replace their heating systems urgently.

The Boiler Upgrade Scheme (BUS) grant increased to £7,500 in October 2023, and in May 2024 the minimum insulation criteria for eligibility was removed. This increase in financial aid and relaxation of requirements provides welcome support for consumers, considering the current high purchase price of a heat pump, but more work is needed to accelerate the adoption rate of this low carbon heating technology to achieve emissions targets.

The number of qualified installers continues to increase since more companies have entered the heat pump installation market, driving competition. These economies of scale should help to drive down installation costs, but the number of qualified installers needs to stay ahead of demand to prevent becoming a blocker. It is also critical that installers are sufficiently trained to install, set up and inform households of heat pump best practices and how they differ to a boiler system.

All net zero pathways have similar levels of heat pump uptake up to 2035. All pathways require heat pump grants to reduce capital costs and make heat pumps an attractive option until a 100% fossil fuel boiler phase-out is implemented in the pathways in 2035. The narrow range between high installation rates in Holistic Transition and Electric Engagement, compared to the lowest uptake rate to achieve the Sixth Carbon Budget in Hydrogen Evolution, emphasises that it is crucial for heat pump uptake to increase now.

The **Counterfactual** has a low level of heat pump uptake following current trends and does not achieve emissions targets.

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The route to net zero

Improved public messaging will boost confidence in a technology that is already used across the globe.

Key Action 4

Extending the Clean Heat Market Mechanism (CHMM) out to the gas boiler phase-out will create certainty for the industry for planning and investment.

A minimum performance requirement will ensure only high-efficiency heat pumps or heat networks are used in new builds, preventing a mass rollout of direct electric heating, building up supply chain and experience.

There are currently no operating cost benefits for consumers on standard tariffs due to high electricity-to-gas ratio. Levies must be rebalanced from electricity to gas.

Accessible guidance on installation and operation will benefit consumers and electricity networks.

Key Action 8

With further adoption of the technology and more installation specialists moving into the field, improved understanding and quality of training will increase over time.

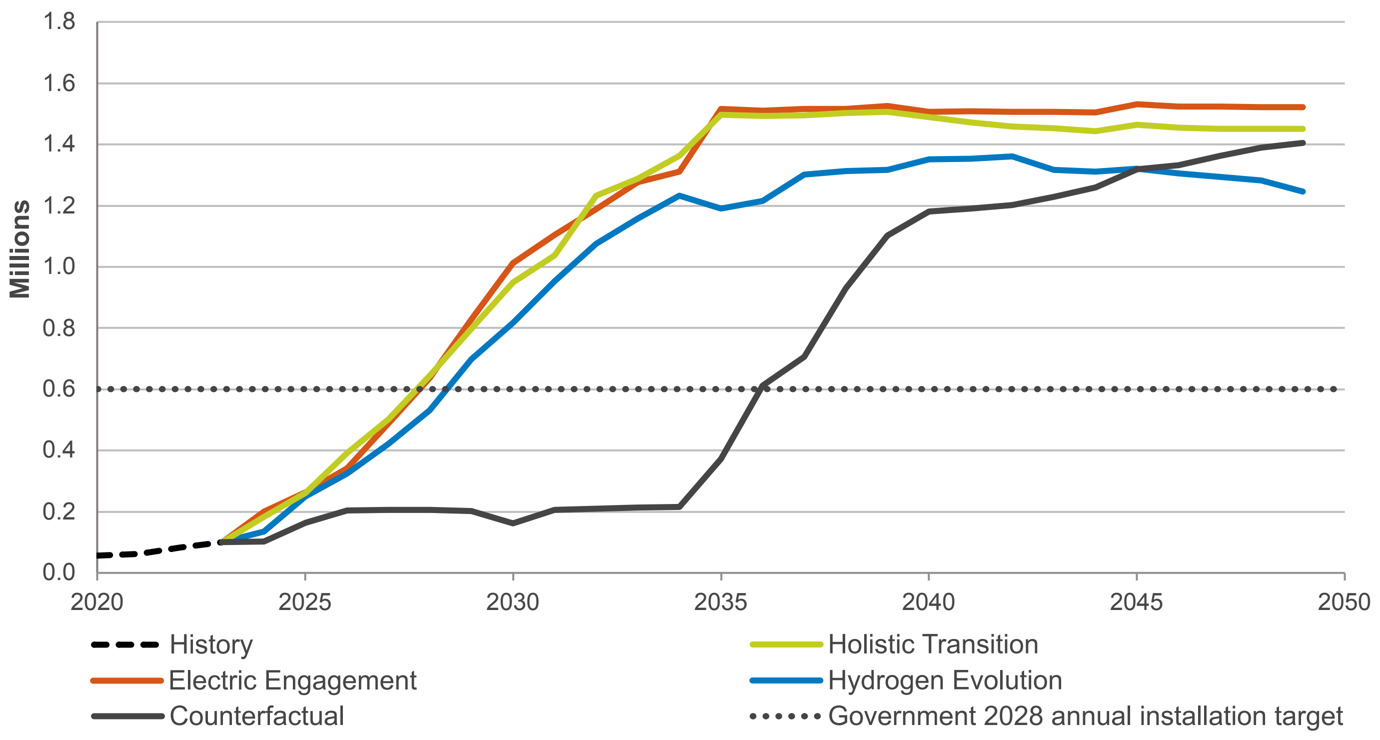
Greater engagement between manufacturers, installers, consumers and electricity suppliers will ensure consumers understand how to operate heat pumps in the most cost-effective way.

Minimum heat pump efficiency standards to be raised over time

Key Action 6

The Microgeneration Certification Scheme's (MCS) minimum design standard efficiency is currently 2.8 SCOP. This needs to gradually increase over time in line with development of best installation and operating practice.

Figure EC.18: Annual heat pump installations



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Hydrogen boilers

Hydrogen boilers offer a potential low carbon heating solution and, for consumers, present a more familiar heating technology than that of a heat pump or connecting to a district heat network in the future.

Hydrogen boilers could have the potential to reduce electricity network congestion and accelerate heat decarbonisation if hydrogen could be deployed more rapidly than electricity network upgrades. In the long term, however, lower whole system efficiencies of hydrogen boilers result in higher operating and lifetime costs for consumers, compared to competing low carbon technologies. A comprehensive assessment of the relative costs, benefits and risks of deploying hydrogen heating is required to establish if hydrogen should be considered an option, whether transitionary or long-term. This may include identifying more suitable geographical areas and end users.

While a government decision on the use of hydrogen for heat is expected in 2026, the cancellation of hydrogen village trials and postponement of the hydrogen heating town pilot has likely delayed implementation at scale. Furthermore, in its response to the Climate Change Committee (CCC) 2023 annual progress report[8], the UK Government sets out that it expects heat pumps to play a prominent role in all future scenarios, and that no one should hold back on installing a heat pump or connecting to a heat network on the basis that hydrogen may become available.

Hybrid heat pumps with hydrogen boilers could have the potential to offer additional demand during peak electricity demand. However, as hybrid boilers are optimised to use low quantities of hydrogen, they currently offer low utilisation of a potential future hydrogen network.

In the event of a positive decision on hydrogen for heat in 2026, government will need to quickly set out a comprehensive strategy for network and consumer switchover to hydrogen, recognising that new-build infrastructure will be required in some areas.

8 theccc.org.uk/publication/2023-progress-report-to-parliament

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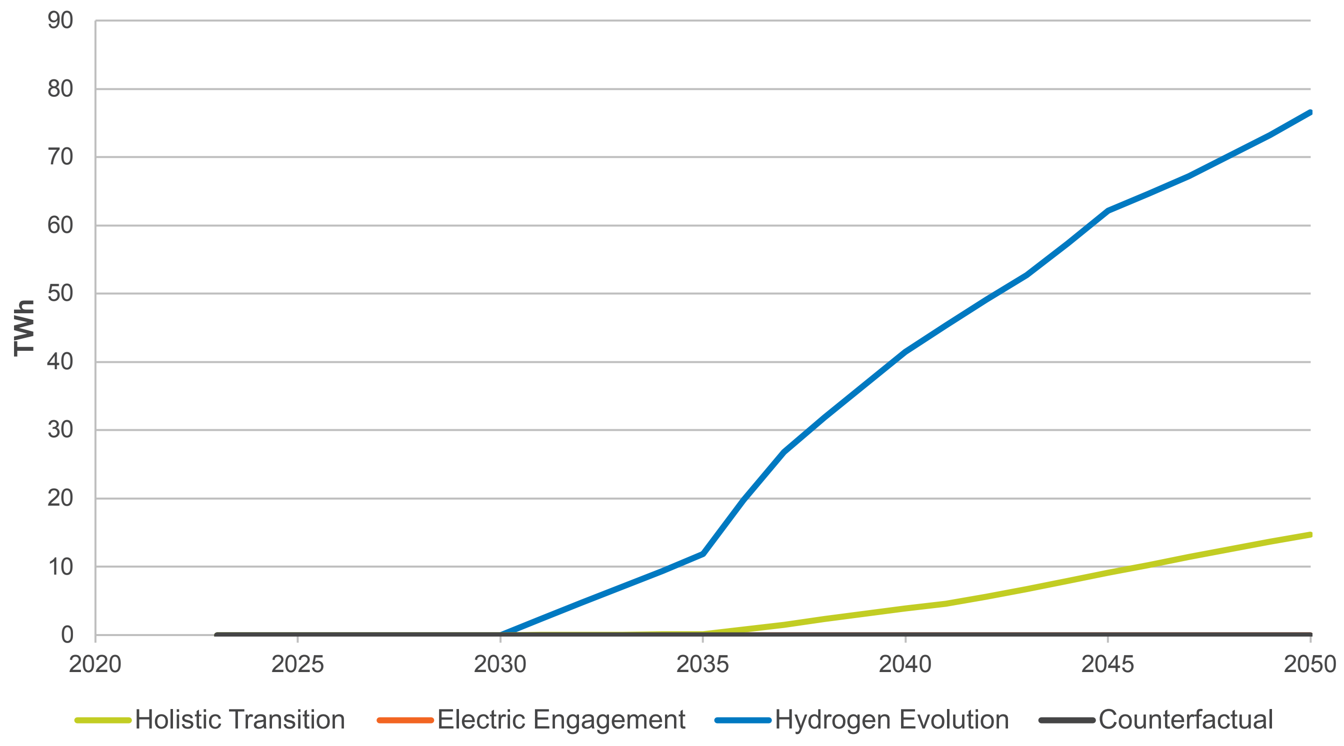
Holistic Transition sees a hydrogen network build around three industrial hydrogen clusters from 2035, also giving access to consumers in these regions. Subsidising the cost of hydrogen will drive hydrogen boilers and hydrogen hybrid boilers to 1.7 million by 2050.

Electric Engagement projects no residential access to hydrogen for heat. This is also the case in the Counterfactual.

Hydrogen Evolution sees hydrogen gradually becoming available to consumers from 2030, initially around hydrogen clusters, before quickly accelerating to develop a full hydrogen network by 2050. This results in 77 TWh of hydrogen use in residential heating in this pathway. To achieve this, significant development of the gas transmission and distribution networks would need to start immediately to make these suitable for hydrogen access in the 2030s. Without fast development towards hydrogen, the deployment of other low carbon heating will limit the number of households available to use hydrogen, reducing the utilisation of a potential hydrogen network. Fast deployment of low carbon heating is needed to achieve the Sixth Carbon Budget.

The increase of hydrogen for heat in the analysis simulates hydrogen access over time and gas-to-hydrogen boiler conversion. The increased rate emulates the growth of conversion of gas-to-hydrogen use in the distribution network, where all boilers and network in the area need to be hydrogen-ready prior to conversion.

Figure EC.19: Annual low carbon hydrogen demand for residential heat



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Commercial

Energy demand

We consider all heating, appliances and general process demand in commercial buildings, ranging from offices and warehouses to retail and healthcare in our commercial energy demand.

Short-term trends show expected demand growth back to pre-energy crisis levels due to a reduction in energy costs, despite the ongoing cost of living crisis. In the net zero pathways, this demand growth is partially offset by improved appliances and building thermal efficiencies.

Medium- and long-term trends are caused by fuel switching away from gas for heating to electrification and in part hydrogen. The projected growth of data centres out to 2050 heavily drives a growth in electricity demand, as Great Britain continues to digitise and adopt cloudbased services. This investment will underpin the establishment of a smart energy system.

Centrally located commercial facilities like new data centres have the potential to act as an important energy source for heat networks by using their waste heat, reducing the need for electricity network upgrades. On the other hand, thermal demand from hospitals and swimming pools can act as key anchor loads for heat networks.

All net zero pathways feature a phase-out of gas and oil boilers for heating new commercial buildings from 2025, followed by a phase-out of new installations in existing commercial buildings in 2035.

These pathways also feature varying degrees of hydrogen for commercial use for gaseous process requirements where hydrogen can be made available, such as off-road machinery and gas for the food industry.

Holistic Transition features low levels of hydrogen for heat in pockets around industrial hydrogen clusters. Appliance efficiency improvements reduce commercial demand by 10% by 2030. Holistic Transition has the highest deployment of data centres in 2050, with their electricity consumption totalling 62 TWh, 39% of commercial demand.

Electric Engagement features no hydrogen for commercial heat that is delivered on an existing gas network. This is also the same for the Counterfactual. All decarbonisation of heat in Electric Engagement comes from electrification of heat or via heat networks, reaching 30 TWh in 2050.

Hydrogen Evolution has access to hydrogen, quickly ramping up from 2030 to a national network by 2050. This is coupled with high operational incentives creating a high uptake of hydrogen for heating. This pathway sees 46 TWh of demand increase from data centres.

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Commercial

Figure EC.20: Electricity demand in the commercial sector

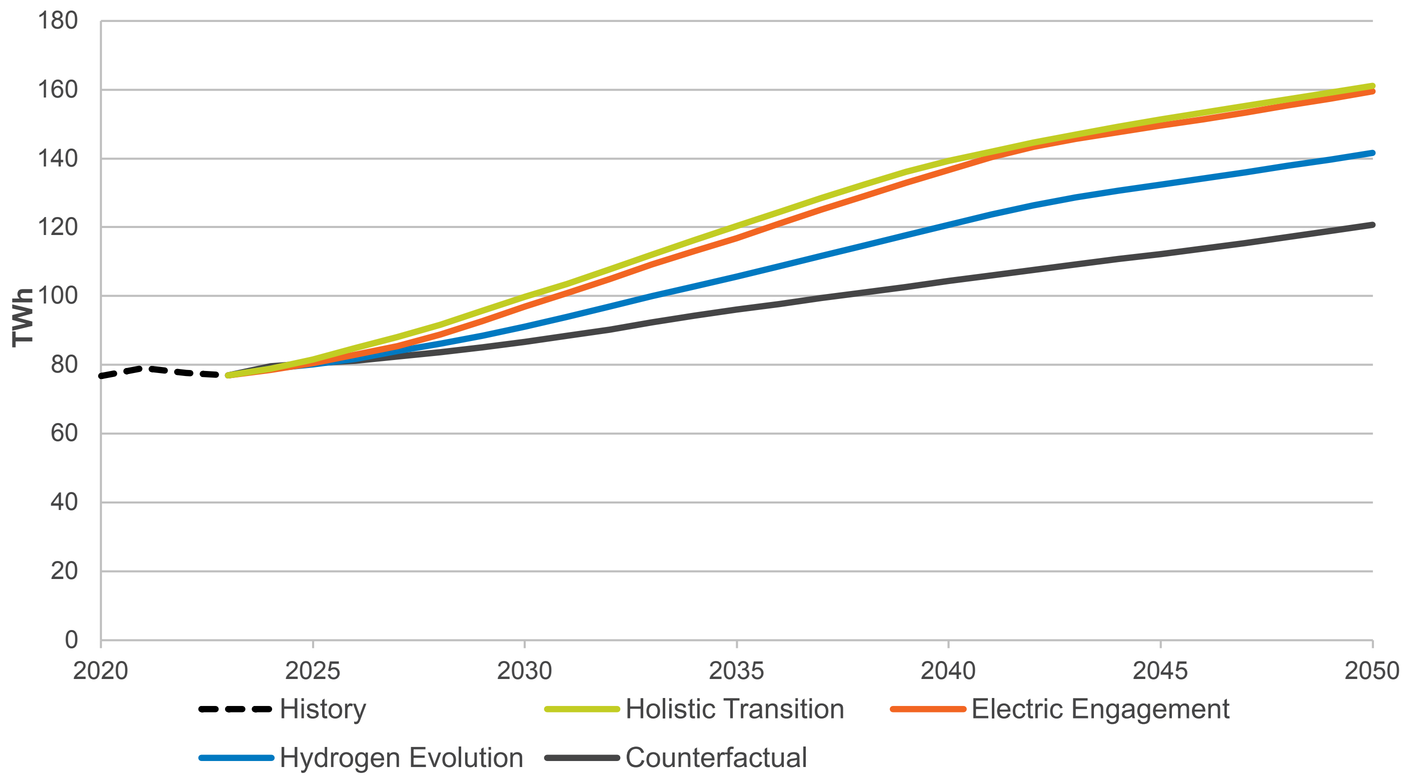
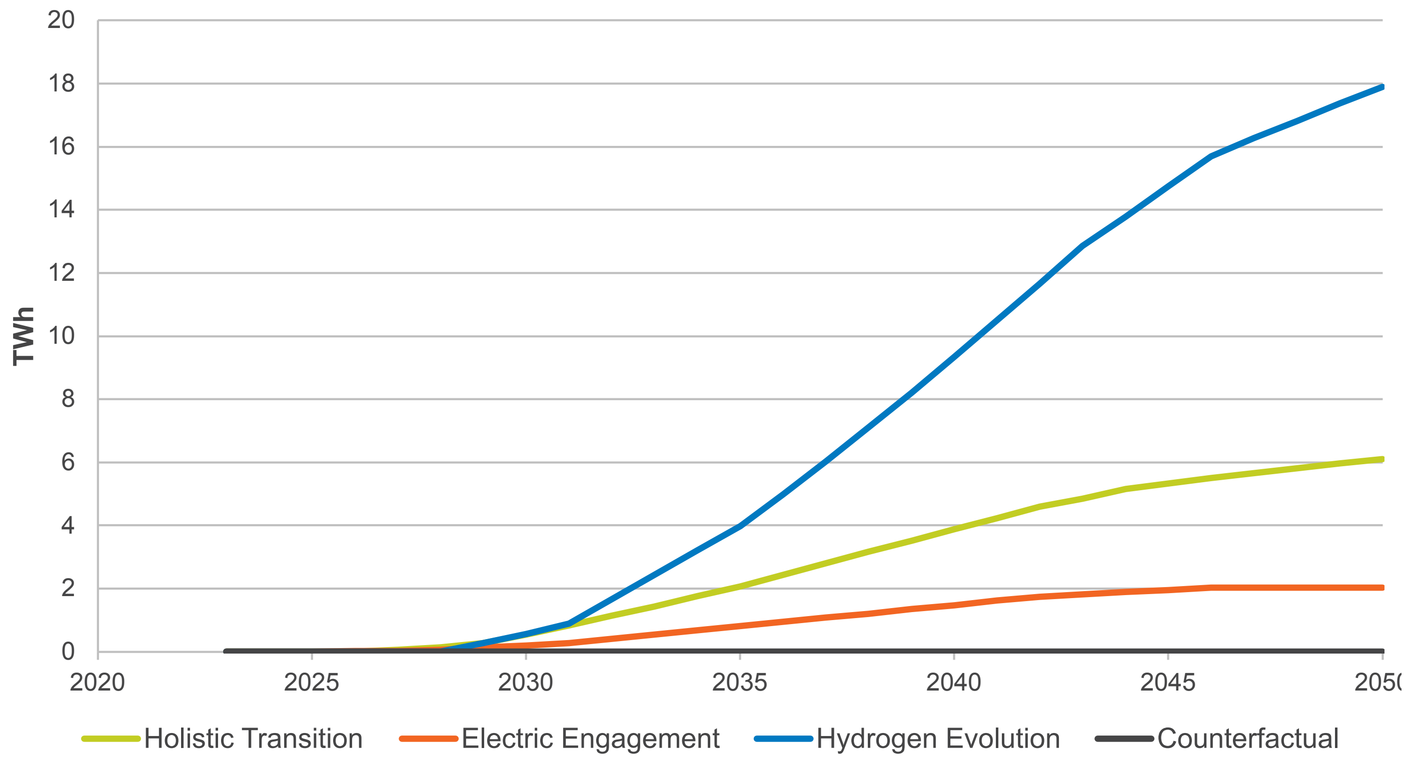


Figure EC.21: Low carbon hydrogen demand in the commercial sector



Please note the scale difference across these two charts.

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Commercial

The route to net zero

Insulation improvements for new and existing commercial buildings will provide long-term whole system benefits.

Key Action 6

Improved insulation for new builds and retrofits in existing commercial buildings will reduce heat demand, lowering costs for businesses and reducing the requirement for additional network infrastructure. These cost-saving opportunities are beneficial for all businesses, regardless of which heating technology they opt for.

Flexibility

Demand side response opportunities

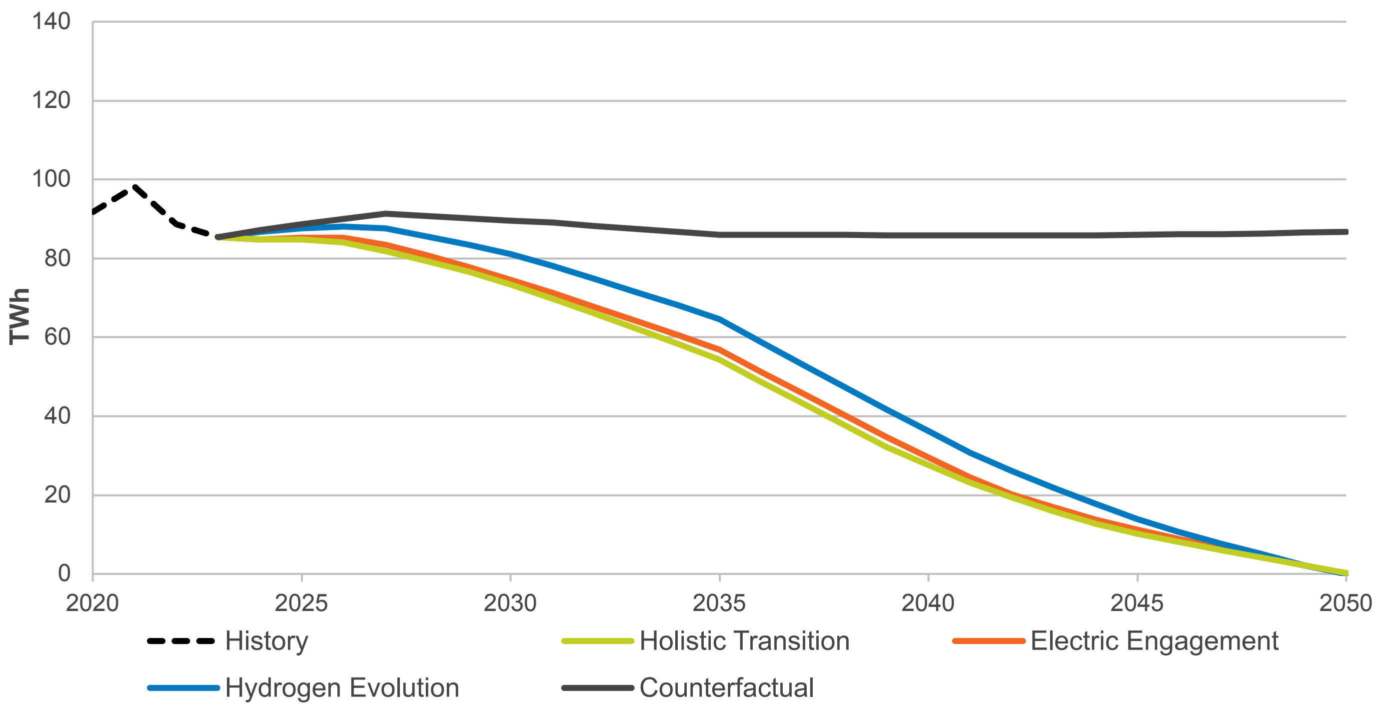
Key Action 5

A range of commercial building demands, such as supermarket fridges, already reduce network constraints by actively engaging in DSR to help balance the electricity system during periods of high demand. Non-time-critical data centres could reduce power consumption at peak times to help balance the grid. Other data centres could reduce electricity demand at peak times by using thermal storage.

Optimising the location of some new data centres may reduce the requirement for additional electricity network infrastructure. Further analysis will be required to establish the feasibility of moving data centres and optimum locations at the planning stages of investment proposals.

Electrification of heat in larger commercial buildings could play an important role in providing DSR. Those with higher levels of thermal storage could self-sufficiently heat their facilities during periods of high demand.

Figure EC.22: Gas demand in the commercial sector



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Electricity and natural gas demand

Currently, industrial demand is fuelled by 48% gas, 43% electricity and 9% combined oil and coal[9]. These will switch to electrification, low carbon hydrogen or abated gas use via carbon capture and storage (CCS) depending on the application, access to infrastructure, available space and supply. Some industries may require CCS alongside fuel switching, due to the carbon emissions from their processes.

As electricity consumption is projected to increase in industry in the 2030s, new electricity grid connections must continue at pace to support timely industry fuel switching.

Building on the strategic network investment and connections reforms already proposed will accelerate network connections and further support industry in fuel switching from high-emission energy sources.

Within industrial clusters, gas-powered businesses will have the opportunity to reduce their CCS costs through shared infrastructure to transport captured carbon to its dedicated storage location, reducing the investment required per organisation.

All net zero pathways feature improvements in energy efficiency measures in the near term, which offsets demand growth. This is followed by an increase in fuel switching from gas to electricity in the 2030s at varying rates.

In pathways with lower levels of access to hydrogen, large facilities located further away from industrial hydrogen clusters will see higher levels of electrification, to decarbonise alongside the use of abated gas or biofuels to a lesser extent.

A limited amount of industrial gas usage remains out to 2050 for gaseous processes which cannot be electrified, with associated emissions abated with CCS.

Holistic Transition sees an additional 14 TWh electrification of industry out to 86 TWh in 2050. This is supplemented by hydrogen adoption, prioritised for industrial, high temperature processes, which cannot easily electrify using available technologies.

Electric Engagement has the largest level of electrification in the industry sector to 117 TWh, but is steadier to transition away from gas than Holistic Transition and Hydrogen Evolution, due to the limited development of hydrogen in Electric Engagement.

Hydrogen Evolution sees a minimal increase in electrification of industry out to 2050, which is offset by energy efficiency improvements, leading to no overall increase in electricity demand. Hydrogen is the main route to industrial decarbonisation in this pathway.

9 gov.uk/government/statistics/energy-consumption-in-the-uk-2023

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Industrial

Figure EC.23: Industrial electricity demand (excluding hydrogen production)

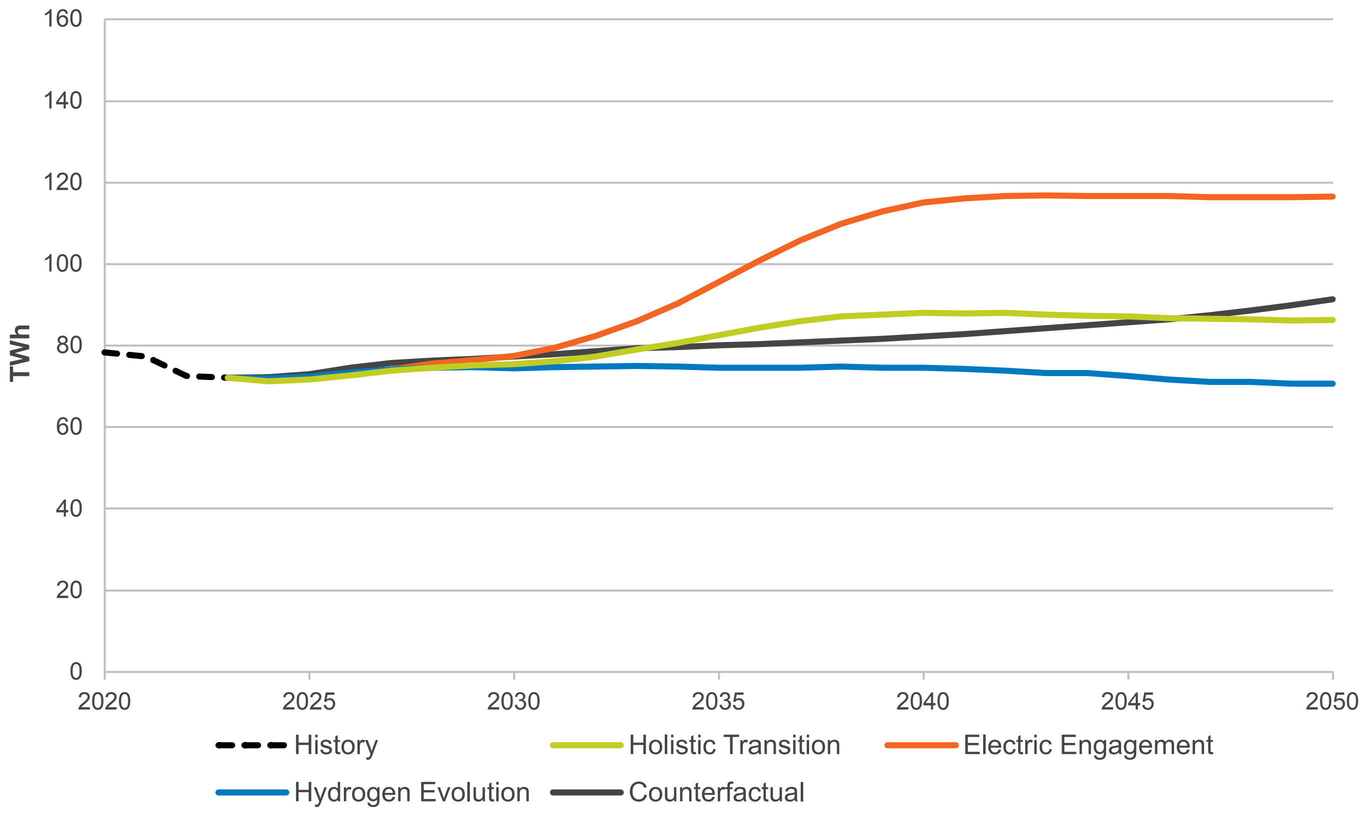
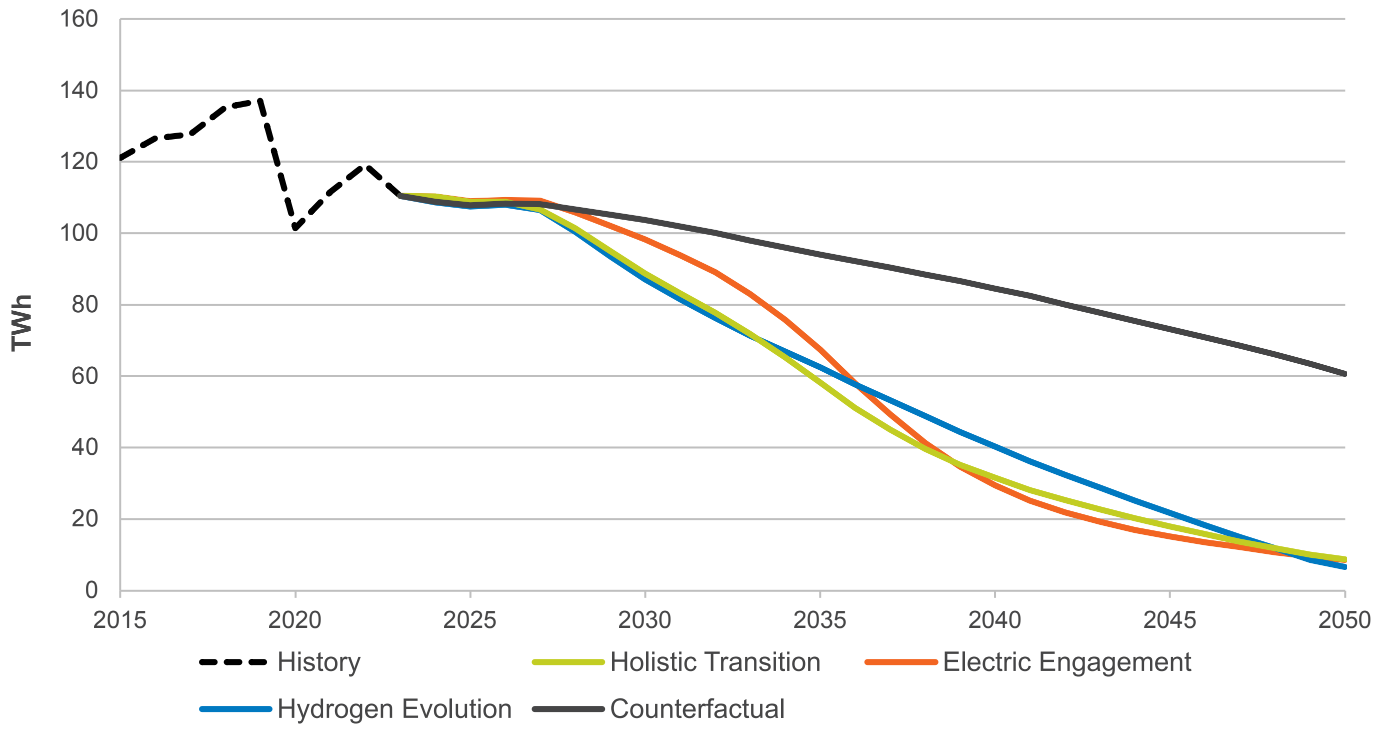


Figure EC.24: Industrial gas demand



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Industrial

The route to net zero

Incentives promoting the adoption of low carbon fuels will help Great Britain move away from energy sources with unabated emissions.

Key Action 2

A review of electricity and gas retail price difference will incentivise the electrification of industry. While widely discussed for residential consumers, there is an opportunity for similar reviews for industry to balance decarbonisation while ensuring Great Britain remains a competitive market for industry.

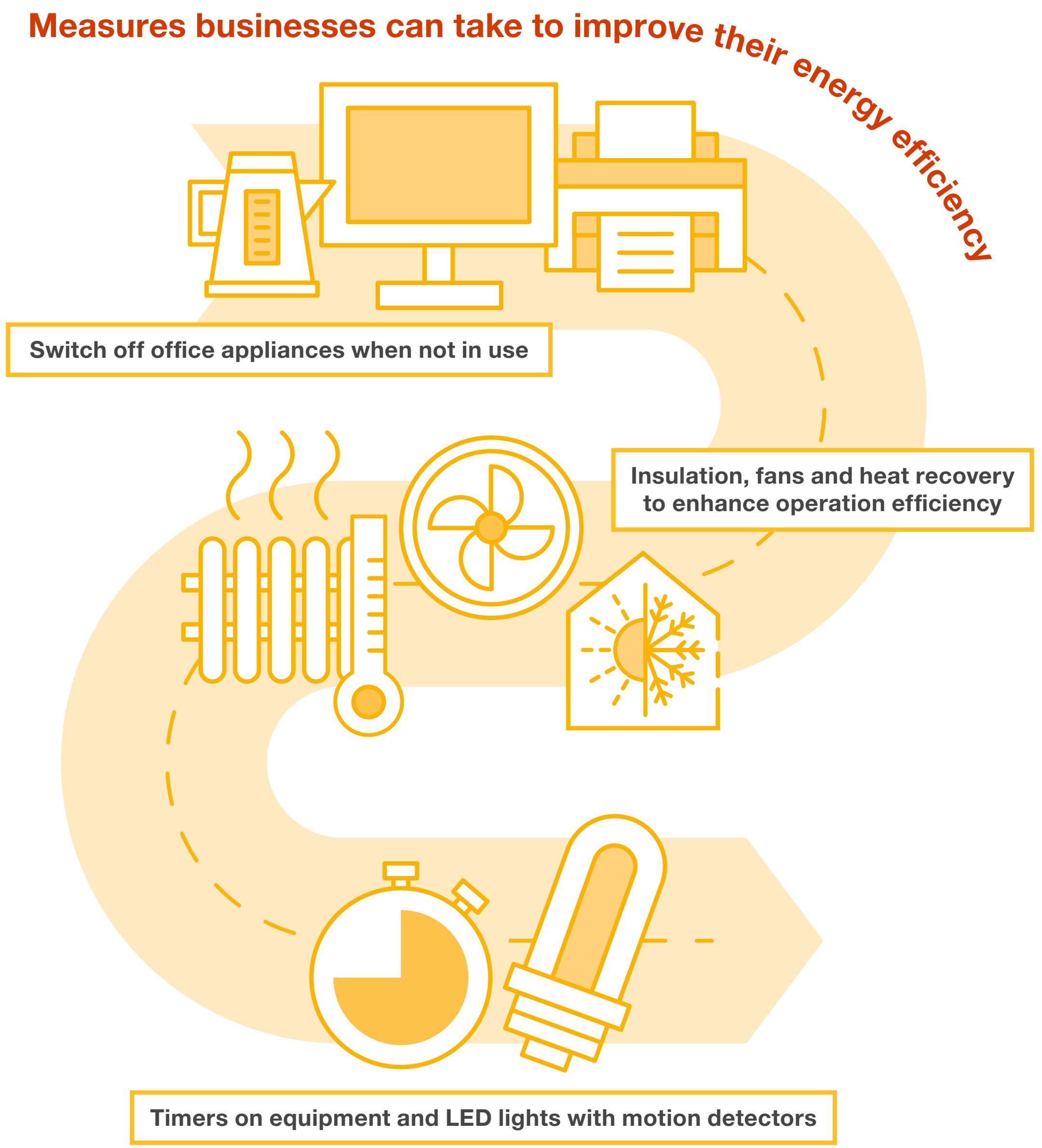
A clear comprehensive carbon accounting policy is needed to make sure that all businesses are aligned with decarbonisation goals. The inclusion of a Carbon Border Adjustment Mechanism (CBAM) would prevent carbon leakage from imports.

While there has been progress and announcement of further industrial clusters, a clear long-term plan and support are required to implement CCS for industries that will still require gas due to their processes.

Improving energy efficiency measures will help businesses benefit from thermal process efficiency gains, reducing their energy bills while providing long-term whole system benefits.

Key Action 6

With consumers more engaged in their chosen brand's environmental and sustainable credentials, implementing sustainable best practice will contribute towards businesses achieving their own net zero targets, helping to not only reduce their emissions but positively engage with their customers.



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Hydrogen demand

Hydrogen could help to rapidly reduce industrial gas use and associated emissions, compared to relying on electrification alone.

Large industrial clusters will offer powerful potential for hydrogen growth by guaranteeing the support and supply for industries that are the hardest to electrify. This includes businesses with industrial processes requiring larger investment to switch to electricity over hydrogen or those that operate at very high temperatures, which are easier to reach with gaseous fuels than electrified heating.

Hydrogen may be a better solution than abated gas solutions for some applications as it requires less space than post-combustion carbon capture.

A fast transition of these large industries is required to meet the Sixth Carbon Budget. Hydrogen can also prevent additional burden on the electricity network.

Low carbon hydrogen will be a highly important commodity and its use should be prioritised for hard-to-decarbonise sectors that face larger challenges in fuel switching to other fuels or abate current emissions.

All net zero pathways see the initial supply of hydrogen supported by hydrogen produced through reformation of natural gas to reduce risk of supply and increase speed of rollout, but electrolytic hydrogen will increase to become dominant over time. Please refer to The Energy System chapter *(page 145)* for more information on hydrogen supply.

Holistic Transition and **Hydrogen Evolution** see a fast acceleration of hydrogen in industrial clusters in the late 2020s and this is essential to reduce emissions. For industry, fuel switching to hydrogen initially occurs in these clusters at a faster rate than electrification in both pathways. Hydrogen Evolution has 78 TWh of hydrogen use in 2050 in industry, the largest of any consumer demand, and Holistic Transition sees 3.5 times more growth in low carbon hydrogen than in electrification of industry.

Electric Engagement sees the lowest level of hydrogen, which still grows 16 TWh for industries that are hardest to decarbonise via electrification. Hydrogen clusters do not grow as extensively in this pathway, compared to Holistic Transition and Hydrogen Evolution.

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Industrial

The route to net zero

Hydrogen capacity needs to be developed at pace towards the targets in the UK Government's Hydrogen Strategy Delivery Update.

Key Action 3

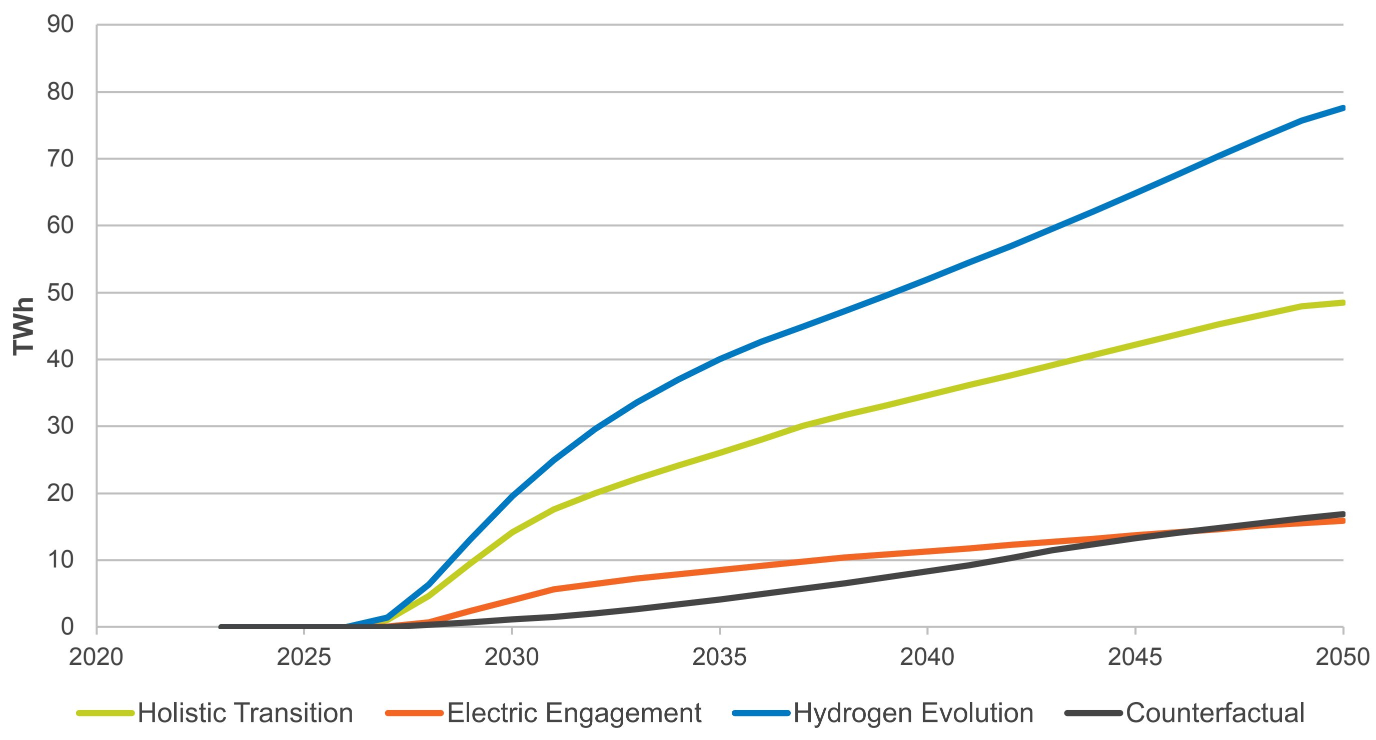
A fast rollout of clean hydrogen production capacity and adequate network could catalyse industrial decarbonisation. The development or conversion of existing gas storage must work in parallel with hydrogen capacity development to underpin this rapid transformation.

More information on hydrogen supply and hydrogen capacity targets can be found in The Energy System chapter *(page 145)*.

Clarity on the availability of hydrogen beyond the first industrial clusters is needed to give industry outside these areas certainty on the options available.

Further clarity is required to reduce investment uncertainty for industry. This will need to consider longer-term whole energy market strategy, ensuring that supply, networks and demand grow at similar pace.

Figure EC.25: Industrial low carbon hydrogen demand



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Emerging technologies

Our modelling considers fully established or newly developed technologies that can play a role in decarbonising our energy system. However, the scale and pace of innovation in the energy sector is rapidly accelerating, and we continuously monitor emerging technologies that may unlock new potential in Great Britain's journey to net zero.

If you know of a new and innovative technology that could be considered in the modelling of our pathways, please contact fes@nationalgrideso.com.

We've summarised some of the latest technologies currently in development, in the consumer space.

Autonomous vehicles

Autonomous vehicles could achieve improved energy efficiency compared to human-driven vehicles through eco-driving and platooning. Platooning reduces aerodynamic drag by grouping vehicles together and safely decreasing the distance between them via electronic coupling, which allows multiple vehicles to accelerate or brake simultaneously. Autonomous vehicles also have the potential to lead to greater car sharing, reducing car ownership. However, advances in software and hardware are needed for widespread deployment, as well as the ethical and societal challenges to consider.

Energy management systems

By using smart technologies and the Internet of Things (IoT), buildings can optimise electricity consumption to maximise utilisation of renewable sources, minimise the need for network upgrades and reduce consumer bills. Smart technologies can act as a significant source of flexibility for the wider energy system as well as giving consumers additional control over their demands. However, to enable this flexibility buildings will need time-of-use tariffs using smart meters and smart appliances for example white goods, heat pumps and electric vehicles that can operate flexibly.

Thermal batteries

Electricity can be converted to heat where the thermal energy can be stored. A range of storage mediums can be used from liquids, bricks, phase-changing materials or thermo-chemical materials. The thermal energy can be used directly to meet thermal demand, or it can be converted back into electricity. For the generation of electricity from thermal energy any heat engine technology may be used ranging from Rankine, Brayton or different thermodynamic cycles, to thermoelectric generators. Similar to electrical batteries, thermal batteries offer the ability to redistribute electricity from active renewable periods to peak demand periods.

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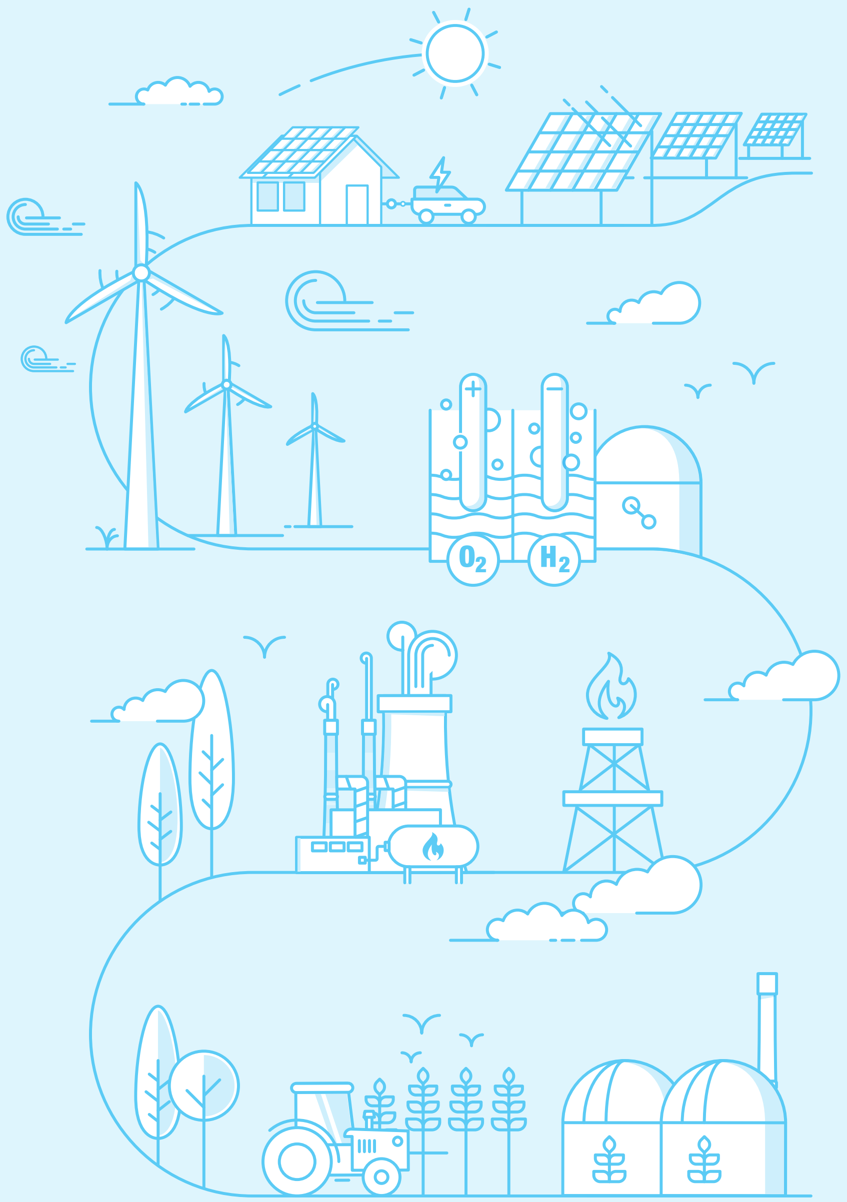
The Energy System



Introduction

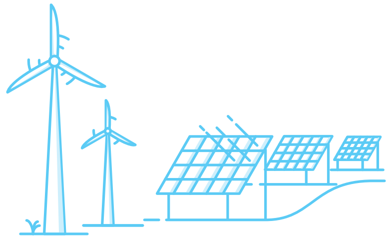
The energy system is undergoing rapid transformation on the route to delivering a fair, affordable, sustainable and secure energy future for consumers. At the heart of this lies strategic coordination and whole system thinking across sectors, vectors and regions.

Decarbonisation of the power sector will mark a critical milestone in our journey to become net zero by 2050. One of the crucial first steps towards this will be establishing the infrastructure needed across Great Britain for all low carbon fuels to work together, with strategic development of energy networks, markets and technologies. Reforms to planning, markets and connections must now continue at pace and this will rely on investment in supply chains and skills. Our pathways highlight the importance of renewable energy to meet the demands of a net zero energy system and addressing this challenge will help unlock the opportunities that renewables can offer.

An efficient and reliable system with increased levels of renewables will also need increased levels of flexibility. Our net zero pathways each demonstrate the importance of the interactions between low carbon fuels and technologies, alongside electricity storage, interconnectors and demand side flexibility to deliver a balanced system.

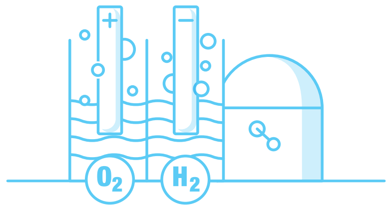
The need for low carbon hydrogen during the energy transition also presents an opportunity for the gas industry to deliver low carbon gas and for Great Britain to become a leader in hydrogen development. The country is well placed to benefit from significant existing assets and expertise in the field of gas transportation and storage through change-of-use to low carbon hydrogen. However, the whole system benefits of hydrogen can only be realised at scale if there is investment in hydrogen transport network and storage infrastructure. Similarly, we need negative emissions technologies to reach net zero by 2050 and this, too, will require investment.

While the power sector has decarbonised significantly in recent years, it's now time to go further and faster.

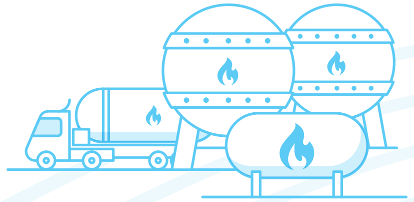


Across all net zero pathways, at least 94 GW of wind and solar is connected in 2030, with 121 GW connected in Holistic Transition.

Between 40–51 GW of electricity storage is operating by 2050 in all our net zero pathways, with 26–35% of this connected at distribution level.



There is over 33 GW of electrolyser capacity and 19 TWh of hydrogen storage needed in Holistic Transition in 2050.



Imported gas volumes fall to between 15–56% of 2023 imports across the net zero pathways.

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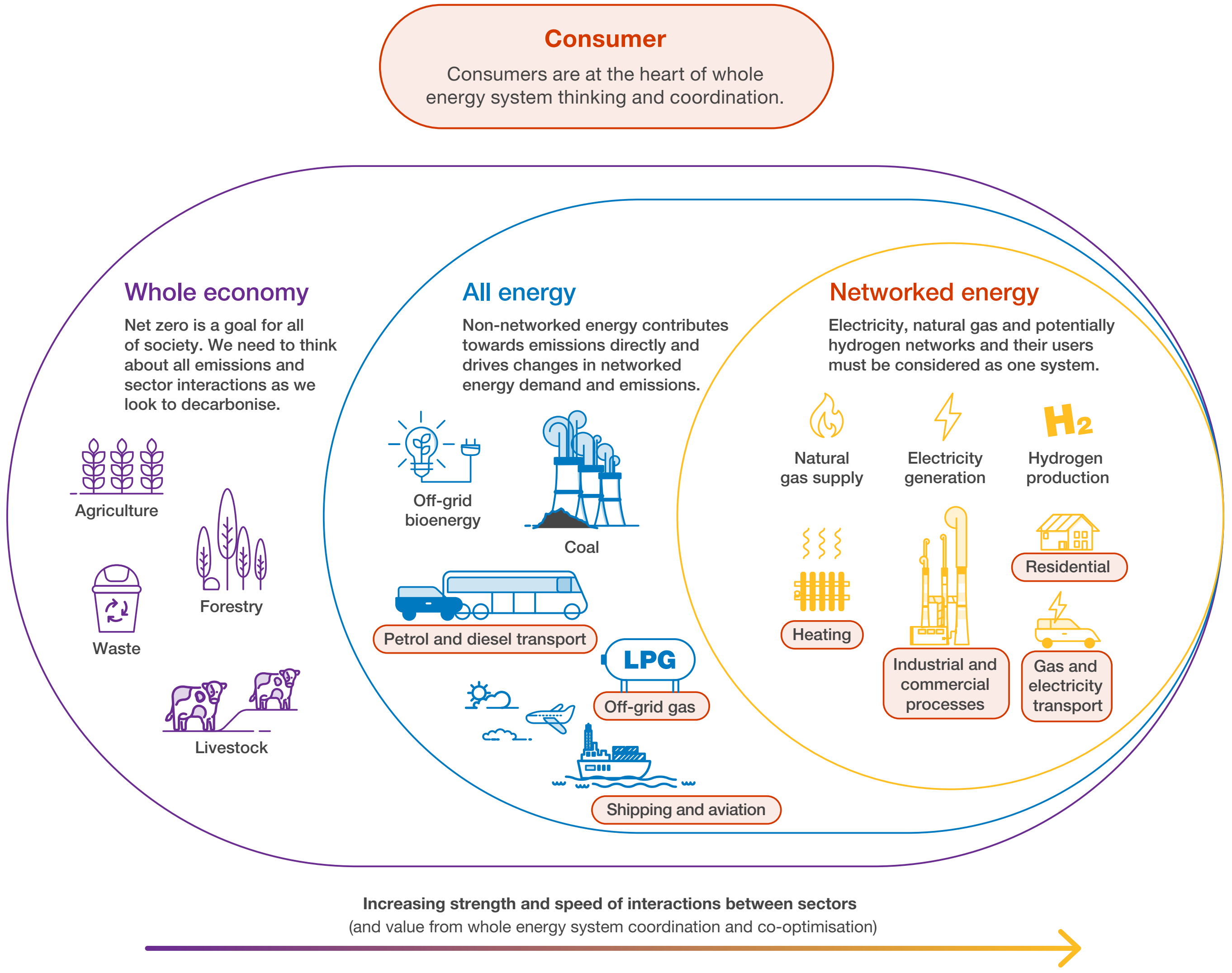
Introduction

What is a whole energy approach?

Whole energy means the interaction between electricity, gas and liquid fuels and how these energy sources can work together to deliver net zero emissions across all sectors. Until now, Great Britain has approached electricity, gas and oil as independent energy vectors to meet our energy needs. Adopting a whole energy approach will ensure that these work together with increasing volumes of low carbon fuels, such as hydrogen and biofuels, to deliver cross-sector decarbonisation, security of supply and reduce costs for consumers. This will require infrastructure investment and market changes that consider interactions between the various fuels.

In 2022, the Department for Energy Security and Net Zero (DESNZ) set out to “create an organisation at the centre of the energy system that can take a whole system view; helping explore and make trade-offs where needed to develop plans and advice that are both robust and fair.” The establishment of the National Energy System Operator (NESO) in 2024 will see one single organisation take on an independent view across the energy system to inform policy and investment decisions. As well as sitting at the heart of both the gas and electricity systems, NESO’s role will also mean taking on additional responsibilities in network operations, strategic network planning, long-term forecasting and market strategy.

Carbon emissions across the whole economy, including the energy system, are covered in the Reducing Great Britain’s Emissions chapter *(page 32)*.



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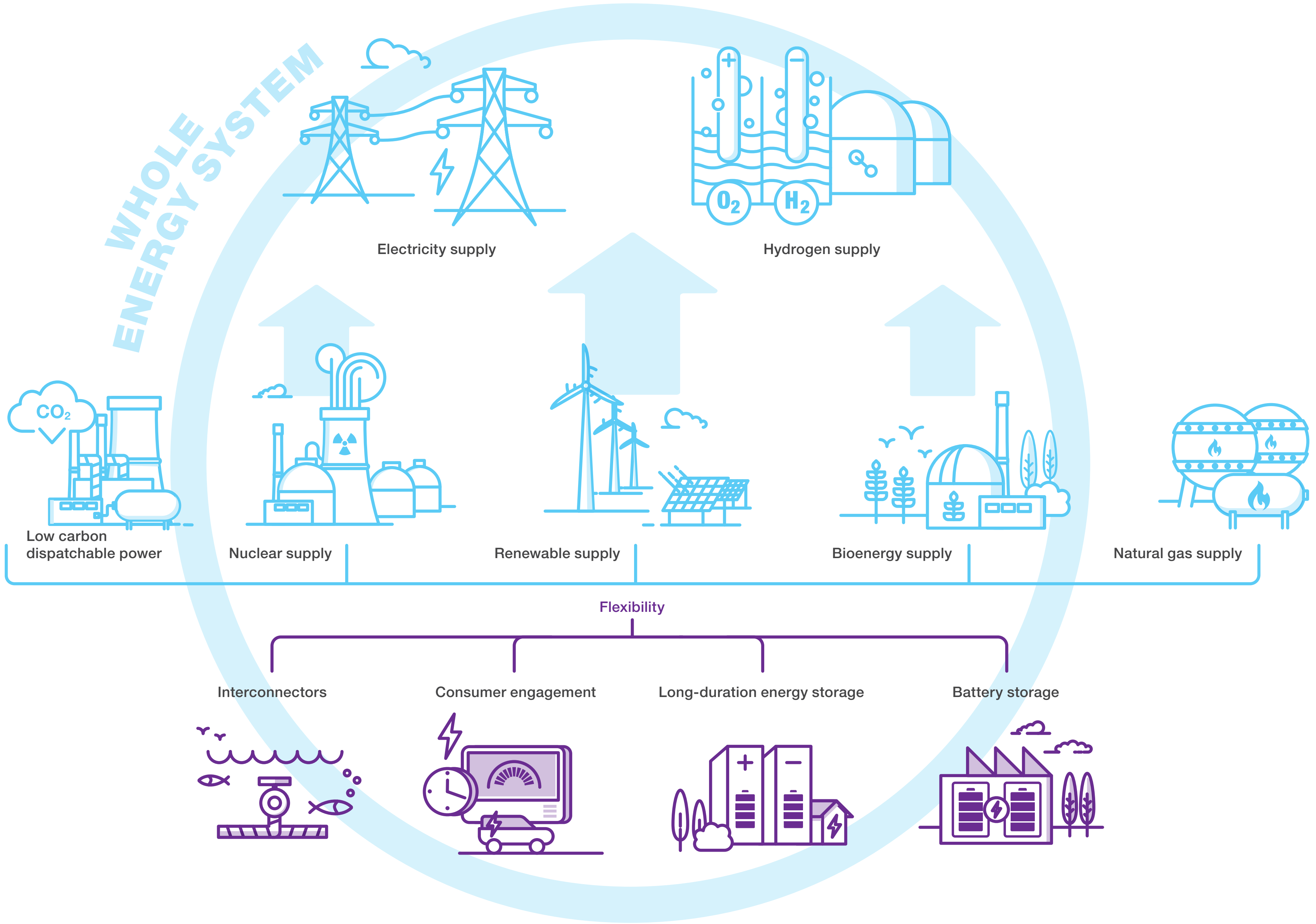
Flexibility

We define flexibility in Future Energy Scenarios (FES) as the ability to shift, reduce or increase energy supply and demand in real time or by location. This is driven by either market signals or the system operator. It's important that flexibility comes from both demand and supply sides to achieve an effective and balanced grid.

Consumer engagement and participation, through demand side shifting or reduction, will play an important role in getting the best value from flexibility services and will help drive Great Britain's decarbonisation journey. For more details on demand side response (DSR), see *The Energy Consumer chapter (page 51)*.

In this chapter, we examine grid-scale, supply side flexibility through low carbon dispatchable power, electricity and hydrogen storage as well as interconnector flows. We also look at aggregated smaller-scale flexibility via battery storage, which will become increasingly important as we move towards a net zero system.



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Energy supply and demand

Primary energy supply

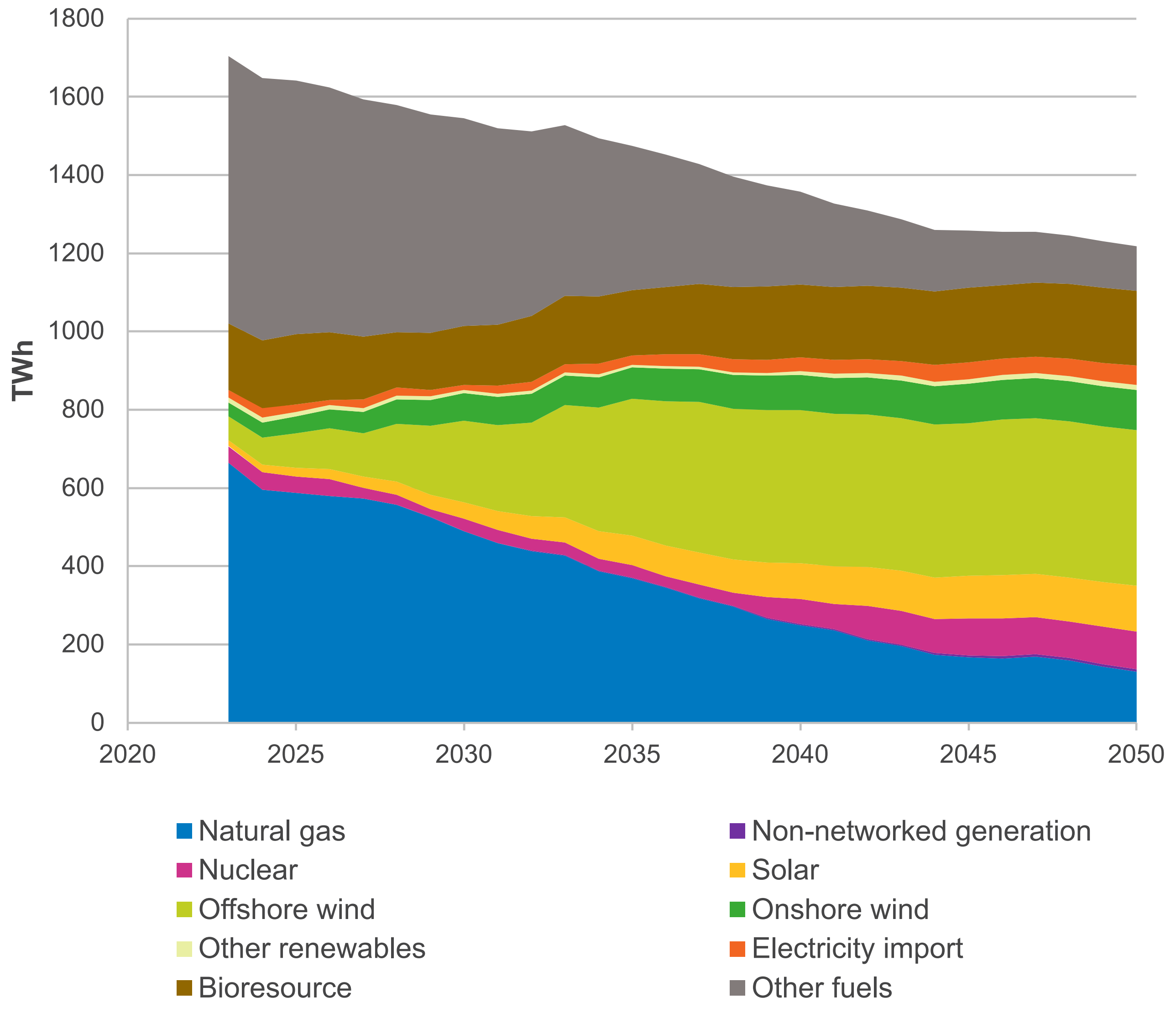
Figure ES.01 shows how primary energy supply changes up to 2050 in Holistic Transition. Where electricity is generated using fossil fuels or bioenergy, the primary energy is classed as being fossil fuels or bioenergy and not electricity.

Low carbon energy from renewables, nuclear and bioenergy provides 21% of primary energy input today, with the remaining 79% split approximately between natural gas and other fossil fuels. Electrification of heat and transport in Holistic Transition has the largest impact on reducing reliance on natural gas and oil (oil is included in ‘other fuels’). Electric vehicles and heat pumps are significantly more efficient than their fossil fuel equivalents, which leads to a reduced primary energy requirement.

Reducing demand through energy efficiency measures, such as insulation, is another important factor in reducing overall energy supply requirements. As most energy sectors switch away from fossil fuels at point-of-use, this increases demand for electricity, hydrogen and bioenergy. The use of unabated fossil fuel as an energy source for electricity and hydrogen decreases over time to ensure reduction in emissions from energy production. Wind generation plays an important role, with its share of energy supply increasing from 6% today to 41% in 2050.

Although fossil fuel use declines out to 2050, this continues to supply 20% of the energy demand, where it is mainly used for shipping and aviation, and hydrogen and electricity production where CO_2 emissions are captured.

Figure ES.01: Primary energy supply in Holistic Transition in 2050

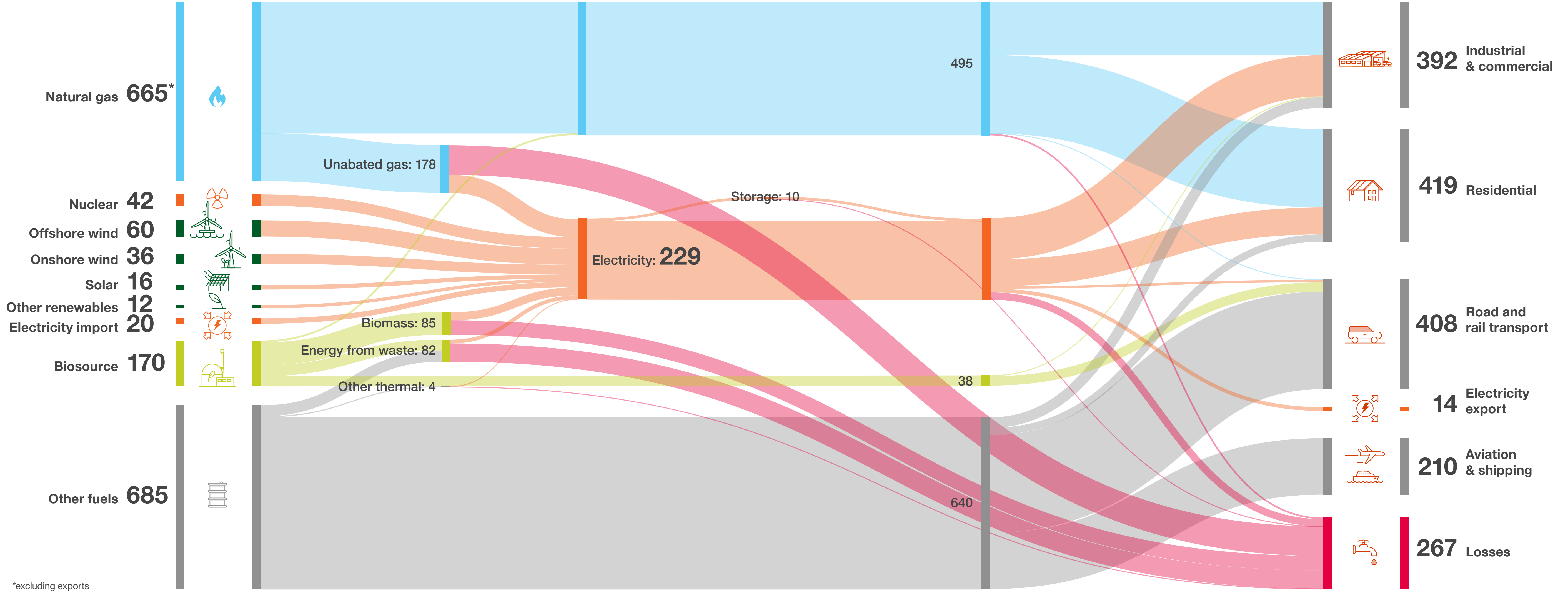


Energy supply and demand today

2023

Interactions between different fuels are low, demonstrating limited whole system thinking or cross-sector decarbonisation. Fossil fuels make up 79% of total energy supply. Petroleum supplies over 90% of road transport demand and 100% of aviation and shipping demand.

Total energy supply
1706 TWh



Please note that TWh figures are rounded to the nearest number.

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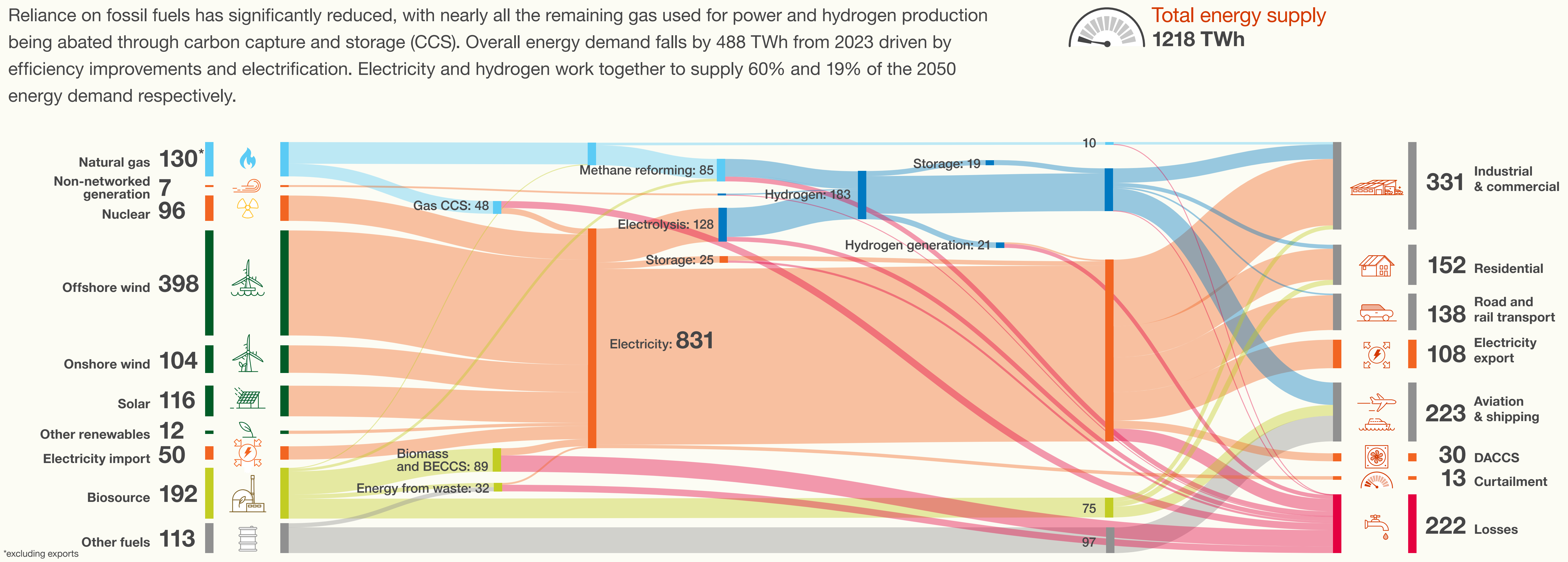
Energy supply and demand in 2050

Holistic Transition

Reliance on fossil fuels has significantly reduced, with nearly all the remaining gas used for power and hydrogen production being abated through carbon capture and storage (CCS). Overall energy demand falls by 488 TWh from 2023 driven by efficiency improvements and electrification. Electricity and hydrogen work together to supply 60% and 19% of the 2050 energy demand respectively.



Please note that TWh figures are rounded to the nearest number.

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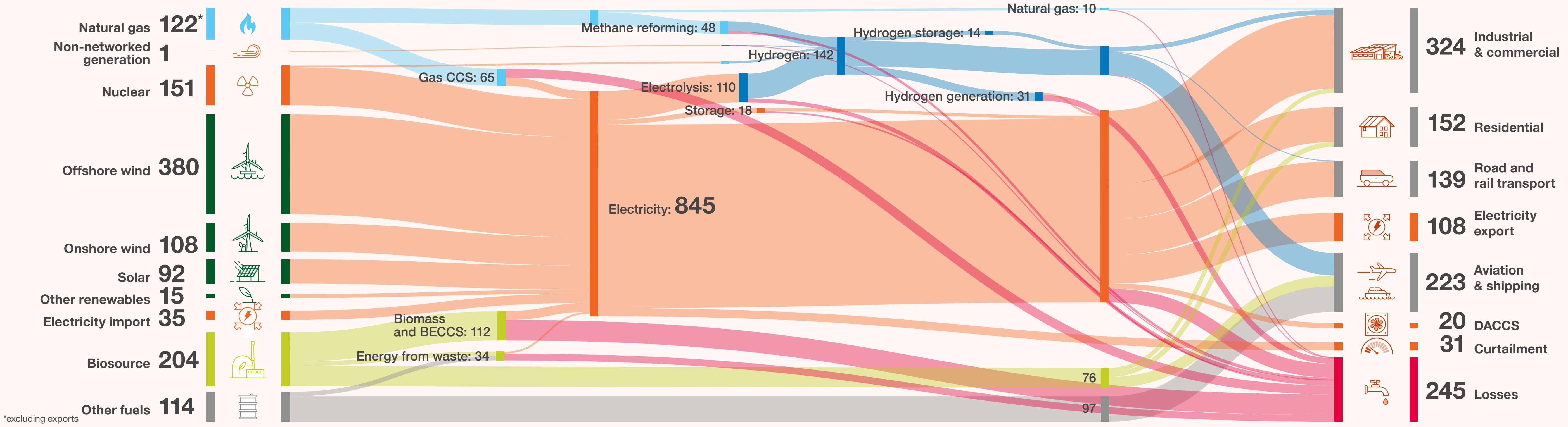
Energy supply and demand in 2050

Electric Engagement

Electricity supplies 66% of overall energy demand in 2050. Electricity generated increases by 616 TWh but overall energy demand falls by 484 TWh compared to today. This is driven by consumer engagement, insulation and efficiency gained through electrification. Hydrogen provides 19% of the overall energy needed for industry, aviation and shipping.

Total energy supply
1222 TWh



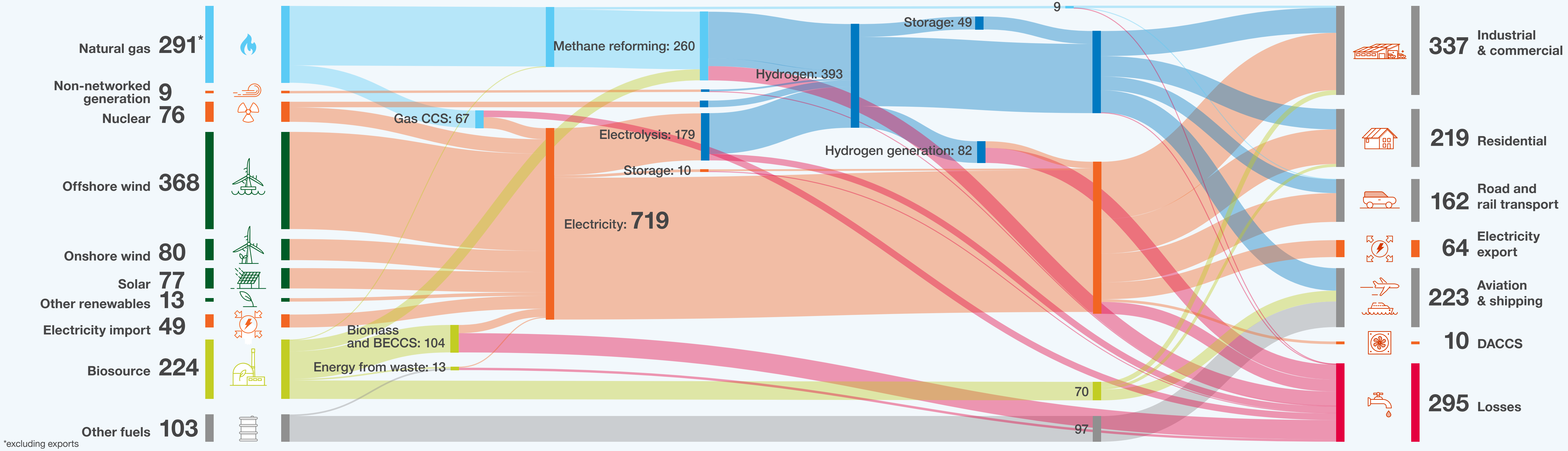
Please note that TWh figures are rounded to the nearest number.

Energy supply and demand in 2050

Hydrogen Evolution

Hydrogen supplies 30% of overall energy needed in 2050 used across all sectors. Overall energy demand drops by 414 TWh driven primarily by the remaining demand that is electrified. Natural gas is still used for electricity and hydrogen production in 2050 but it is abated through CCS.

Total energy supply
1292 TWh



Please note that TWh figures are rounded to the nearest number.

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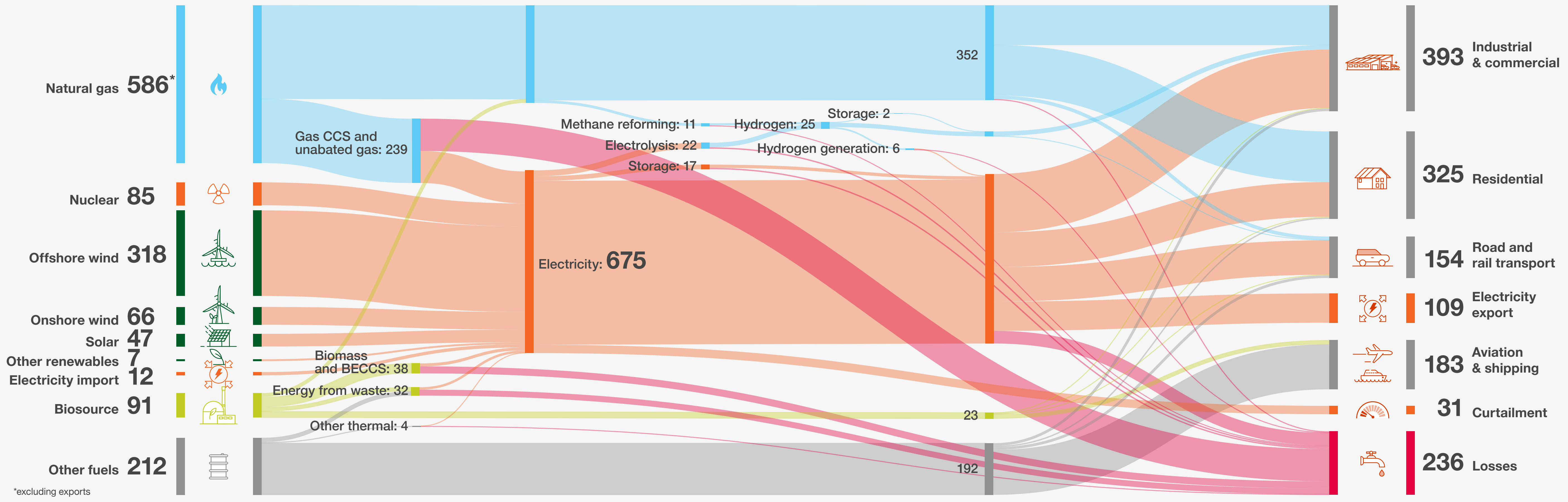
Energy supply and demand in 2050

Counterfactual

Heavy reliance on fossil fuel remains, supplying 56% of energy needed across all sectors, predominantly supplied by natural gas. Hydrogen use is limited due to the continued use of natural gas. Road transport sees the most decarbonisation with 85% of demand met by low carbon fuels.

Total energy supply
1423 TWh



Please note that TWh figures are rounded to the nearest number.

Key comparison chart of decarbonisation milestones

Key comparison chart

This chart contains a selection of recent policy ambitions in relation to net zero and energy security and highlights how they compare to the different pathways. The chart also shows non policy-related items that are key decarbonisation milestones.

Note that energy demand will be affected by policy on the demand side which is set out in the comparison chart in the Energy Consumer chapter *(page 56)*. It is critical that policy considers the whole energy system and not supply and demand in isolation.

Please note analysis for FES 2024 commenced before the publication of several key policy documents and the UK general election and reflects policy targets and ambitions at the time of analysis.

		2023	2025	2030	2035	2040	2045	By 2050	Maximum potential by 2050	Maximum potential pathway
Emissions	Meets 2050 net zero target	422 $MtCO_2e$						HT EE HE	Net zero by 2050	HT
	Meets Fifth Carbon Budget			HT EE HE CF						
	Meets Sixth Carbon Budget				HT EE HE					
Electricity generation	50 GW of offshore wind	15 GW		HT	EE HE CF				101 GW	HT
	5 GW floating offshore wind	0 GW			HT EE HE	CF			20 GW in HT 19 GW in EE and HE	HT EE HE
	70 GW of solar	15 GW				HT	EE	HE	108 GW	HT
	No unabated natural gas-fired generation capacity, subject to security of supply	36 GW				HT	EE	HE	HT reaches this target in 2036	HT
	24 GW nuclear generation capacity	6.1 GW							22 GW	EE

In developing the pathways we balance current ambitions, progress towards targets, stakeholder feedback and what we have modelled for an optimal pathway. Policy assumptions vary across the pathways in line with the pathway narrative. More information can be found in our "Future Energy Scenarios: Pathway Assumptions 2024[1]" document.

HT Holistic Transition
EE Electric Engagement
HE Hydrogen Evolution
CF Counterfactual
Government policy

1 nationalgrideso.com/future-energy/future-energy-scenarios-fes/fes-documents

Key comparison chart of decarbonisation milestones

Key comparison chart (continued)

		2023	2025	2030	2035	2040	2045	By 2050	Maximum potential by 2050	Maximum potential pathway
Hydrogen	10 GW low carbon hydrogen production capacity in operation or construction	<1 GW		HE	HT	EE			75 GW	HE
	5 GW hydrogen production from electrolysis	<1 GW			HT HE	EE			49 GW	HE
	2 GW of low carbon hydrogen production capacity in operation or construction	<1 GW		HT EE HE	CF				75 GW	HE
Natural gas	40% reduction in gas consumption				HT EE	HE			85% reduction	EE
Bioenergy	Biomass supply consistent with Climate Change Committee Sixth Carbon Budget - not directly modelled									
Energy storage	100 GWh of non-battery electrical storage	2.75 GW / 28 GWh				HT			118 GWh in HT	HT
	30 GWh of battery electrical storage	4.7 GW / 5.8 GWh		HT EE HE					65 GWh in HT	HT
Interconnectors	18 GW capacity	8.4 GW			HT EE				25 GW in HT	HT

HT Holistic Transition
EE Electric Engagement
HE Hydrogen Evolution
CF Counterfactual
Government policy

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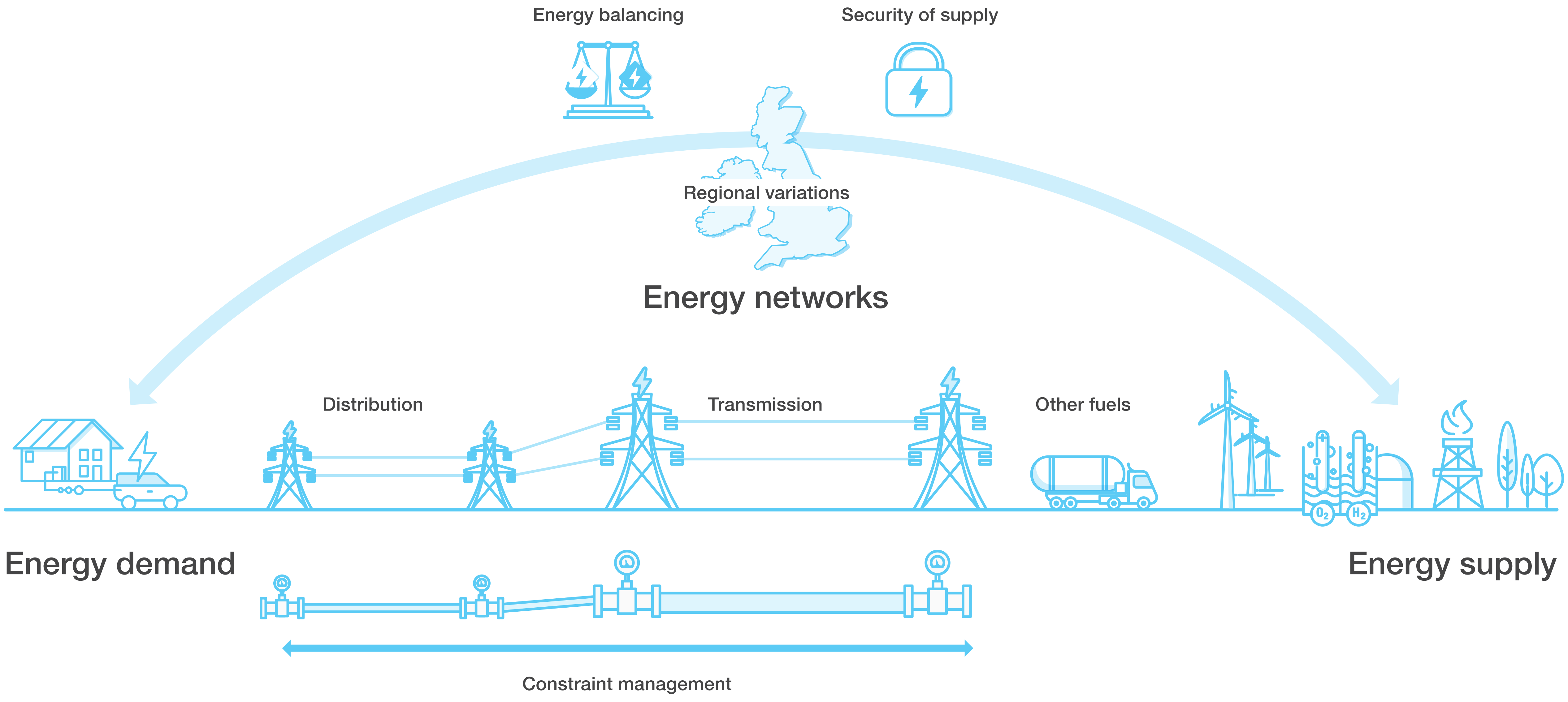
Managing the energy system

Managing the energy system means balancing supply and demand. This means moving energy from where it is produced to where it is needed, storing it to use later at times of over or undersupply, managing constraints in the system and ensuring security of supply.



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Managing the energy system

Energy balancing and security of supply

Security of supply refers to managing supply and demand at any given time to keep the energy system running (reliability standards for this are set by UK Government). Risks around meeting electricity security of supply typically arise during times of high demand, which is managed by switching on dispatchable gas plants.

As we move to higher volumes of weather-dependent renewable energy, we will also face additional challenges around both the oversupply and undersupply of renewable generation, and these fluctuating levels will require alternative methods for managing security of supply. Market and policy reforms, such as the Review of Electricity Market Arrangements (REMA), will inform future approaches to ensuring a cost-effective, secure and reliable decarbonised energy system.

Managing oversupply

During periods of high renewable generation and low demand, oversupply leads to lower system prices. This incentivises an increase in demand or charging of energy storage units to reduce the risk of curtailing generation. Improved market signals through market reforms should soon help the market play a key role in delivering economically efficient curtailment and minimising operability challenges for the system operator.

Flexible demand sources, such as electrolysers which use electricity to produce hydrogen, can be stored during periods of oversupply and can increase demand when needed. Other forms of flexibility can also help manage the system. For shorter and less sustained supply peaks, residential, transport, commercial and industrial DSR could be used, as well as batteries, low carbon dispatchable generators (hydrogen peaking plants) and interconnectors.

Managing undersupply

More extreme but extended periods of low weather-dependent generation may also pose a security of supply risk and extended periods could exhaust storage options. A combination of flexible technologies will, therefore, be needed to ensure security of supply.

The level of impact during these periods will be determined by the level of renewable generation and how much this fluctuates in relation to demand. Weather patterns in neighbouring countries and interconnector flows can also have an impact. To manage this, dispatchable thermal power plants (gas with carbon capture and storage (CCS) and/or hydrogen) can be used, as well as long-duration energy storage and interconnectors.

We continue to work with industry experts to improve our understanding of the potential impact of dunkelflaute periods in future FES iterations[2].

2 For more information, please see our recent spotlight piece on resource adequacy in the 2030s: Resource Adequacy in the 2030s (May 2024)

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Managing the energy system

Moving energy around the country

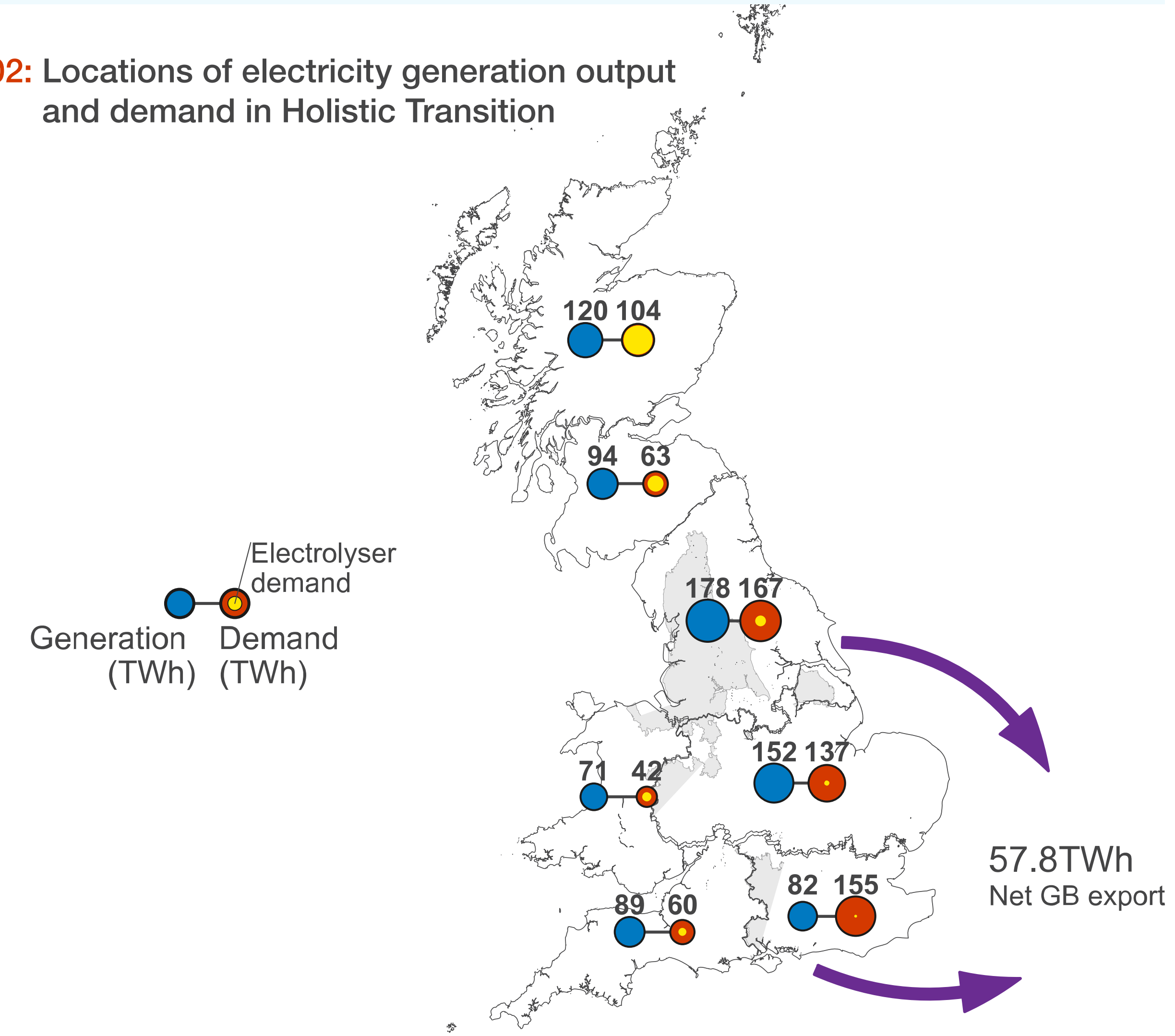
Accelerating the delivery of whole system infrastructure requires strategic network investment with energy vectors working together to overcome the challenges of the changing energy mix. For example, producing hydrogen to balance the weather dependency of renewables in areas further away from demand centres. This whole system approach will enable optimisation of the future level of network investment and minimise network constraints.

All net zero pathways continue to show growth in renewable generation out to 2050 with offshore wind accounting for a significant proportion of this growth.

Holistic Transition sees net generation and demand set to grow. The regional split of these across the country is also expected to change in the future years. This year, we have taken a more strategic decision to colocate electrolysers closer to locations with high renewable generation, such as the north of the country.

Our network planning process is undergoing major transformation as we transition to the Strategic Spatial Energy Plan (SSEP) and the Centralised Strategic Network Plan (CSNP). These processes are being developed through collaboration with UK Government and Ofgem. More information on the changes to the network planning process can be found in the Introduction chapter *(page 05).*

Figure ES.02: Locations of electricity generation output and demand in Holistic Transition



Managing the energy system

Electricity peak demand

Electricity peak demand in our analysis is defined using the average cold spell (ACS). This is the maximum demand over an average winter (after smart charging and residential heat demand side flexibility), and has, on average, a 50% chance of being exceeded in any given year. We expect electricity peak demand to increase in all pathways as consumers switch to electrification, particularly for heat and transport. In the short term, high energy costs suppress demand peaks and counter initial fuel switching to electricity.

Electricity peak demand tends to occur on winter weekday evenings, when industrial and commercial demand overlaps with residential. However, as the share of renewable electricity supply increases, electricity peaks could occur at other times. Distributed generation connected to the distribution network will meet an increasing share of local demand at varying times, changing the demand profile seen on the transmission network.

Other forms of flexibility, such as electrolysis and direct air carbon capture and storage (DACCS), will change operation patterns according to market conditions. For example, in Hydrogen Evolution in 2050, a typical daytime demand could be increased by up to 30 GW from electrolysers alone. Low market prices or other incentives could lead to this taking place during periods of high renewable output.

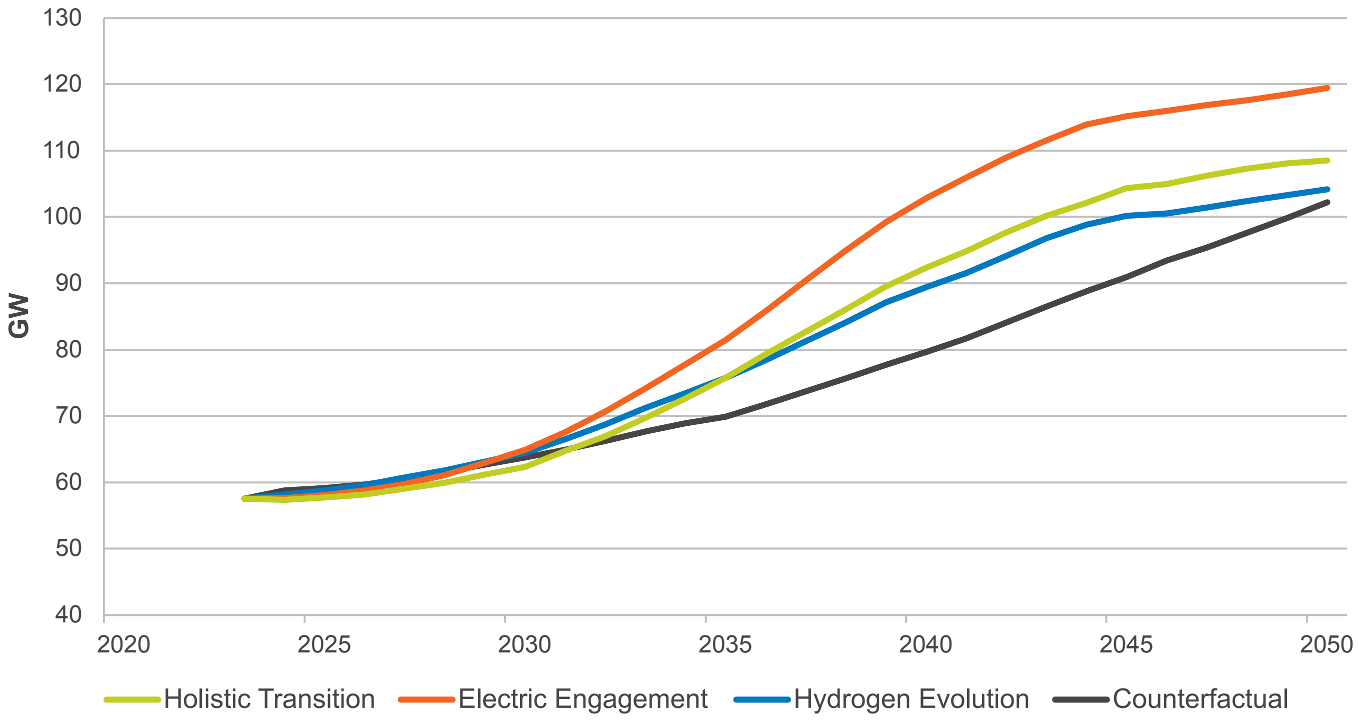
All net zero pathways see continued data centre growth in the 2040s, increasing peak demand. Electrification of heat continues to be the main driver for rising peak demand out to 2050. The contribution to peak demand from residential appliances and the transport and industrial sectors starts to level out from the mid-2040s.

Holistic Transition and **Electric Engagement** see peaks remain low for the next three years due to greater implementation of energy efficiency measures.

Electric Engagement sees the greatest electrification of heating. With no hydrogen for heat, electricity peak demand increases at a faster rate than the other pathways. This pathway also features a high level of industrial demand fuel switching to electricity in the 2030s.

Hydrogen Evolution initially has the highest peak demand due to low levels of consumer engagement in DSR and smart charging. This is also the case for the Counterfactual. The late 2020s sees electrification of transport and heating increasing peak demand. Hydrogen for heat is adopted in the late 2030s.

Figure ES.03: Electricity average cold spell peak demand (including losses)



Managing the energy system

Natural gas peak demand

Natural gas peak demand is expected to decline in line with the reduced use of natural gas across our net zero pathways. Peak demand for natural gas is linked to heat demand for residential homes – on cold winter evenings this will continue to remain high while large numbers of homes still remain on gas boilers. As the heat sector decarbonises, the peak demand for natural gas will reduce.

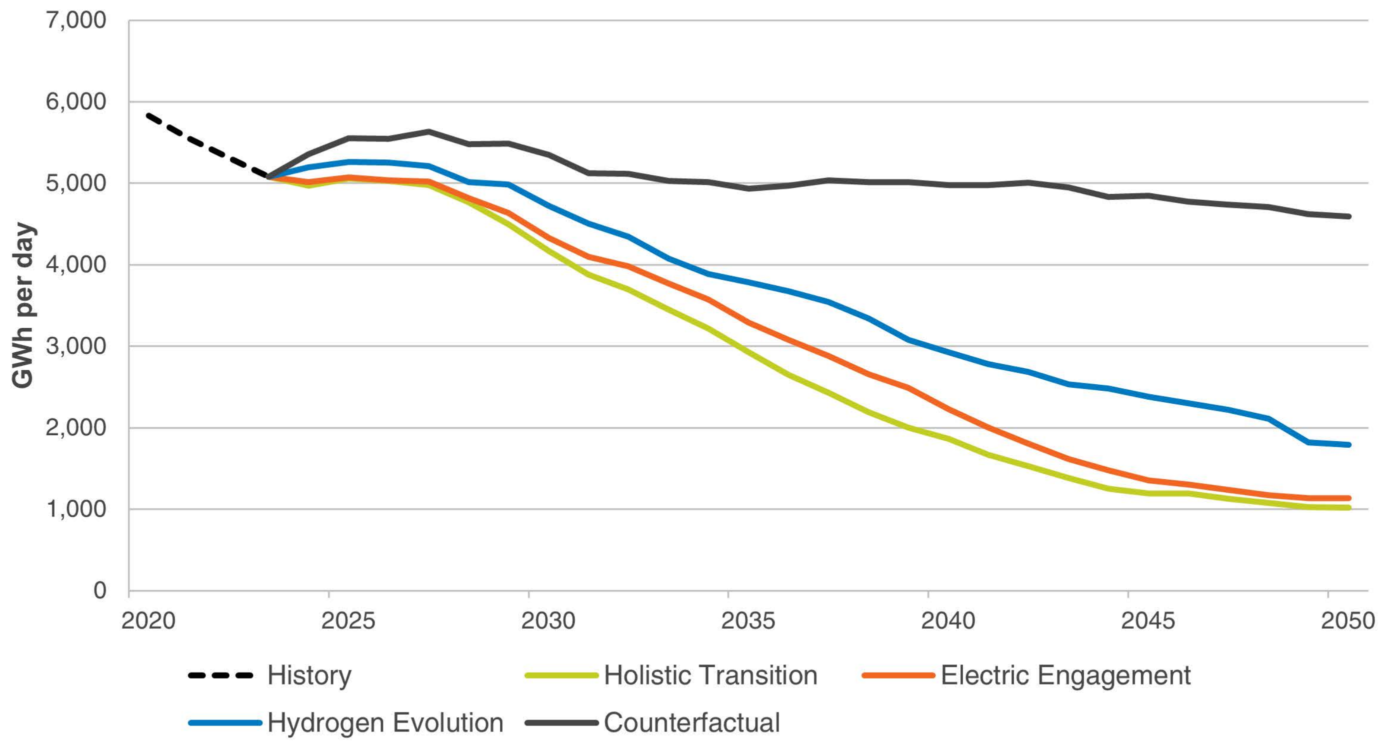
Industry and power sectors use a large proportion of gas today. This reduces to a lesser extent in power but becomes abated in both sectors across our net zero pathways.

Holistic Transition and **Electric Engagement** see natural gas demand declining to nearly a fifth by 2050 as unabated gas is phased out completely. The remaining amount is used predominantly for abated power generation.

Hydrogen Evolution sees natural gas still used to produce hydrogen via methane reformation with CCS. However, the peak demand is lower than today as this process takes place throughout the year.

The **Counterfactual** shows little progress in decarbonising heat, with 188 TWh of natural gas used for residential heating in 2050. Gas use increases in power in 2050, although 60% of this is combined with CCS. Overall, this leads to a 10% reduction in peak gas demand.

Figure ES.04: Natural gas peak demand (1-in-20 day)



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Managing the energy system

Low carbon hydrogen demand

In our net zero pathways, low carbon hydrogen demand increases across several sectors. Industrial applications requiring high-temperature heat, for instance, may be more suited to hydrogen than electrification. Additionally, hydrogen has a role to play in industrial combustion applications with limited space for the retrofit of carbon capture technology.

Low carbon hydrogen also holds promise in hard-to-decarbonise sectors such as shipping, aviation and agriculture. Its role is more uncertain in other applications, such as road transport and residential heating. However, the Government's planned 2026 decision on the role of hydrogen in heat decarbonisation will clarify this role.

Prioritisation of hydrogen for hard-to-electrify applications is needed.

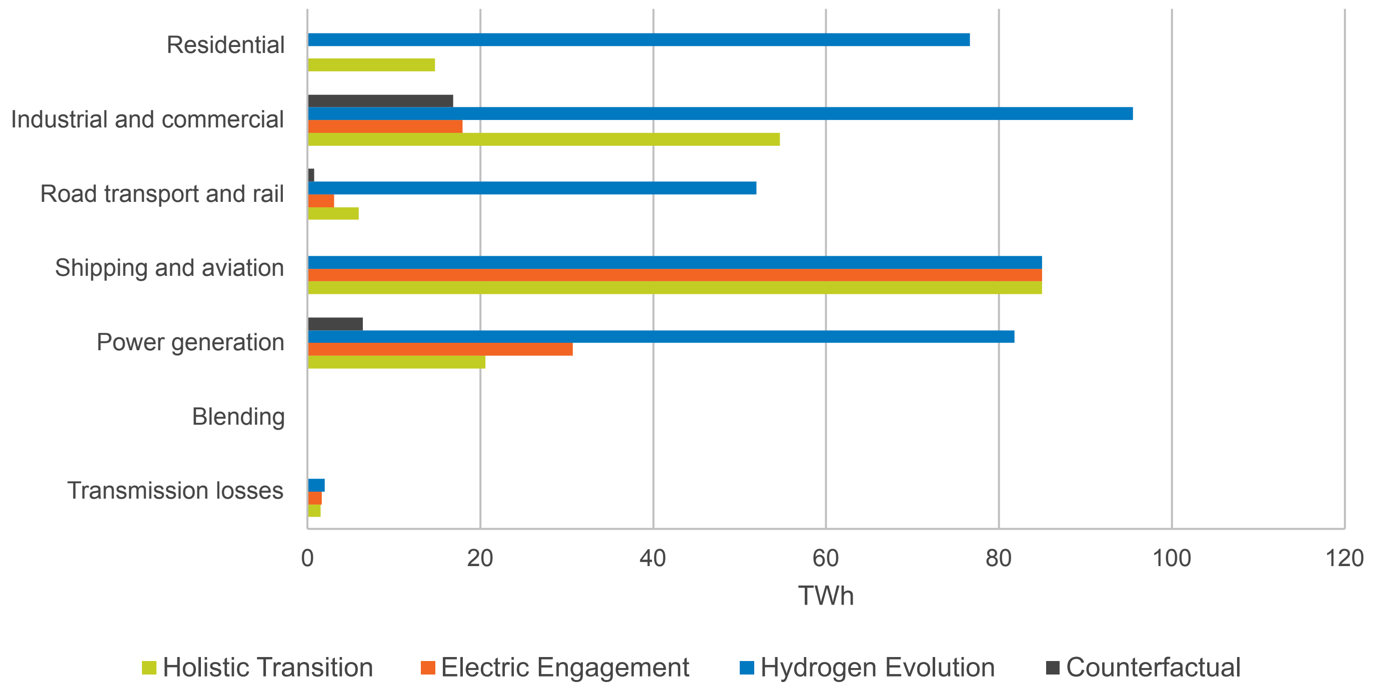
All net zero pathways see hydrogen deployed in industrial fuel switching ranging from 18–95 TWh in 2050.

Holistic Transition and **Hydrogen Evolution** both see hydrogen used in residential heat, ranging from 15 TWh in Holistic Transition (where it is localised around industrial clusters) to 77 TWh in Hydrogen Evolution (which has widespread access to hydrogen and policy support).

Electric Engagement has no hydrogen for heat. Shipping and aviation follow the Climate Change Committee's (CCC) Balanced Pathway for hydrogen use, while road transport features lower hydrogen demand but still has a range to represent some uncertainty.

The **Counterfactual** has limited hydrogen use, with 24 TWh by 2050, which is primarily used in industry.

Figure ES.05: Hydrogen demand by pathway and end user in 2050



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The route to net zero

Strategic and timely investment across the whole energy system is critical to achieving decarbonisation targets and minimising constraints.

Key Action 1

Coordinated planning and delivery of strategic, whole system investment through the SSEP, CSNP and Regional Energy System Planner (RESP) need continued collaboration with UK Government, Ofgem, local communities, industry and the supply chain.

Connections reform is required to facilitate quicker, more coordinated and efficient connection to Great Britain's energy system.

Key Action 7

The process must be future-proofed to facilitate potential prioritisation of connections for delivery of whole system benefits and net zero, in line with strategic network planning.

The retirement of older power stations must be effectively managed alongside bringing forward investment in new capacity to ensure security of supply.

As our energy mix is changing, it is important to manage the retirement of power stations nearing their end of operational life, while ensuring the infrastructure and markets support the new capacity needed for security of supply.

Electricity, hydrogen and CO_2 storage are vital to provide the adequacy needed to ensure a reliable whole energy system.

Key Actions 3,4&7

Policy support is essential to help bring forward the investment needed for long-duration energy storage. With the retirement or conversion of unabated gas plants post-2030, delivering the levels of energy storage and low carbon dispatchable power needed for security of supply will be essential.

The operational impact of a net zero power system is manageable.

As part of our effort to make the grid ready to operate with 100% zero carbon electricity by 2025, we will continue to deliver frequency services.

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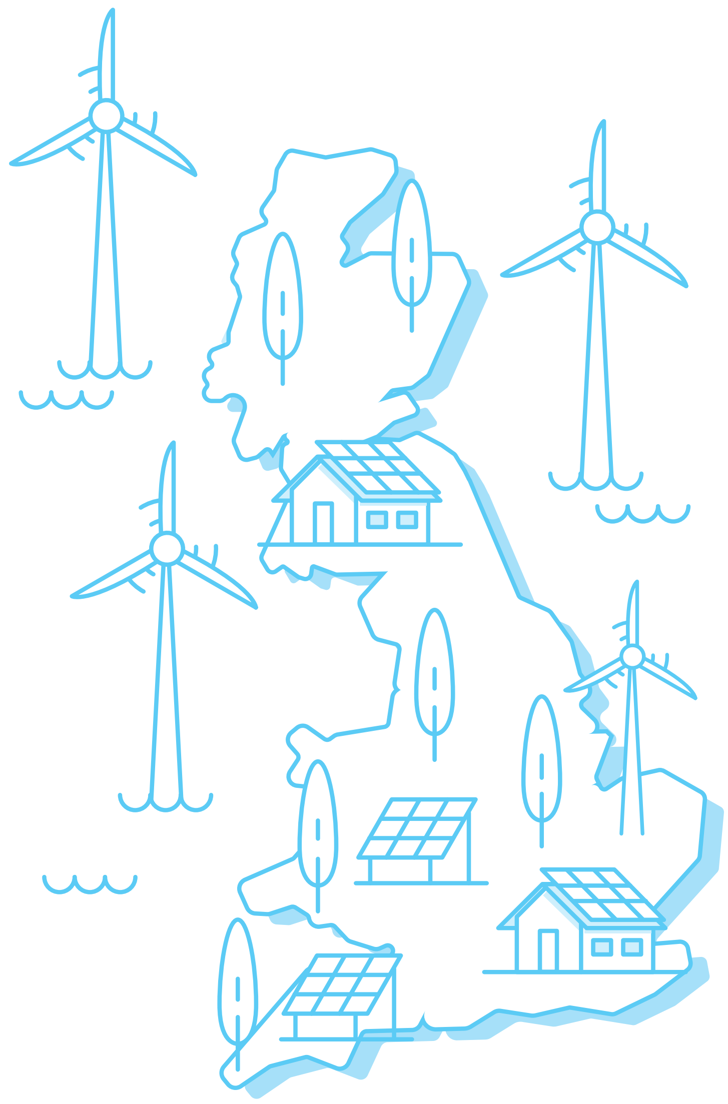
Electricity

Great Britain's electricity needs are set to significantly rise by 2035, as we move towards more electrified heat and transport options. A coordinated and strategic approach is needed over the next decade to build the infrastructure required to support this[3].

The electricity system is transitioning to a net zero system with high levels of weather-dependent renewable generation. All our net zero pathways show significant growth of offshore and onshore wind, together with high levels of solar deployment. Investment in renewable energy supply chains, market reform and improvements to the planning and connections processes could unlock huge opportunities around the delivery of renewable energy in Great Britain. Our pathways show varying levels of nuclear, bioenergy with carbon capture and storage (BECCS), low carbon dispatchable power and electricity storage.

As we rely upon more renewable energy generation, we will also need new forms of flexibility to ensure security of supply. Electricity storage and interconnector flows will help manage renewable variations, as will low carbon dispatchable generation, such as hydrogen peaking plants and/or gas CCS.

Our modelling considers fully established or newly developed technologies that can play a role in decarbonising our energy system, including electricity-centric innovations. For more information, please see the "Emerging technologies" page at the end of this chapter *(page 161)*.



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Total capacity and electricity output

Generation capacity is expected to increase rapidly across all our pathways to meet increased demand from electrification of transport and heat. We expect a higher contribution from distributed generation in 2050.

Recent capacity auction results, market and project intelligence and data from the distribution and transmission-connected capacity registers guide our short-term projections. We have adopted a capacity expansion model (CEM) for electricity and hydrogen supply beyond 2030. This seeks the lowest cost mix of transmission-connected generation and storage which meets the Sixth Carbon Budget and net zero emissions reduction targets. The model balances estimated build rates alongside capital and operational costs of different technologies against their ability to meet electricity demand. The aim of this is to minimise the total long-term cost of operating the system.

To ensure supply meets demand, the model includes 'expansion' plants (by region and technology) when or where these may be economically viable. Distribution-connected electricity supply beyond 2030 is calculated separately using bottom-up assumptions. We have added a reserve margin to CEM which ensures the firm capacity of all generation plants meets peak demand, plus 4%. This means we can ensure our generation capacity mix is applicable for multiple (and even more extreme) weather years.

Pre-2030, our generation build is based upon the Transmission Entry Capacity and Embedded Capacity Registers. This guarantees that there should be no connection for generation in regions with significant network constraints. After this point, the impact of electricity network constraints helps inform a suitable regional distribution and mixture of technologies. These constraints reflect the expected level of network reinforcement to be proposed in the CSNP. Including these constraints means the model favours colocation of increased generation capacity with large electricity demand, such as electrolysers, to reduce the peak flows of electricity between regions within Great Britain.

While the pathways seek to find a narrower, strategic range of routes to net zero, there remains some uncertainty over the role that various technologies will play in the energy mix. This is highly dependent on policy and markets. To address this, we have set minimum build limits for technologies in some instances to ensure there remains a range across the pathways which supports the narrative of a given pathway. Further detail on our inputs and assumptions can be found in our "Future Energy Scenarios: Pathway Assumptions 2024[4]" document.

4 nationalgrideso.com/future-energy/future-energy-scenarios-fes/fes-documents

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Electricity

Figure ES.06: Installed electricity supply capacity

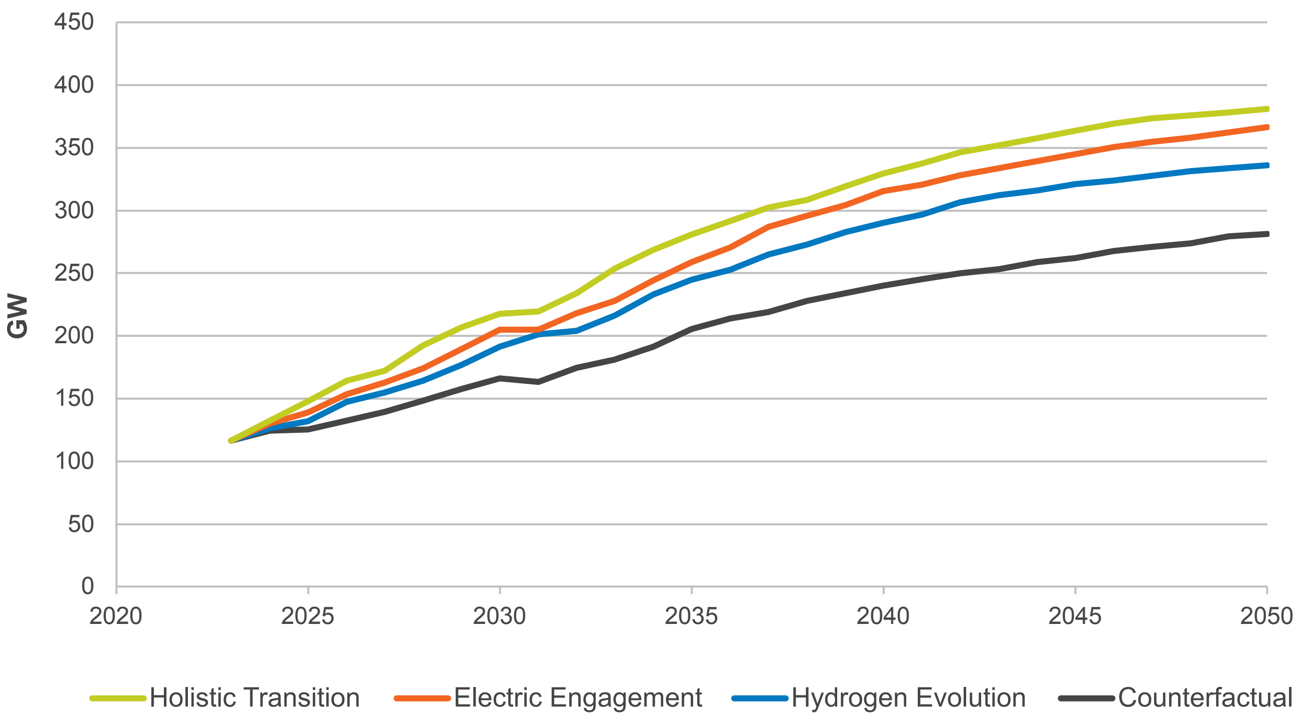

Figure ES.07: Installed generation capacity, peak demand and percentage of distribution-connected capacity

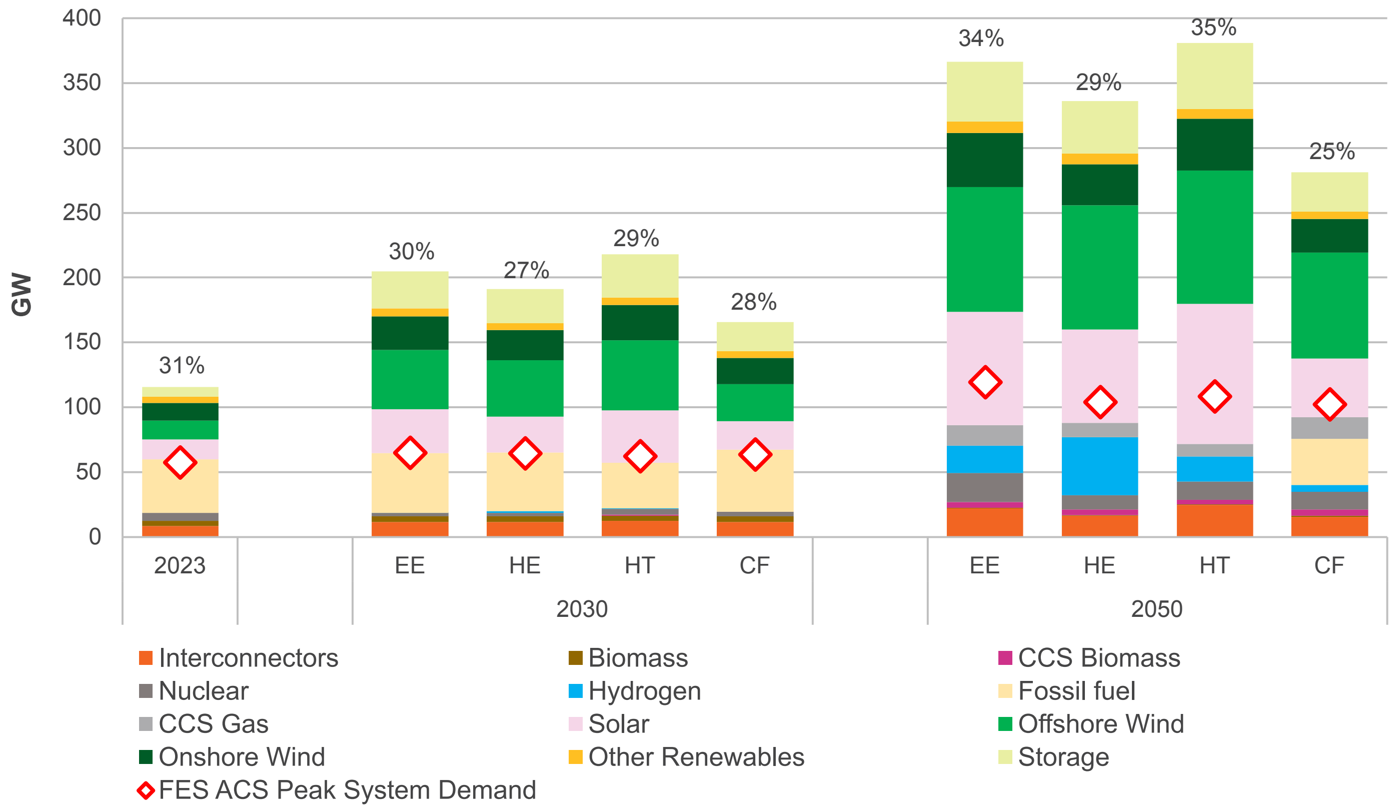

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Figure ES.08: Electricity output by technology in Holistic Transition

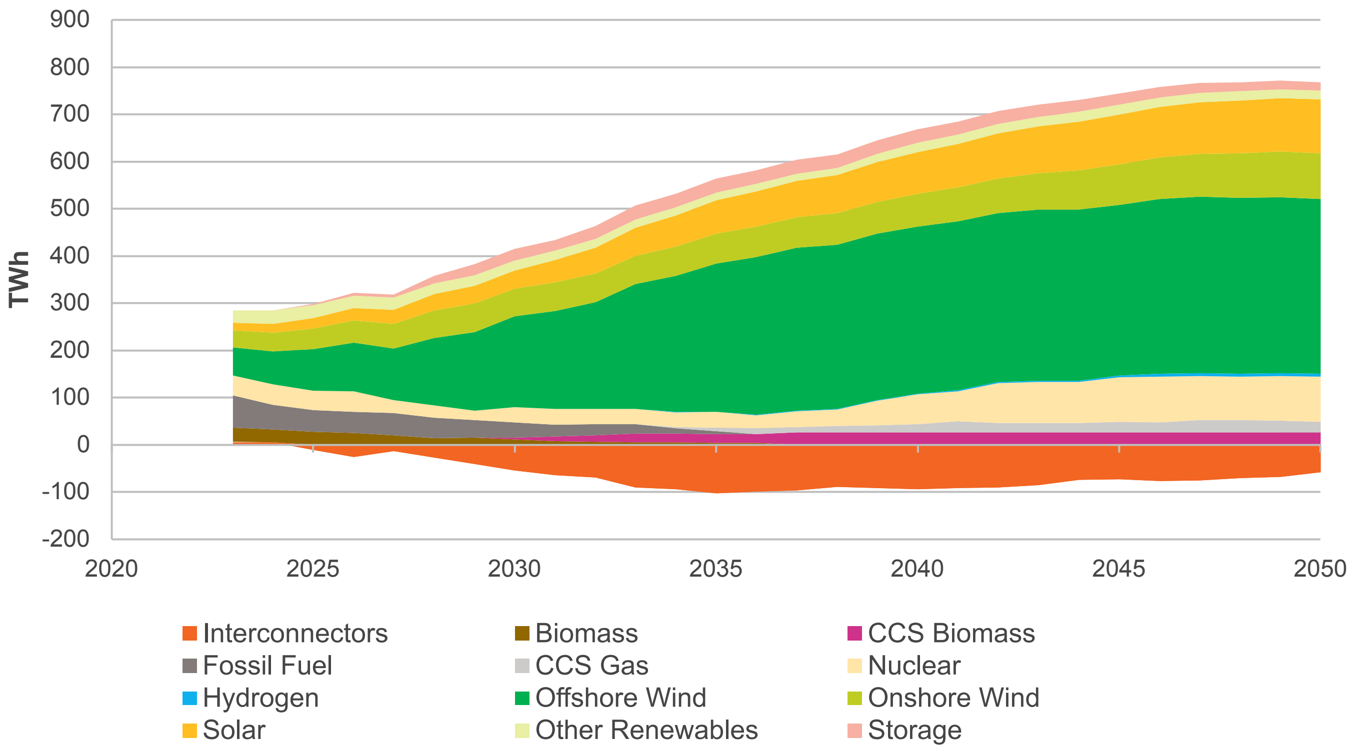
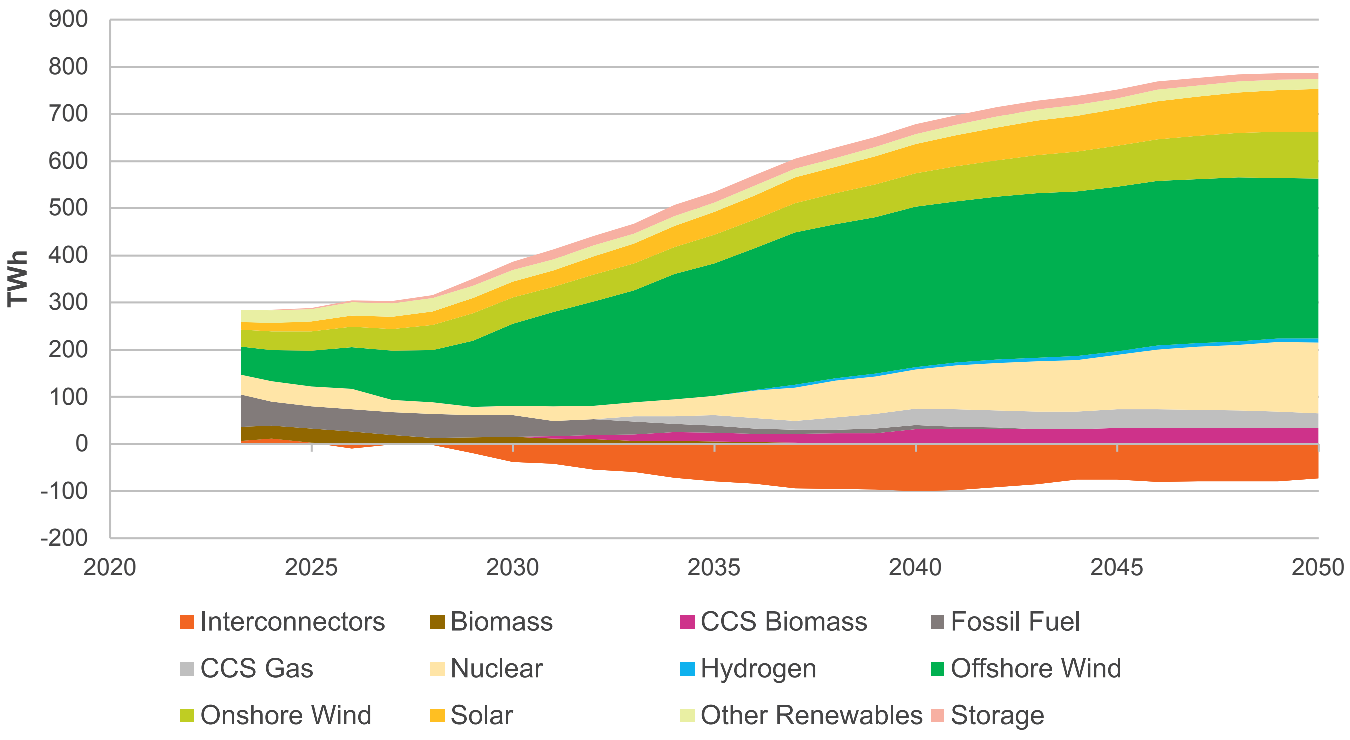


Figure ES.09: Electricity output by technology in Electric Engagement



Holistic Transition sees unabated fossil fuel generation reducing sharply to zero after 2035. Any remaining fossil fuel usage is abated through CCS. This pathway has the highest renewable dispatch from wind and solar, reaching 581 TWh in 2050. Electricity storage generation, needed to enable the renewable transition in this pathway, is also the highest of the net zero pathways and reaches 17 TWh in 2050. Interconnectors start to export to the rest of Europe post-2030.

Electric Engagement has the highest total electricity generation in 2050. Nuclear generation is the highest of the net zero pathways, reaching 151 TWh in 2050. As with the other pathways, offshore wind generation makes up most of the generation output. Unabated fossil fuel generation output falls to zero by 2045. Interconnectors start to export to the rest of Europe post-2030.

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Figure ES.10: Electricity output by technology in Hydrogen Evolution

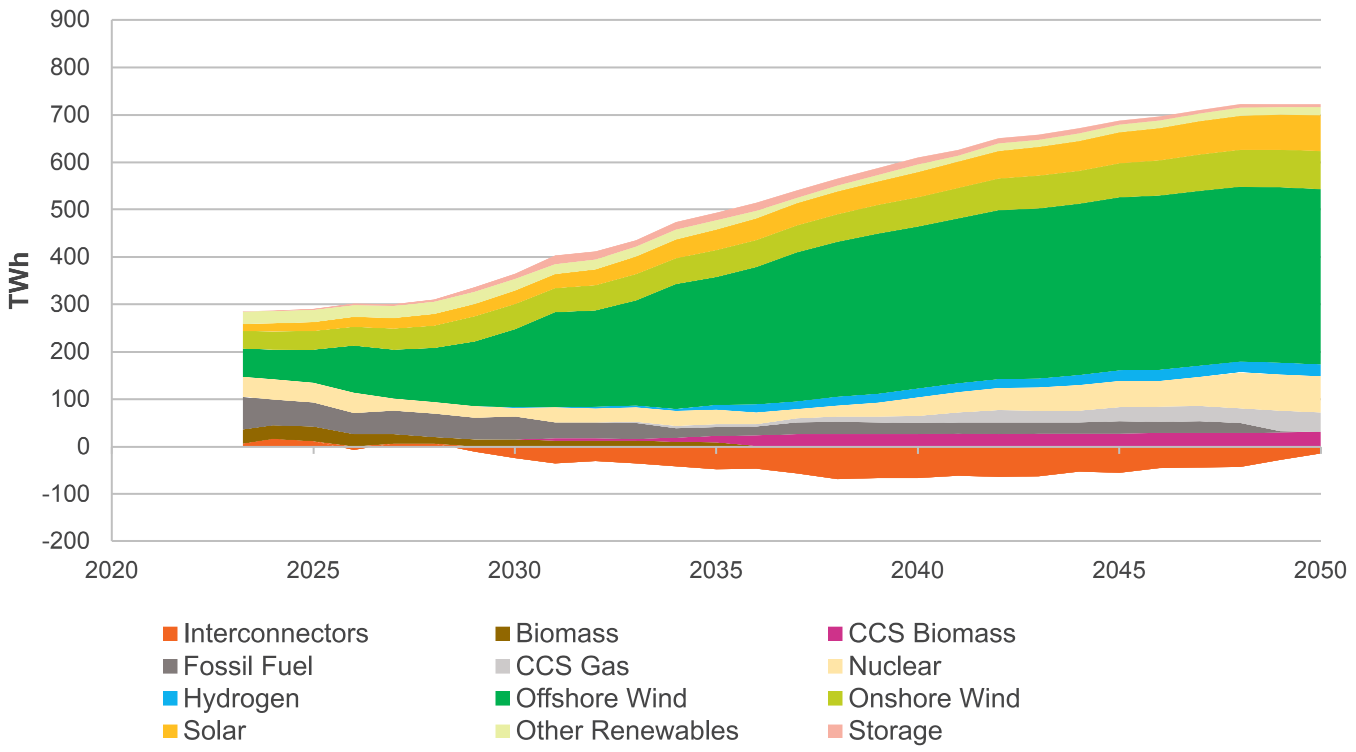
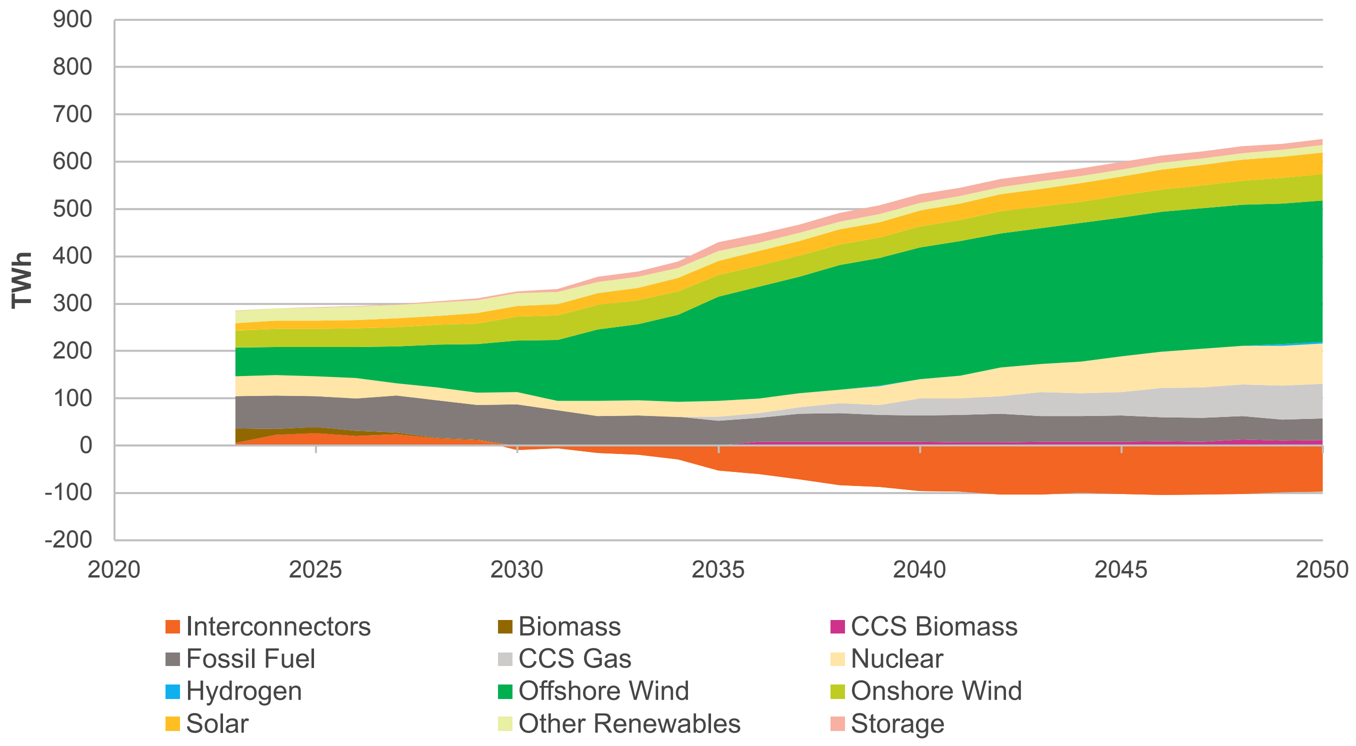


Figure ES.11: Electricity output by technology in the Counterfactual



Hydrogen Evolution sees some unabated gas remaining in the system in the later years for security of supply. This pathway has the highest gas CCS and hydrogen generation, reaching 66 TWh in 2050. As with all pathways, electricity generation from renewable sources increases out to 2050 with offshore wind accounting for the majority of this. Interconnectors start to export to the rest of Europe post-2030.

The **Counterfactual** sees both the lowest overall electricity generation and lowest contribution from renewable sources. There is a heavy reliance on fossil fuels until 2050. Gas CCS generation is very high in 2050 but this does not begin before 2035. Interconnectors start to export to the rest of Europe post-2030.

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Offshore wind

The UK has established itself as a world leader in offshore wind deployment. Continued growth, however, requires significant infrastructure investment to move the power from coastal landing points to demand centres. Challenges remain around addressing supply chain considerations and improving connection times to the network. ESO's work on the CSNP aims to deliver an integrated approach to connect new offshore wind to Great Britain and ensure sufficient growth in the sector.

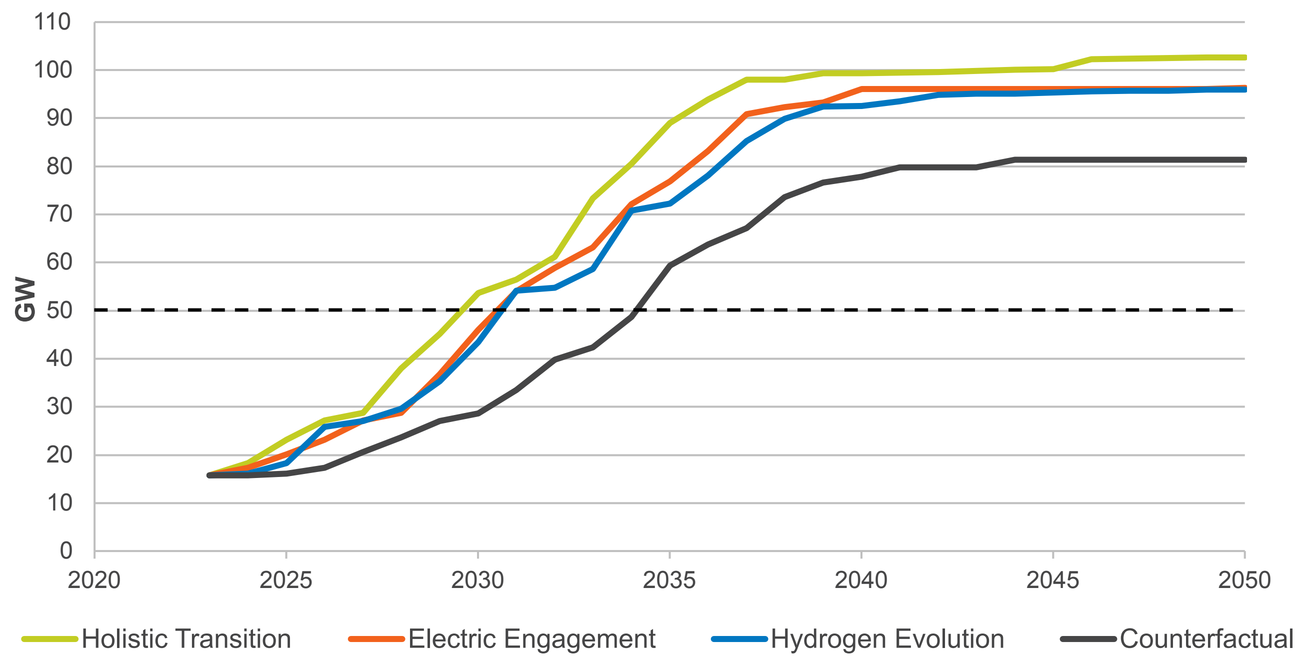
Government support through the next Contract for Difference (CfD) allocation rounds is also of vital importance to ensure continuous offshore wind deployment. Our modelling assumes that projects which have secured a CfD will secure financing.

Holistic Transition sees a higher build speed compared to the other net zero pathways. This pathway assumes infrastructure and CfD wind projects are delivered at pace, without significant delays. This is the only pathway that meets the UK Government target of 50 GW installed (networked and non-networked) capacity by 2030, with 100 GW installed offshore wind capacity reached in 2046.

Electric Engagement and **Hydrogen Evolution** assume supply chain constraints and delays in the delivery of some wind projects. Electric Engagement reaches 96 GW installed capacity and Hydrogen Evolution reaches 93 GW by 2050.

The **Counterfactual** sees a greater reliance on thermal generation and has the slowest development of offshore wind, with 81 GW installed wind capacity by 2050. The net zero target is not reached.

Figure ES.12: Offshore wind capacity



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Offshore wind

The route to net zero

Offshore wind generation remains one of the lowest cost options to meet our energy needs and, if efficiently integrated, can minimise the total system cost.

Key Actions 1,2&7

Levels in the next decade depend on policy, market and connections reform across Great Britain, as well as strategic network investment and delivery through ESO's "Beyond 2030[5]" report and the upcoming SSEP and CSNP. These will be shaped by coordination with other sources of flexibility, such as electricity storage and interconnectors, through markets and policy.

Planning, connections and market reform are needed to ensure delivery of ambitious national and regional targets.

Key Actions 2&8

Barriers around supply chain and both the planning and connections processes need to be addressed if we are to achieve some of the most ambitious targets, such as widespread deployment of large-scale offshore wind. Policy and market reform will need to drive generation build at the necessary pace alongside network expansion. Locational signals and market reforms will be key to ensuring efficient investment and efficient dispatch and, ultimately, the timely delivery of a cost-optimal power mix.

There must be sufficient capacity of leases to enable the required amount of offshore wind.

Alongside new offshore wind, the capacity of all offshore wind projects with agreed leases is needed to deliver net zero under our pathways but have a range of delivery dates across our pathways. The progress of these projects must continue to be reviewed to ensure sufficient seabed leasing opportunities are provided to mitigate the risk of non-delivery and accommodate any increase in required capacity.

5 nationalgrideso.com/document/304756/download

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Onshore wind

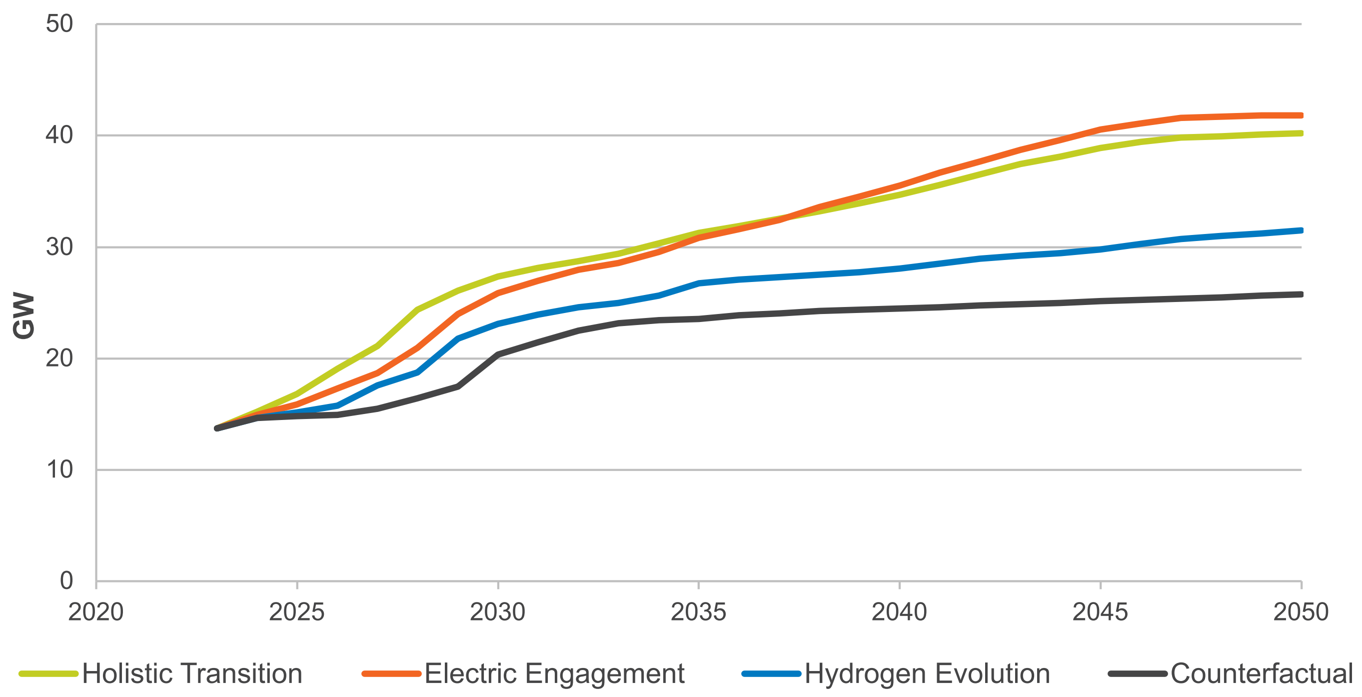
Onshore wind will play an important role as we move towards net zero. However, deployment of onshore wind has been slower over recent years due to planning restrictions across England and Wales, network connections considerations and inflation of materials costs. The de facto ban on onshore wind in England, in place since 2015, was lifted on 8 July 2024.

Holistic Transition and **Electric Engagement** are the pathways with most onshore wind deployment, with 40–42 GW installed capacity by 2050. In Holistic Transition, 52% of this is expected to be connected to the distribution network, and 46% is connected to the distribution network in Electric Engagement. In these pathways, we assume that planning reforms enable further investment and deployment.

Hydrogen Evolution assumes more local opposition and difficulties in securing planning permission in the short term. Planning reform leads to the growth seen in later years. This pathway reaches 31 GW of installed capacity by 2050 and assumes that hydrogen generation plays an important role.

The **Counterfactual** does not meet the net zero target and has a greater reliance on thermal generation. It reaches 26 GW installed onshore wind capacity in 2050.

Figure ES.13: Onshore wind capacity



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Onshore wind

The route to net zero

Onshore wind generation remains one of the lowest cost options to meet our energy needs and, if efficiently integrated, can minimise the total system cost.

Key Actions 1,2&7

Levels in the next decade depend on policy, market and connections reform across Great Britain, as well as strategic network investment and delivery through the upcoming SSEP and CSNP. These will be shaped by coordination with other types of flexibility, such as electricity storage and interconnectors, through markets and policy.

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Solar

Solar generation is a clean source of energy and can play an important role in meeting demand, particularly when used alongside storage. In Great Britain, most of the solar generation is currently connected to the distribution networks, with the first larger-scale solar plant only connecting onto the transmission network during spring 2023. The British Energy Security Strategy targets 70 GW installed capacity of solar generation between today and 2035, representing a five-fold increase.

We see a large growth of solar generation in our pathways, which is largely dependent upon improvements in the sector, such as price reductions of solar panels, improved future home standards and electricity network capacity. As micro-solar generation in the residential sector is vital for solar deployment in Great Britain, continuous support is needed in this area.

The case for solar generation is strong and DESNZ is due to publish an updated solar roadmap in summer 2024, which may offer updated targets. As solar installed capacity grows, UK Government and industry must work closely together to ensure a cohesive approach to supply chains, jobs, skills, innovation and infrastructure.

Holistic Transition sees the Government's ambition of 70 GW installed capacity by 2035 met in 2036. This pathway assumes higher consumer engagement, leading to a greater volume of micro-solar (less than 1 MW) generation. Solar generation is co-located with flexible technologies at different connection voltages to optimise grid connection, such as electrolysis to produce hydrogen or grid-scale battery storage for solar farms.

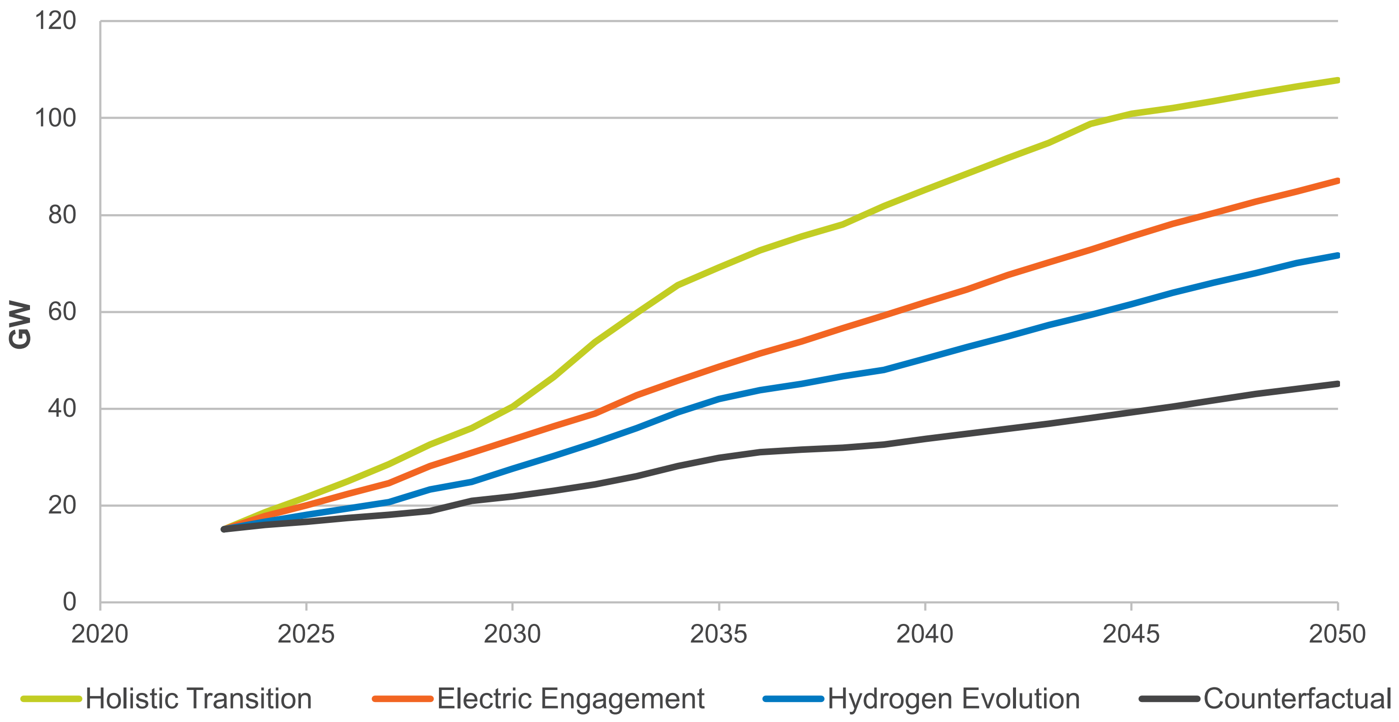
Electric Engagement assumes lower consumer engagement, leading to lower deployment of micro-solar generation in the residential sector. This pathway sees less colocation between solar and other flexible assets compared to Holistic Transition. The 70 GW Government 2035 ambition is met in 2043.

Hydrogen Evolution assumes lower solar generation and fewer community and distributed projects. This pathway sees more centralised hydrogen generation connected to the electricity transmission network and meets the 70 GW Government 2035 target in 2049.

The **Counterfactual** sees greater reliance on thermal generation and does not meet the net zero target, reaching 45 GW installed solar capacity by 2050.

Solar

Figure ES.14: Solar capacity



The route to net zero

Solar power generation remains one of the lowest cost options to meet our energy needs and, if efficiently integrated, can minimise the total system cost. Local deployment rates and government ambitions may drive higher uptake than we have predicted if the right action is taken.

Key Actions 1,2,7&8

Barriers around supply chain and both the planning and connections processes need to be addressed if we are to achieve some of the most ambitious targets, such as widespread deployment of residential rooftop solar. Policy will need to drive generation build at the necessary pace alongside network expansion through strategic investment and delivery through the upcoming SSEP and CSNP. Locational signals and government targets will also be key to ensuring efficient investment and dispatch and, ultimately, the timely delivery of a cost-optimal power mix.

Locating solar power generation with flexible technologies at different connection voltages can optimise grid connections.

Key Actions 1&7

Colocated assets, such as electrolysis to produce hydrogen and grid-scale battery storage for solar farms, can leverage the combined power of solar generation and other flexible technologies over shared connections. Improvements in the planning process and engaging with communities will be vital for the deployment of these colocated assets and for ensuring a greener and cost-effective energy source for consumers.

Tidal

Marine energy generation uses the natural movement of water to produce electricity and is a highly predictable form of generation across all seasons. It is estimated that the UK has around 50% of Europe's tidal energy resource[6]. There are two main types of tidal generation – tidal stream and tidal range.

The British Energy Security Strategy outlines the nation's intention to further explore tidal opportunities[7]. While tidal generation is a reliable source of power and the tidal assets have a long lifespan, these assets do have a high upfront cost and limited subsidy support.

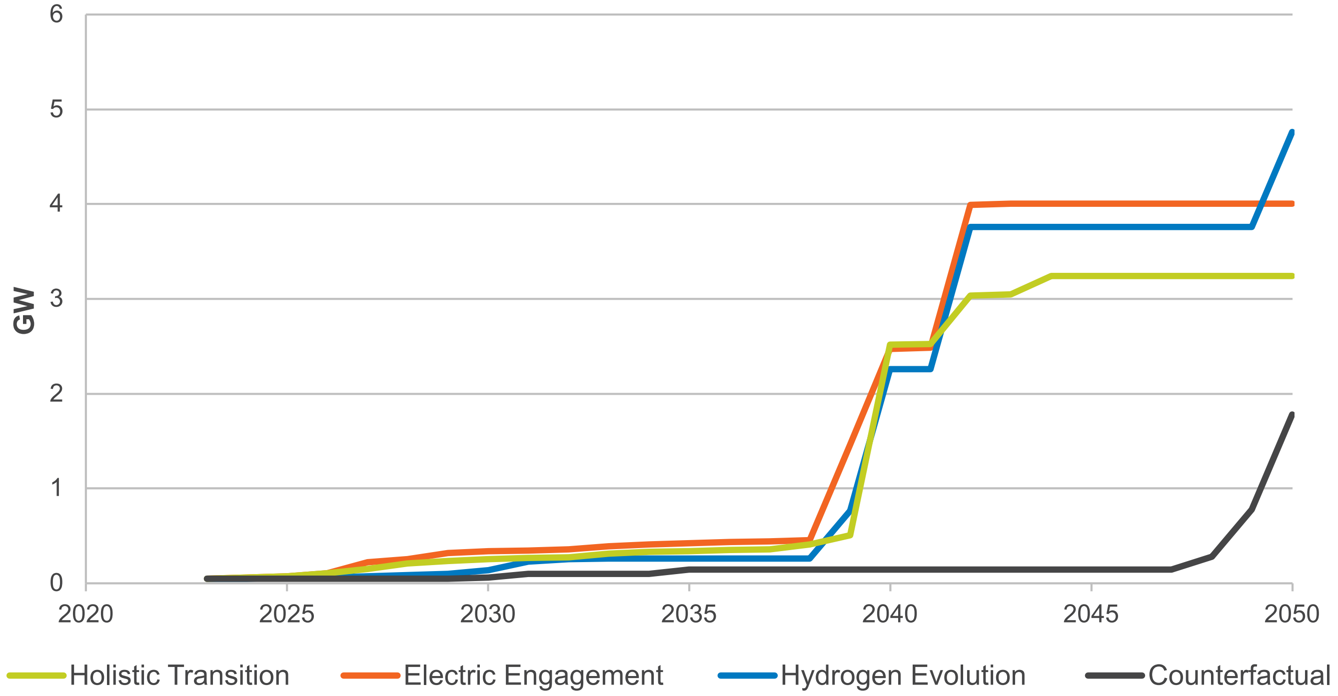
All net zero pathways see low scale and gradual growth post-2030 due to tidal stream, which is a novel technology. Tidal range is a well established technology that can be deployed at scale but requires additional government support. Tidal range is, therefore, deployed at large scale during the early 2040s in our pathways.

Holistic Transition sees 3 GW of total installed tidal stream and range capacity by 2050. This is the lowest tidal capacity across our pathways, as demand is met by lower-cost alternatives.

Electric Engagement and **Hydrogen Evolution** both see successive tidal range projects in the early 2040s which bring capacity up to 4 GW by 2042. Hydrogen Evolution sees the completion of additional projects of around 5 GW by 2050.

The **Counterfactual** does not meet the net zero target and has greater reliance on thermal generation. This sees 2 GW of installed tidal capacity just before 2050.

Figure ES.15: Tidal capacity



6 marineenergycouncil.co.uk/marine-energy/tidal-stream-energy
7 British Energy Security Strategy (publishing.service.gov.uk)

Tidal

The route to net zero

While tidal generation technology is mature and assets can have a long life, cost and environmental barriers must be addressed to ensure delivery.

Key Actions 1&2

The British Energy Security Strategy outlines an intention to explore tidal opportunities. Further Government support would be needed in tidal generation, such as allocating additional budget through the CfD scheme, to unlock the potential for a thriving UK tidal power sector.

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Electricity storage

Flexibility

Electricity storage is necessary across all our net zero pathways to help balance the grid and ensure security of supply.

Different durations of energy storage offer different benefits. Two to four-hour storage can meet short variations in demand and supply, provide short-term reserve and help manage the network. Long-duration storage can help secure the system over longer periods of high or low renewable generation output. The electricity storage sector is a rapidly developing one. In our modelling, we have considered battery storage, pumped hydro storage (PHS), compressed air energy storage (CAES) and liquid air energy storage (LAES).

Other emerging technologies, such as iron air batteries and gravitational storage, are not yet included in our analysis. As these develop, it is possible they may displace some of the capacity and volume currently allocated in our modelling to other storage technologies. We will continue to review our assumptions as more market information becomes available.

Between 23–30 GW of electricity storage is now expected to connect into the system by 2030. Our pathways reflect this increase and also consider the relevant supply chain issues, planning considerations and connection delays.

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Battery storage in our pathways

Flexibility

Great Britain currently has 4.7 GW of operational battery storage capacity. Longer-duration batteries have been introduced onto the distribution network this year, with a shift from one-hour to two-hour batteries.

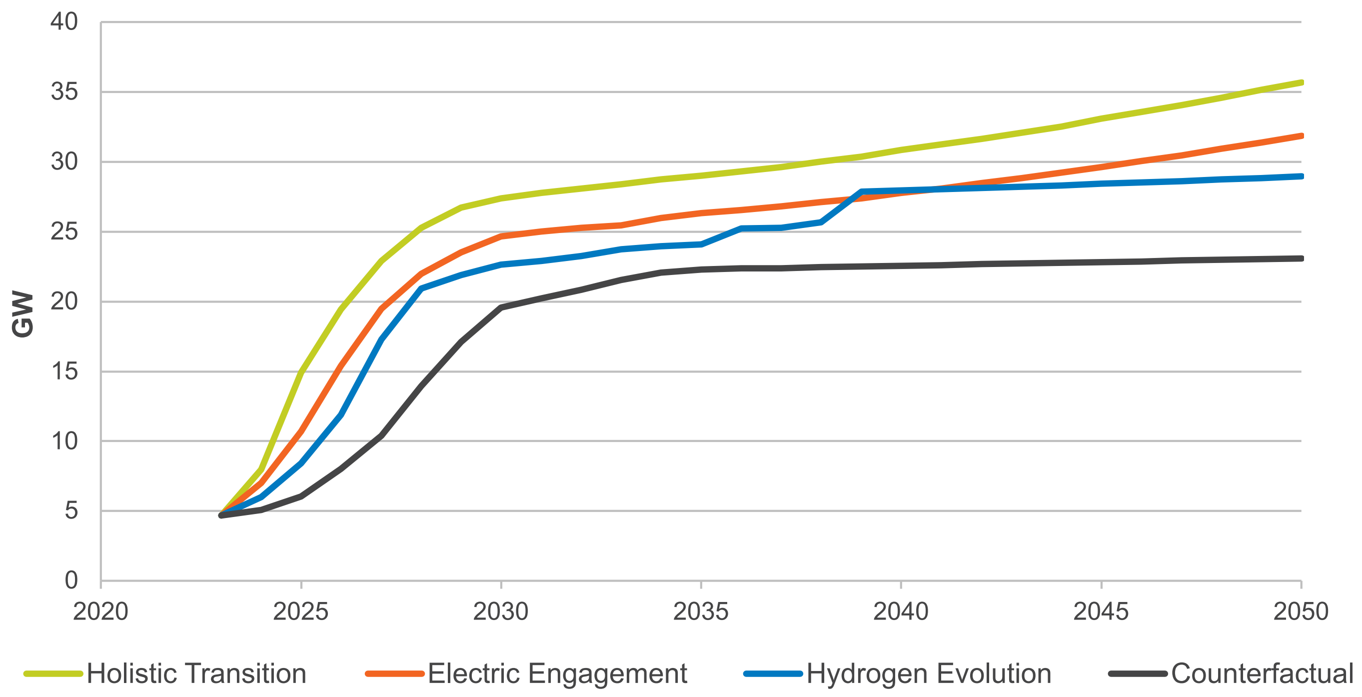
There has also been a shift towards longer-duration batteries due to changes to the de-rating factors (availability) for battery storage projects in the Capacity Market (CM). Nonetheless, challenges may remain around the supply chain and aligning battery growth with the lithium reserves available.

Holistic Transition and **Electric Engagement** are the pathways with the highest levels of renewable capacity and, therefore, require more flexibility. We expect to see 28 GW of battery storage by 2030 in Holistic Transition, reaching 36 GW in 2050.

Hydrogen Evolution meets flexibility requirements primarily through higher levels of hydrogen storage. As a result, this pathway sees the lowest levels of installed battery storage deployment, reaching 29 GW by 2050.

The **Counterfactual** requires less flexibility and, therefore, has the lowest volume of battery capacity by 2050, reaching just under 23 GW.

Figure ES.16: Battery storage installed capacity (excluding vehicle-to-grid)



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Long-duration energy storage in our pathways

Flexibility

Long-duration energy storage helps ensure security of supply, particularly in constrained periods (for instance, during periods of low renewable output or where renewable excess is needed to help meet peak demand). The maximum installed volume of long duration energy storage in the system is currently 25.8 GWh with 2.74 GW of capacity, mainly driven by PHS. We project that 7–15 GW of these (with durations ranging from 6 hours to 2 days) will be needed by 2050 in the energy system.

Due to the longer lead and planning times, as well as high capital expenditure, our pathways don't see many long-duration energy storage projects coming online before 2030.

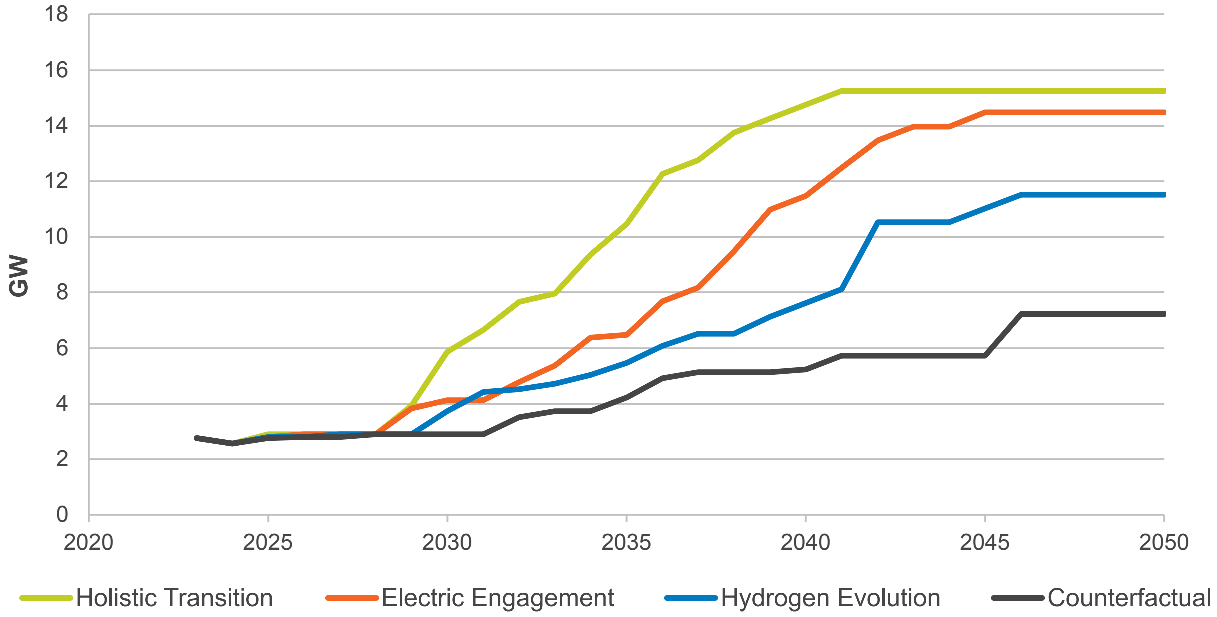
Investment in emerging electricity storage technologies will help ensure the techno-economic performance required for the various storage applications. DESNZ and its Longer Duration Energy Storage Demonstration Competition aims to accelerate the commercialisation of innovative long-duration energy storage projects. Its consultation for the financial remuneration of the Long Duration Energy Storage projects and the proposed cap and floor regime for assets of 6+ hours duration is also vital to further boost investment for electricity storage.

Holistic Transition and **Electric Engagement** have the most deployment of long-duration energy storage, with the higher renewable penetration in these pathways introducing the most need for flexibility with sustained response capability. The installed capacity for long-duration energy storage reaches approximately 15 GW in 2050.

Hydrogen Evolution uses more hydrogen storage for flexibility which requires lower levels of long-duration electricity storage. This pathway reaches 11.5 GW in 2050.

The **Counterfactual** has less need for flexibility and requires less long-duration energy storage due to lower levels of renewable capacity, reaching 7 GW in 2050.

Figure ES.17: Long-duration energy storage installed capacity (excluding vehicle-to-grid and hydrogen)



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Long-duration energy storage in our pathways

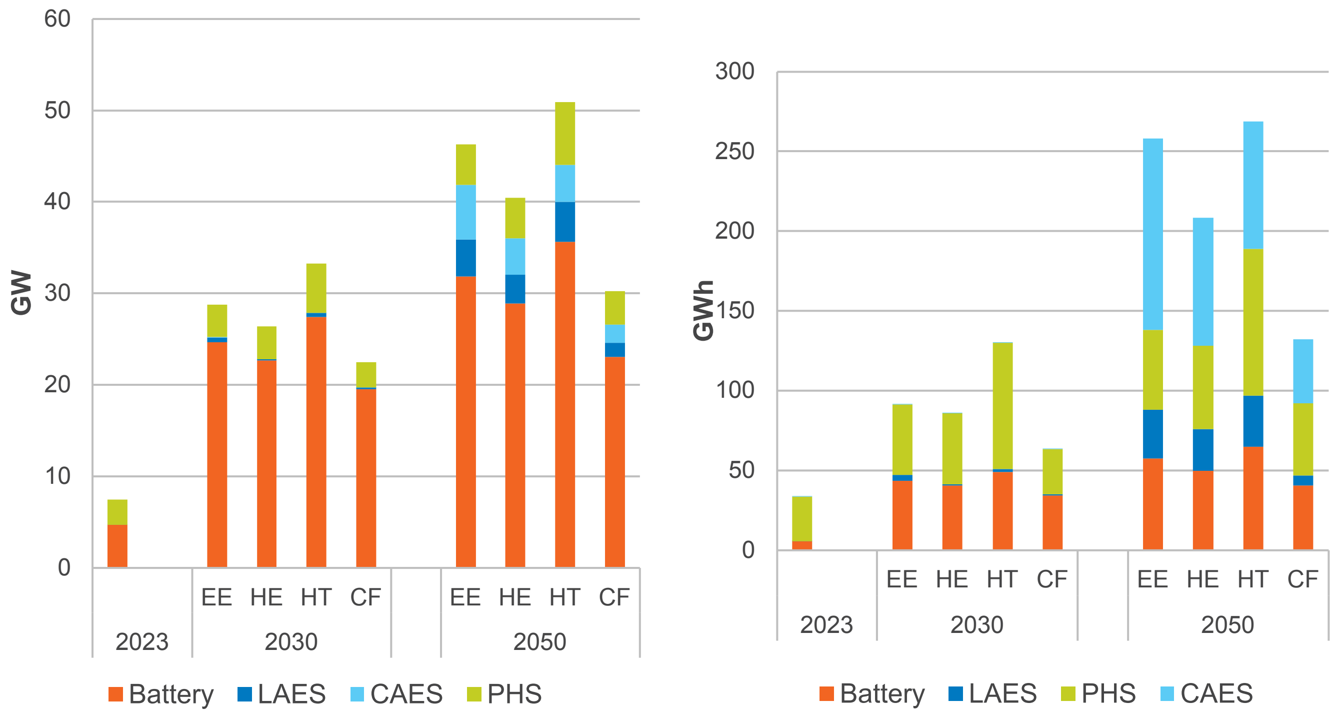
The route to net zero

Electricity and hydrogen storage are vital to provide the adequacy needed to ensure a reliable whole energy system.

Key Actions 3&7

Policy support is essential to help bring forward the investment needed for long-duration energy storage. With the retirement or conversion of unabated gas plants post-2030, delivering the levels of energy storage and low carbon dispatchable power needed for security of supply will be essential.

Figure ES.18: Electricity storage installed capacity and volume (excluding vehicle-to-grid and hydrogen)



Interconnectors

Flexibility

Interconnectors facilitate the integration of weather-dependent and distribution-connected generation. Great Britain currently has 8 GW of installed interconnectors linked to other European countries, with UK Government targeting an additional 10 GW by 2030.

Interconnector deployment is supported by the cap and floor regime (currently regulated by Ofgem), which has added more certainty to help enable the investment needed for these projects. Additionally, the Government's recent proposal to introduce Offshore Hybrid Assets (OHA) as a licensable activity should also encourage investors and developers. The area around the North Sea offers a vast opportunity for offshore developments and we can expect growth in this region.

Potential saturation of markets and constraints around Great Britain's connection locations is a consideration in the future growth of interconnectors. We continue to monitor the market conditions, as well as the appetite and political landscape of the rest of Europe. Reforms to market design and energy asset support policies in the UK and neighbouring countries can significantly influence the future development of interconnectors and their flows.

We have updated our European dataset for FES 2024 to ensure that renewable capacity and government targets elsewhere in Europe are better reflected in our modelling. Post-2030, Great Britain becomes a net exporter of electricity, although levels have reduced compared to FES 2023. After this point, Great Britain retains this net exporting position for all our net zero pathways and the Counterfactual.

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Interconnector capacity in our pathways

Flexibility

Some delayed commissioning dates of projects have led to lower growth, which is reflected in the total interconnected capacity compared to FES 2023. Our pathways also reflect the small delays to projects completing in the early 2030s. The cap and floor regime continues to deliver a steady pipeline of projects out to early 2040.

All net zero pathways see growth in electricity interconnection capacity until the mid-2030s, after which there is some uncertainty.

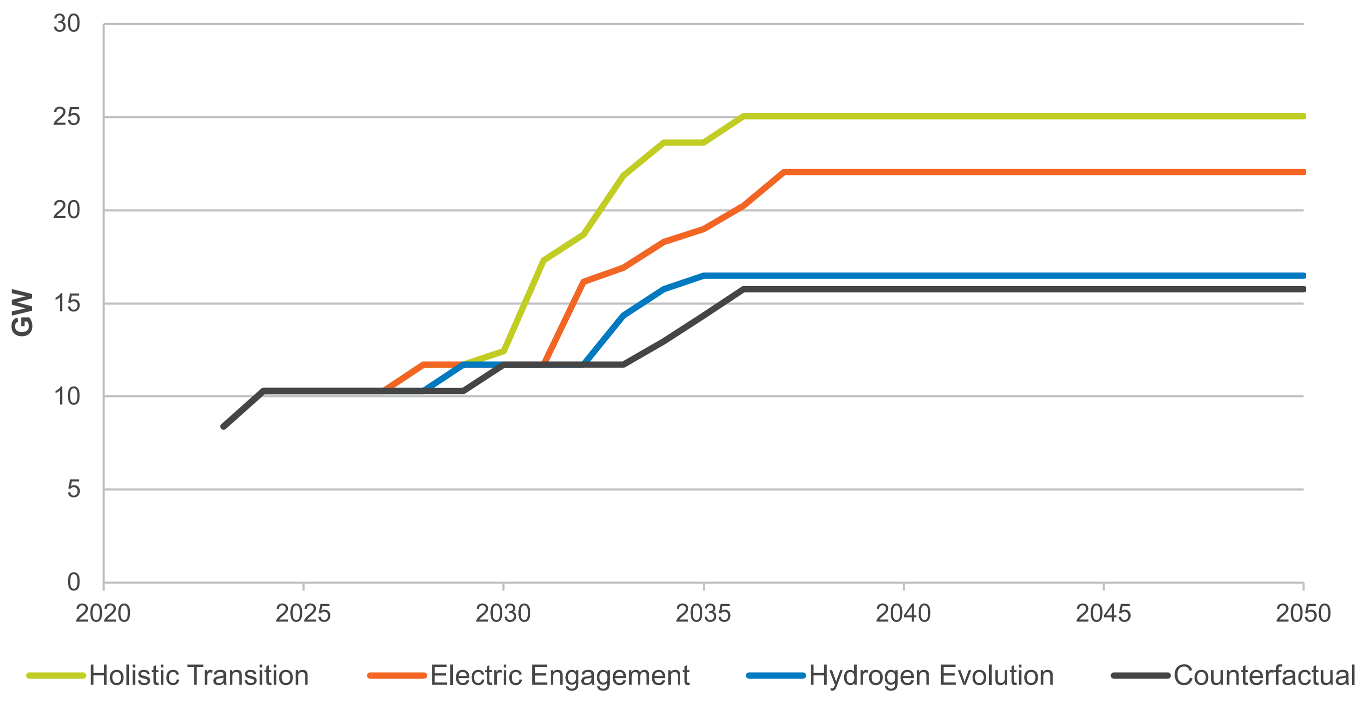
Holistic Transition requires more flexibility due to high levels of weather-dependent generation and represents our most ambitious pathway for interconnection. This pathway also assumes more favourable conditions across Great Britain and its interconnected markets. The Government target of 18 GW by 2030 is reached in 2032.

Electric Engagement sees less favourable conditions across Great Britain and its interconnected markets, leading to lower growth rates compared to Holistic Development. The 18 GW Government target is met in 2034.

Hydrogen Evolution has the highest number of hydrogen storage installations, limiting the flexibility requirements needed from interconnection. This pathway does not reach the 18 GW Government target in 2050 and, instead, assumes a significant increase of hydrogen generation and hydrogen storage after 2030.

The **Counterfactual** does not reach the 18 GW Government 2030 target and the installed interconnection capacity remains below 18 GW until 2050.

Figure ES.19: Interconnector capacity



Interconnector net flows in our pathways

Flexibility

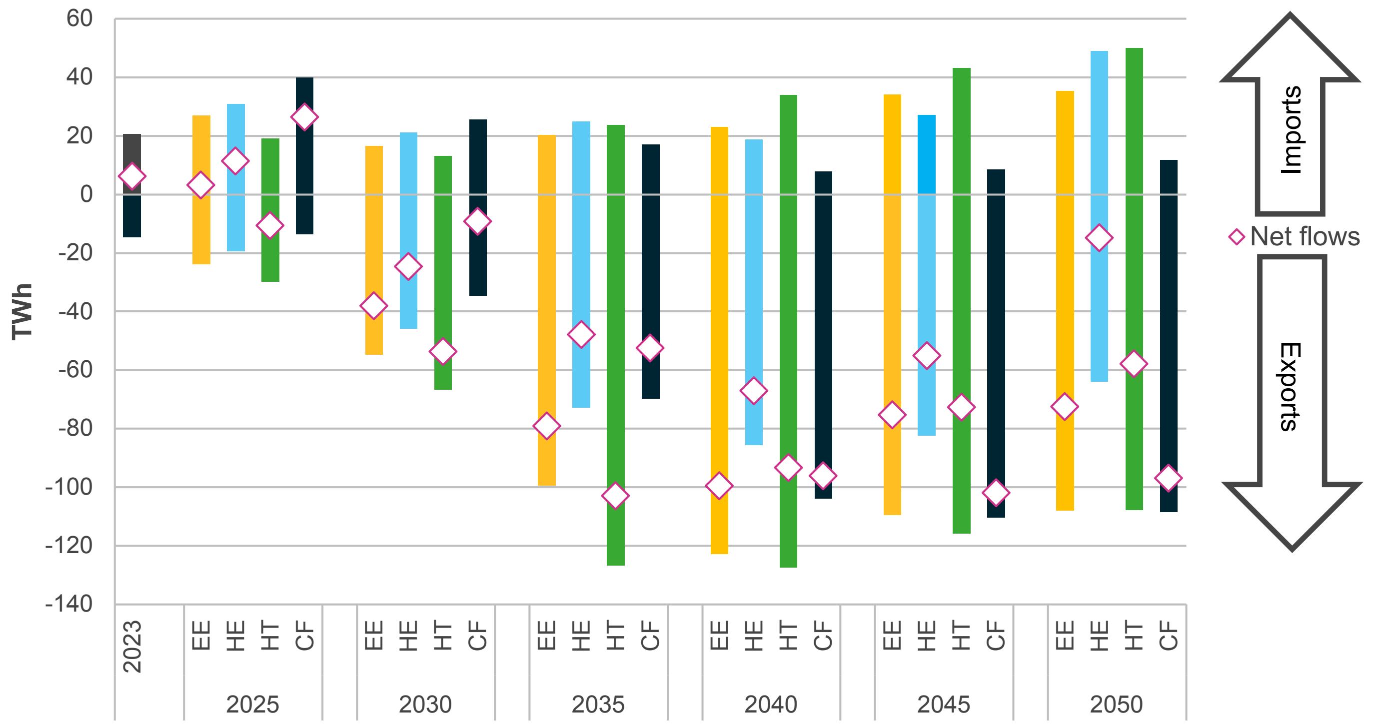
Net flows will continue to be primarily driven by price differentials between electricity markets of the interconnected countries.

Work is underway to ensure excess renewable generation, primarily from offshore wind, is not wasted. The growth of integrated offshore networks can help manage the flow of power between Great Britain, offshore wind farms in the North Sea and Northern Europe, as offshore transmission infrastructure is shared and supply is balanced across the network. Reforms to market design and energy asset support policies in the UK and neighbouring countries could influence future development of interconnectors and their flows.

All net zero pathways see Great Britain becoming a net exporter of electricity post 2030 and retaining that position to 2050. The higher levels of renewable generation, particularly offshore wind, suggest that supply is often higher than demand and that power is exported to the continent. This occurs when consumer demand is low compared to generation or when network constraints lead to restricted flows within Great Britain.

Post-2040, the net exporting position reduces slightly but Great Britain still remains a net exporter.

Figure ES.20: Interconnector imports, exports and net annual flows



The route to net zero

Interconnector flows and their potential to facilitate the integration of weather-dependent and distributed generation are vital as we transition to net zero.

Key Actions 1&2

The longer-term outlook for increased levels of interconnection remains uncertain. Countries on both sides must be confident that projects will be beneficial for consumers. Once delivered, the movement of power over interconnectors will continue to be driven by the price differentials between electricity markets.

Exporting over interconnectors is not a solution for all excess power. For instance, interconnected countries may not have excess demand or there may be network constraints restricting the movement of power within Great Britain. Post-2030, the growth of integrated offshore networks has the potential to help manage the flow of power between Great Britain and offshore wind farms in the North Sea and northern Europe.

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Nuclear

There is currently 6 GW installed capacity of nuclear generation in Great Britain. We expect most of the existing nuclear power stations to retire by the early 2030s, alongside the development of a programme to rollout new SMRs from the mid-2030s. Delays to this rollout, among other factors, could influence the decision to extend the lifetime of current assets. SMR are smaller in size and can be operated more flexibly than larger plants.

Nuclear power can be an important source of reliable, low carbon electricity generation and is proven at scale both in the UK and globally. The UK Government's recent "Civil nuclear: roadmap to 2050[8]" outlines the vision for a dynamic nuclear sector and sets out key elements of delivering against ambitions. The levels of nuclear energy vary across our pathways and levels have increased compared to our FES 2023 analysis following publication of the roadmap.

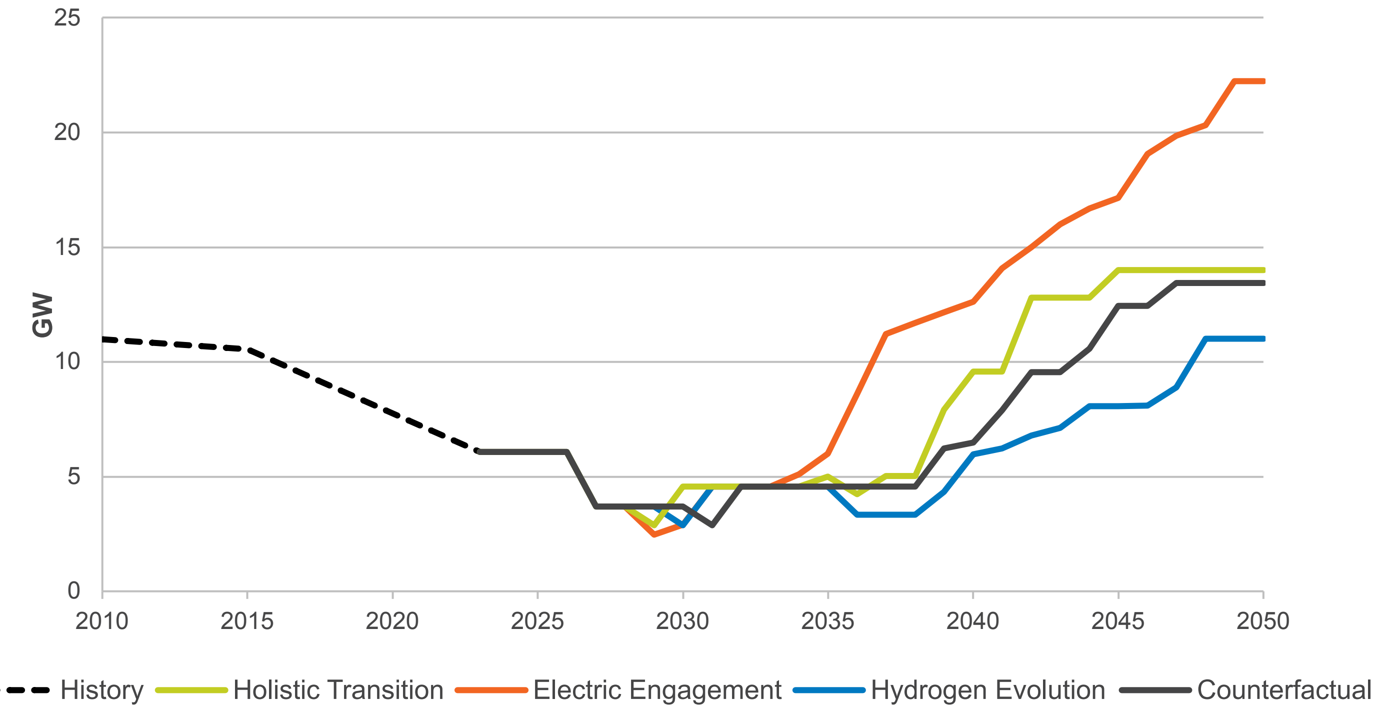
Holistic Transition has 14 GW of installed capacity in 2050 through both conventional nuclear power stations and SMRs, with the former representing 60% of total installed nuclear capacity. This pathway has the fastest rate of renewable growth with high system and consumer flexibility meaning a lesser, but still significant, role for nuclear compared to the other pathways.

Electric Engagement has the highest capacity of nuclear at 22 GW in 2050 to meet the higher electricity demand through an equal mix of conventional nuclear generation and SMRs.

Hydrogen Evolution has 11 GW of installed capacity through conventional nuclear power stations (60% of total installed nuclear capacity) and the building of SMRs until 2050. This pathway has the lowest nuclear capacity due to higher capacity of hydrogen plants.

The **Counterfactual** sees 13.5 GW of installed capacity in 2050 through both conventional nuclear power stations and SMRs, with the former representing 60% of total installed nuclear capacity.

Figure ES.21: Nuclear capacity



8 gov.uk/government/publications/civil-nuclear-roadmap-to-2050

Nuclear

The route to net zero

New nuclear generation is expected to have limited deployment before 2035 but could increase very rapidly after this point.

Key Action 8

Given the complexity of large-scale nuclear projects and the integration challenges of novel SMRs, innovation and financial support is required if we are to sustain the build rates in our pathways. It's also critical that a long-term view of the supply chain is taken. Strategic siting and identification of development locations, in which the SSEP can play a role, will be crucial.

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Low carbon dispatchable power

Flexibility

The bulk quantity of dispatchable generation is currently provided by unabated natural gas generation. This increases in the short term and declines to zero as we reduce our dependency on fossil fuels, with only a small level of capacity retained in the system to meet security of supply and ensure resilience under ACS. In our modelling, low carbon dispatchable power includes gas generation with CCS and hydrogen turbines.

Revenue support from Government for gas CCS generation will be available through Dispatchable Power Agreements (DPAs). The hydrogen producer receives the revenue support for hydrogen turbines via the hydrogen production business model.

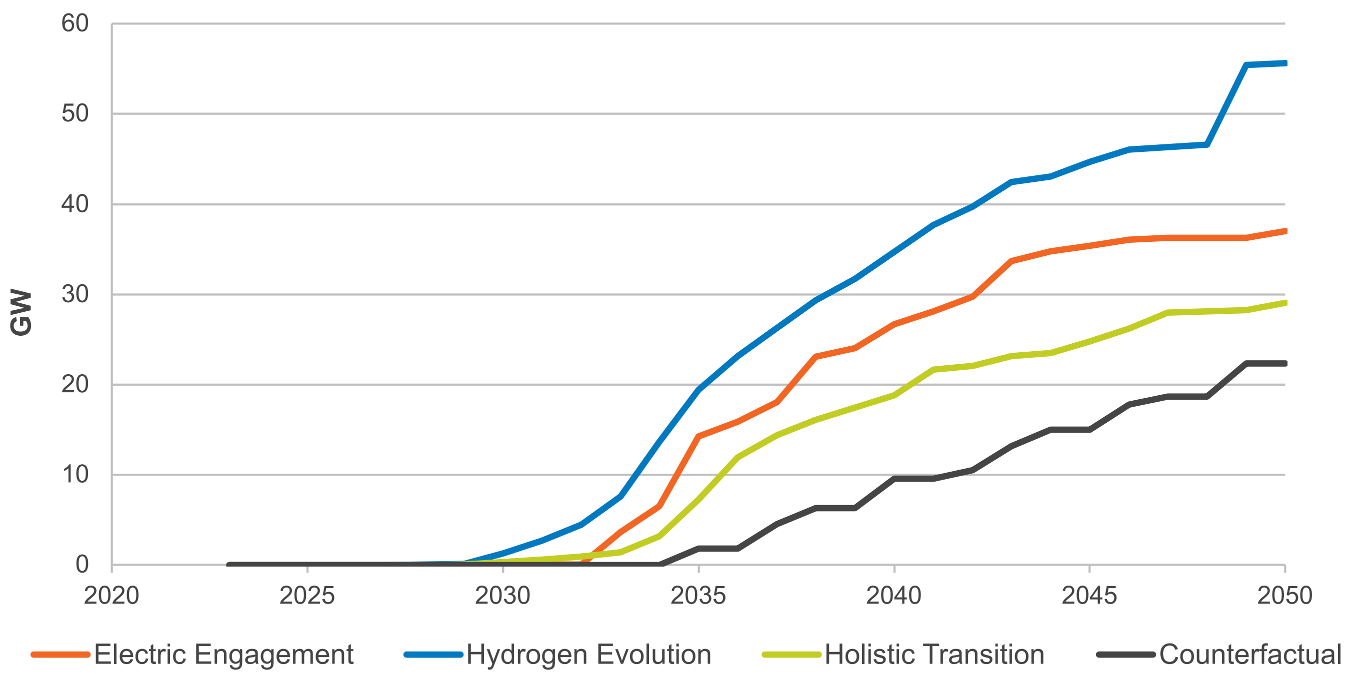
All net zero pathways see low carbon dispatchable power grow sharply post-2030, followed by a gradual decline of unabated natural gas generation. This aligns with the development of CCS transport and storage networks, with the increased need for firm capacity[9] and flexibility previously provided by gas plants. Much of this growth is attributed to the distribution level, particularly hydrogen peaking plants. No gas CCS is present on a distribution level.

Holistic Transition and **Electric Engagement** see most flexibility met through electricity storage and interconnectors, with less requirement for hydrogen and gas CCS deployment. These pathways reach 29 and 37 GW in 2050.

Hydrogen Evolution has the highest levels of low carbon dispatchable power in 2050 (56 GW) comprised of 11 GW gas CCS and 45 GW of hydrogen turbine capacity.

The **Counterfactual** has the lowest levels of total low carbon dispatchable thermal generation and it reaches 22 GW of primarily gas CCS capacity in 2050.

Figure ES.22: Low carbon dispatchable capacity



9 Plants that may be used for a few hours per year and are needed to contribute power during peak demand or other strained periods to ensure security of supply.

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Unabated gas

Gas power remains an important part of today's generation mix and helps ensure security of supply. Capacity is expected to grow in the short term, supported by CM contracts. In March 2024, the Government committed to supporting new gas power stations to ensure a safe and reliable alternative energy source during periods of high demand and low renewable generation.

Delivery dates of new gas plants vary across our pathways. Our pathways see gas remaining on the system for a longer period due to challenges in the deployment of other generation technologies.

All net zero pathways see an increase of unabated gas generation in the short term due to the recent CM auctions. After 2030, unabated gas generation is used sparingly, primarily for dunkelflaute events. This lower utilisation implies the need for government support.

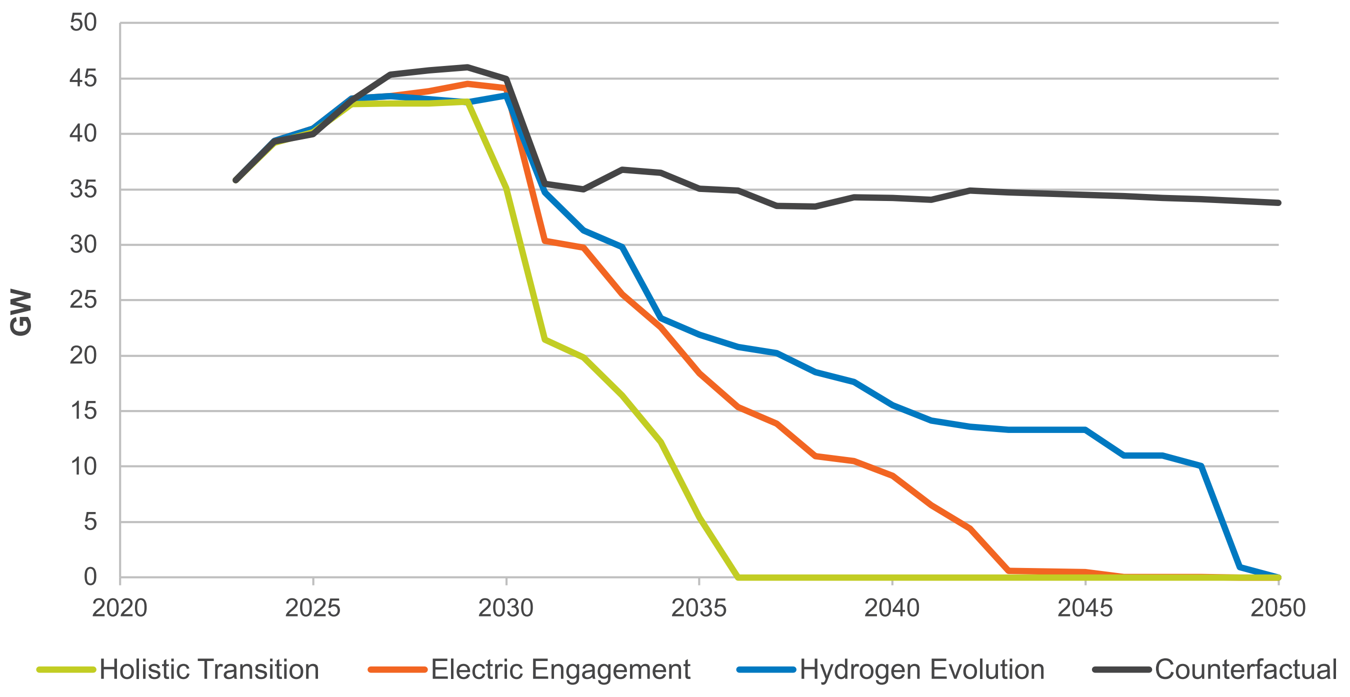
Holistic Transition sees unabated gas generation capacity reducing sharply to zero by 2036. This pathway has a greater share of renewable generation installed in the system, as well as increased flexibility levels from both the demand and supply sides.

Electric Engagement sees unabated gas generation capacity reducing to zero during the early 2040s, replaced gradually by alternative low carbon energy sources.

Hydrogen Evolution sees unabated gas generation decreasing to zero just before 2050, replaced gradually by increasing volumes of hydrogen generation.

The **Counterfactual** sees unabated gas capacity continue to increase, before a drop in the early 2030s due to retirement of some plants. The remaining plants are online until 2050. Emissions reduction targets are not met.

Figure ES.23: Unabated gas capacity



Low carbon dispatchable power and unabated gas

The route to net zero

Gas generation will continue to play an important role in the future, but consideration must be given to how it can remain compatible with a net zero energy system.

All our net zero pathways see natural gas play a role in industry and power generation to provide low carbon flexibility when used with CCS, as well as in the production of low carbon hydrogen. Unabated gas generation is compatible with a net zero power system but developers of new gas plants needed for system adequacy should consider how they would convert to low or zero carbon operation through the adoption of CCS technology or a shift to hydrogen in the longer term. If unabated gas capacity remains on the system operating at low load factors, offsetting emissions through additional negative emissions technologies will be required.

Low carbon flexible energy sources are vital to provide the adequacy needed for a reliable energy system.

Key Actions 1,2&3

Support for low carbon dispatchable power will be needed due to lower load factors out to 2050. In addition, this means delivery of CCS at scale, alongside hydrogen and CO_2 storage, for the adequacy needed to ensure a reliable whole energy system.

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Bioenergy with carbon capture and storage

Bioenergy with carbon capture and storage for electricity generation (power BECCS), plays an important role in our net zero pathways by providing negative carbon emissions to offset residual emissions in hard-to-decarbonise sectors. Negative emissions technologies are discussed in greater detail in the Reducing Great Britain's Emissions chapter *(page 32)*.

Power BECCS is expected to run with a high load factor to maximise the level of negative emissions. It can also operate flexibly, if required. Bioenergy plants provide a source of ancillary services, essential to the operation of a future energy system dominated by renewables.

Following the announcement of successful projects within the first industrial clusters, our pathways don't see the delivery of any large-scale BECCS before 2030. DESNZ's business model for power BECCS is still under development, as is a transitional support mechanism for unabated biomass to convert to power BECCS. Our pathways, therefore, see the development of BECCS from the early 2030s, in line with the availability of CCS networks.

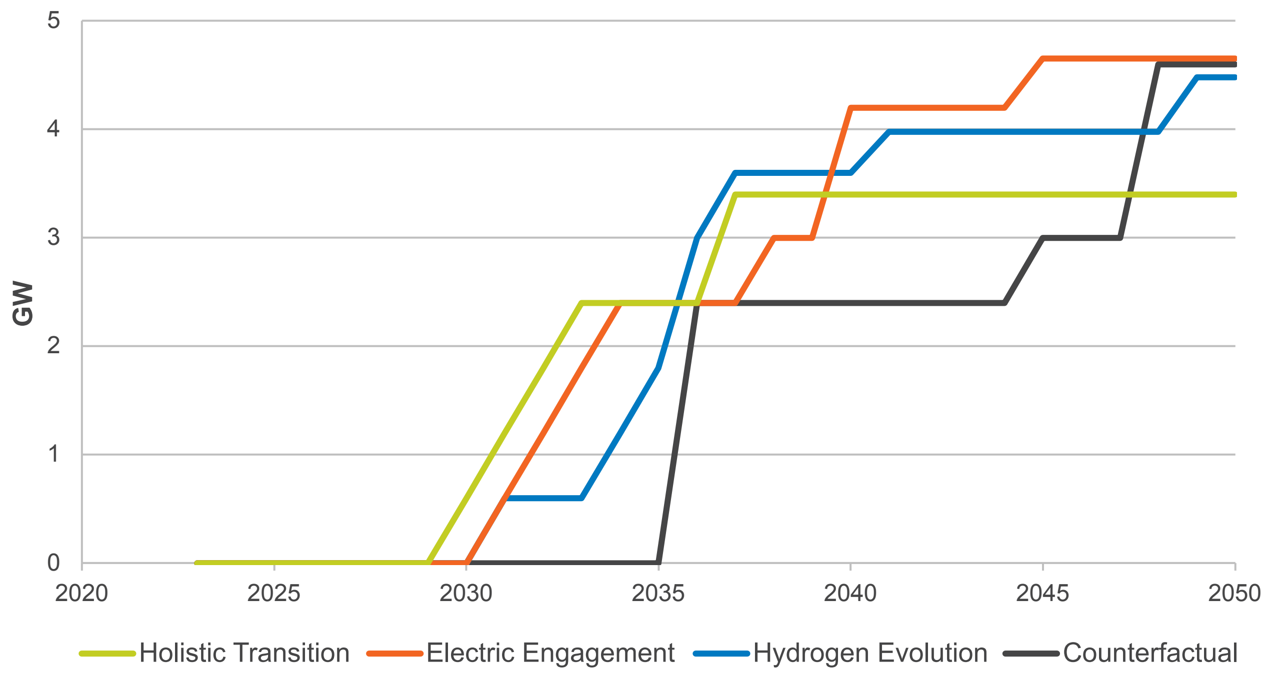
All net zero pathways see levels of BECCS grow. This growth is driven by requirements for baseload generation and conversion of existing unabated biomass plants to BECCS but is limited by sustainable biomass fuel availability.

Holistic Transition has the lowest levels of BECCS. This pathway prioritises emissions reductions through demand side reduction and has the highest levels of DACCS, an alternative negative emissions technology.

Electric Engagement and **Hydrogen Evolution** have higher levels of power BECCS, reaching around 4.5 GW by 2050 due to reduced levels of DACCS.

The **Counterfactual** sees the first increase in BECCS in 2035, with lower growth until 2045. After this point, BECCS capacity increases to serve as baseload.

Figure ES.24: Bioenergy with carbon capture and storage capacity



Bioenergy with carbon capture and storage

The route to net zero

Reducing investor uncertainty by agreeing business models for power BECCS is critical.

Key Action 2

Power BECCS, like all negative emissions technologies, requires economic incentives for widescale deployment. Government consultations have confirmed that a dual CfD approach for both the electricity generation and carbon removal is preferred. Confirming business models will allow existing biomass power stations (otherwise ceasing operations later this decade), to convert to BECCS. Power BECCS and negative emissions technologies should have a high priority for connection to CO_2 networks.

In line with the UK Government Biomass Strategy, support of BECCS should only be for projects that deliver net-negative emissions. This means ensuring a robust sustainability criteria.

Key Action 2

Well-regulated BECCS can achieve its objective to deliver negative emissions. The expert Task-and-Finish group report[10] published alongside the 2023 Biomass Strategy confirmed that BECCS can deliver negative emissions. A key commitment of the Biomass Strategy is to develop and implement a cross-sector common sustainability framework, subject to consultation.

10 gov.uk/government/publications/ability-of-bioenergy-with-carbon-capture-and-storage-beccs-to-generate-negative-emissions

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Distribution connected generation

Generation connected at distribution level will become increasingly important. In Great Britain, there is currently around 15 GW of distributed solar generation, 6 GW of distributed onshore wind and 11 GW of smaller dispatchable generators, such as CHPs and biomass/waste units.

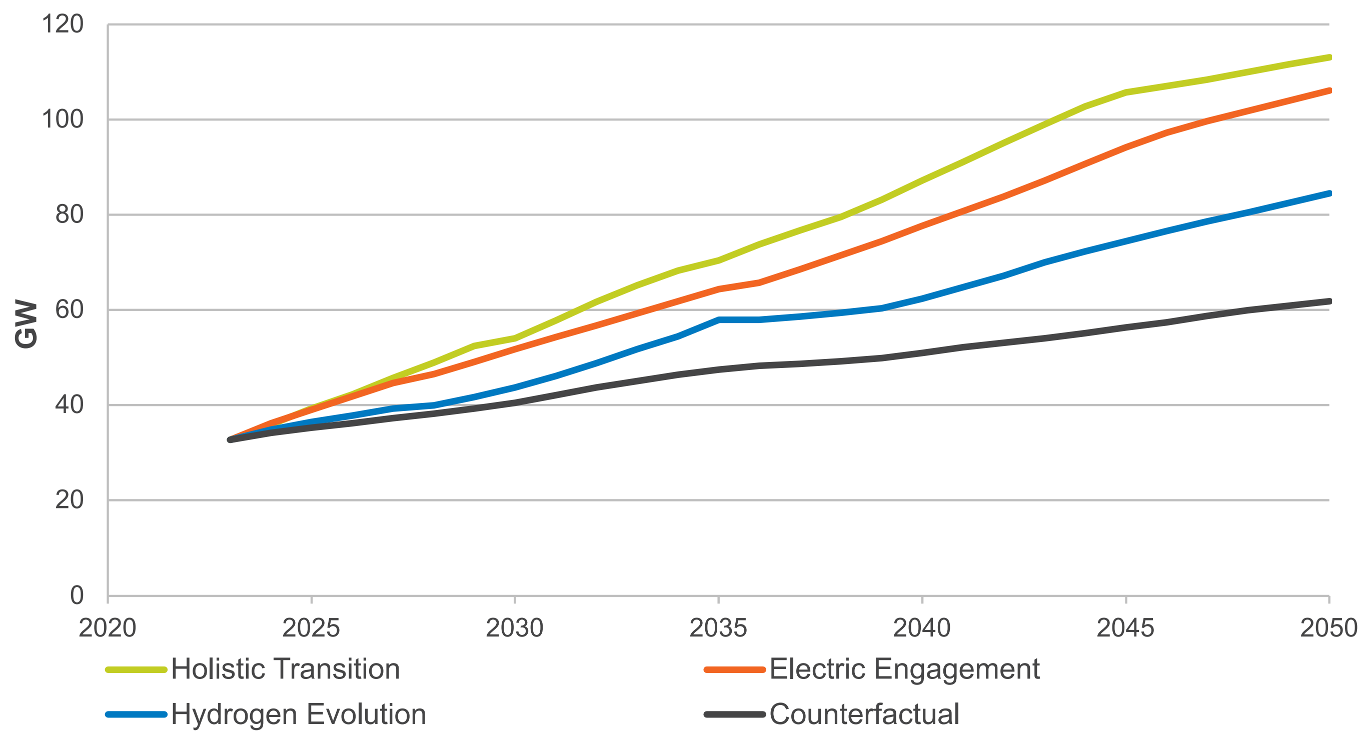
We expect a significant increase in distributed generation capacity across all regions. Our pathways consider a wide range of technologies, such as household rooftop solar PV (photovoltaic) panels, onshore wind turbines, solar farms, local hydroelectricity schemes and fossil fuel peaking plants. A breakdown of all generation types and capacity in each pathway can be found in our "Future Energy Scenarios: Data Workbook 2024[11]" document.

Holistic Transition and **Electric Engagement** assume significant renewable generation deployment from solar and onshore wind, reaching 102 and 96 GW respectively and accounting for 90% of the total distributed generation in each pathway. Societal change leads to the growth of solar generation and significant levels of solar rooftop generation in the residential sector. Improvements to the planning and connections processes enable further deployment of these generation types. The gradual retirement of fossil fuel plants after 2030 is replaced by a mix of hydrogen engines and hydrogen CHP units, reaching 6–7 GW by 2050.

Hydrogen Evolution sees hydrogen generation playing an important role in the energy mix at distribution level post-2030, reaching 13 GW in 2050. This gradually replaces unabated gas generation, which goes off system after 2040. Renewable generation is still present in this pathway but to a lesser extent than the other net zero pathways, reaching 68 GW from solar and onshore wind generation in 2050. A smaller contribution is expected from other thermal plants.

The **Counterfactual** does not meet the net zero target, reaching 54 GW of renewable generation capacity in 2050. It also assumes that 8 GW of distributed-connected thermal generation remains online until 2050 and does not assume any hydrogen generation.

Figure ES.25: Distributed generation capacity (excluding storage)



11 nationalgrideso.com/future-energy/future-energy-scenarios-fes/fes-documents

Curtailment

While flexible technologies can help balance the system, curtailment may still be necessary at times. Electrolysis has the most potential to reduce this, as hydrogen storage can be used to store significant volumes of curtailed energy for long periods. DACCS can also help further reduce curtailment.

Our net zero pathways show significant levels of curtailment of renewable generation, coupled with zonal imbalance between electricity generation in the north of England and energy demand in the south of England. This underlines the importance of strategic network expansion with the necessary policy and market reforms to ensure less curtailment and faster grid build out[12].

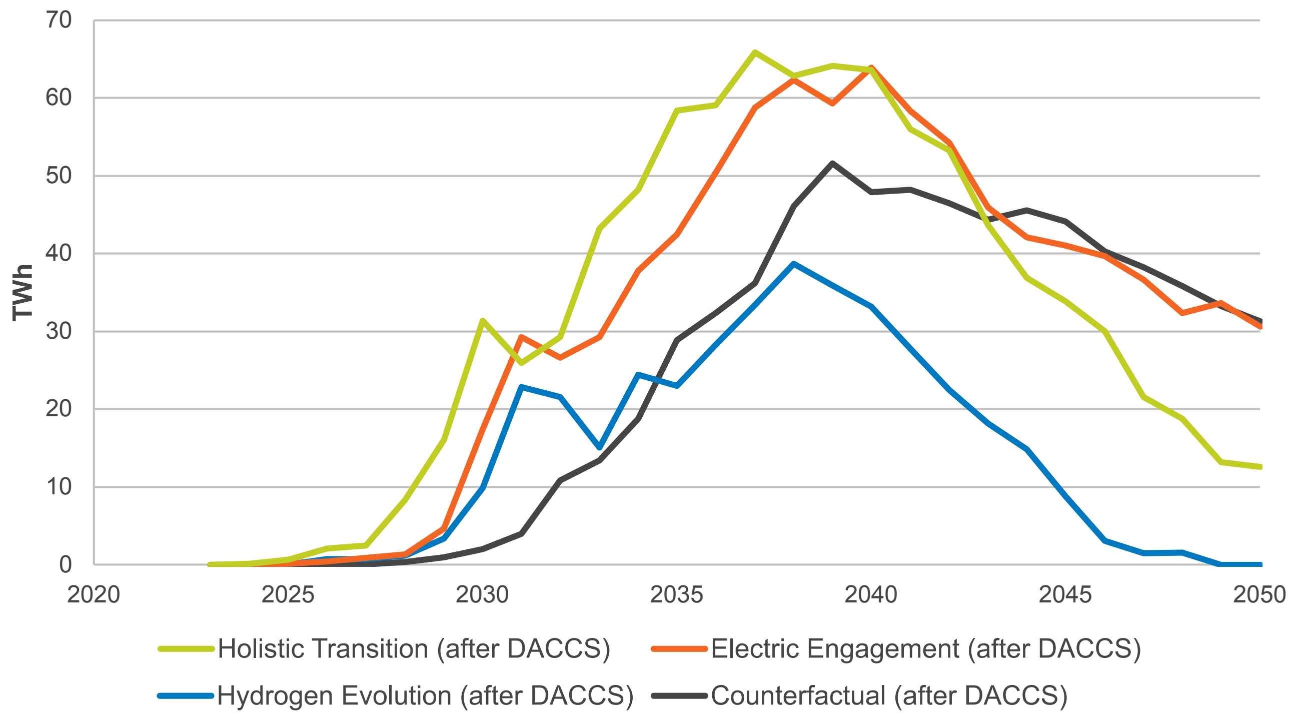
The curtailment explored in this section is from energy balancing only. It does not include curtailment from thermal constraints which are assessed in our downstream network planning processes. Our recently published "Balancing Costs: Annual Report and Future Projections[13]" sets out the measures that the ESO is taking to reduce costs associated with constraints.

Holistic Transition and **Electric Engagement** have the highest installed and dispatched renewable capacity, leading to the highest level of curtailment. This peaks at 62–64 TWh in the late 2030s. Post-2040, larger deployment of electrolysis leads to lower curtailment. DACCS can reduce curtailment in these pathways by either 30 or 20 TWh in 2050 respectively.

Hydrogen Evolution sees the lowest level of curtailment of the net zero pathways, peaking at 39 TWh in 2038. This lower level is due to larger and quicker deployment of electrolyser capacity. DACCS is present in this pathway after 2040 and curtailment reduces to zero in 2050.

The **Counterfactual** sits between Hydrogen Evolution and both Holistic Transition and Electric Engagement. The peak annual curtailment reaches 52 TWh in 2039.

Figure ES.26: Annual curtailment



12 On average a new transmission line would require fourteen years to build. This can be reduced to seven under reforms.
13 nationalgrideso.com/document/318516/download

Natural gas

Natural gas plays a crucial role in meeting Great Britain's energy demand across various sectors. In 2023, natural gas fulfilled 39% of Great Britain's total energy demand and it remains a significant fuel source for electricity generation, heating and industrial processes.

The flexible nature of natural gas generation has, to date, helped enable the transition to renewable sources. While gas use will reduce out to 2050, all our net zero pathways see it play a role in low carbon flexibility and industry when used with CCS, as well as in the production of low carbon hydrogen.

The expected reduction in gas usage to 2050 is due to increased renewable electricity generation, a switch to low carbon fuels and lower energy demand due to energy efficiency improvements. Given the diverse sources of natural gas available in the UK, there is sufficient gas supply until 2050 to ensure security of supply.

International gas prices can be volatile and dependency on imported gas has been a key concern for consumers and Government over the past few years. Gas prices are currently lower and less volatile compared to the last two years but demand remains below average due to warmer-than-average weather, slower demand recovery and the cost of living crisis.

A decline in domestic production and a potential drop in Norwegian imports mean that the UK will be increasingly reliant on liquefied natural gas (LNG) imports to meet natural gas demand needs. The UK has good access to global LNG markets but, in the absence of firm term supply contracts, will need to compete for supply with Asia and continental Europe and will remain exposed to global pricing dynamics.

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Natural gas

Figure ES.27: Natural gas supply in 2023

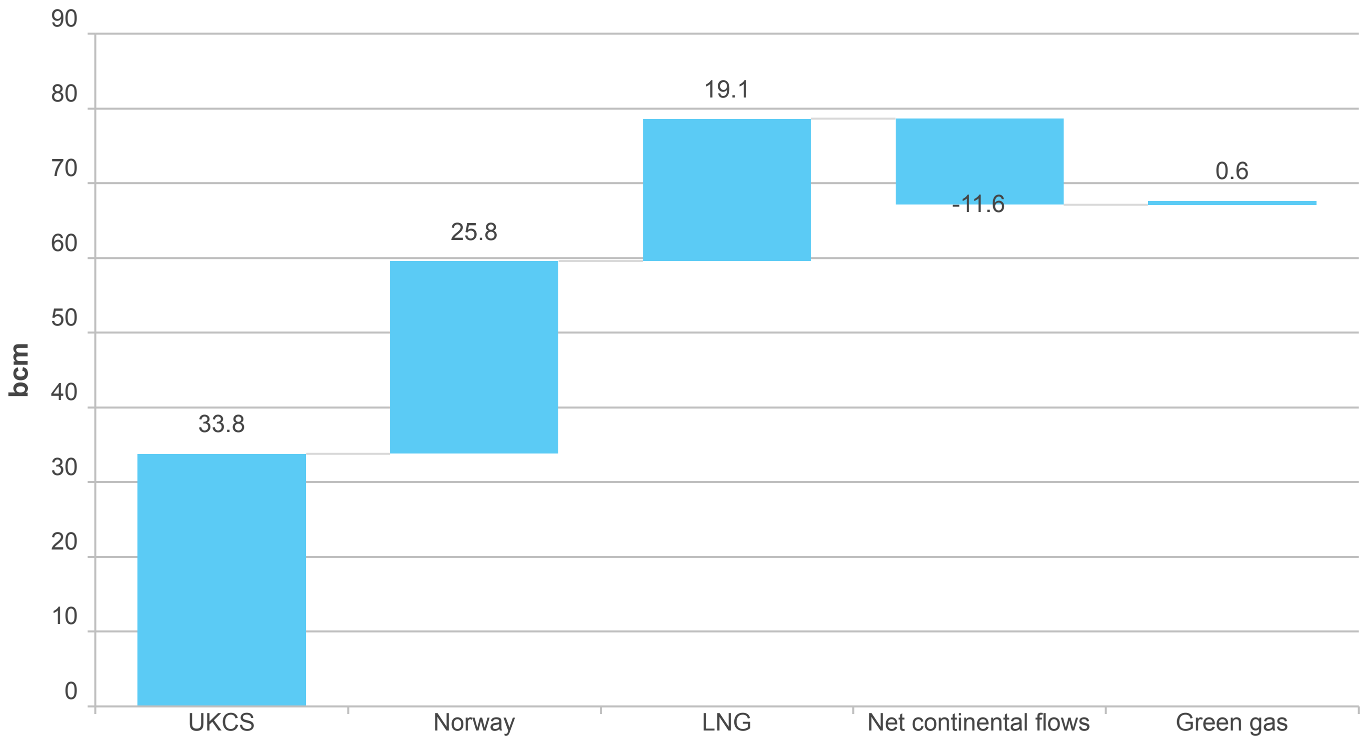
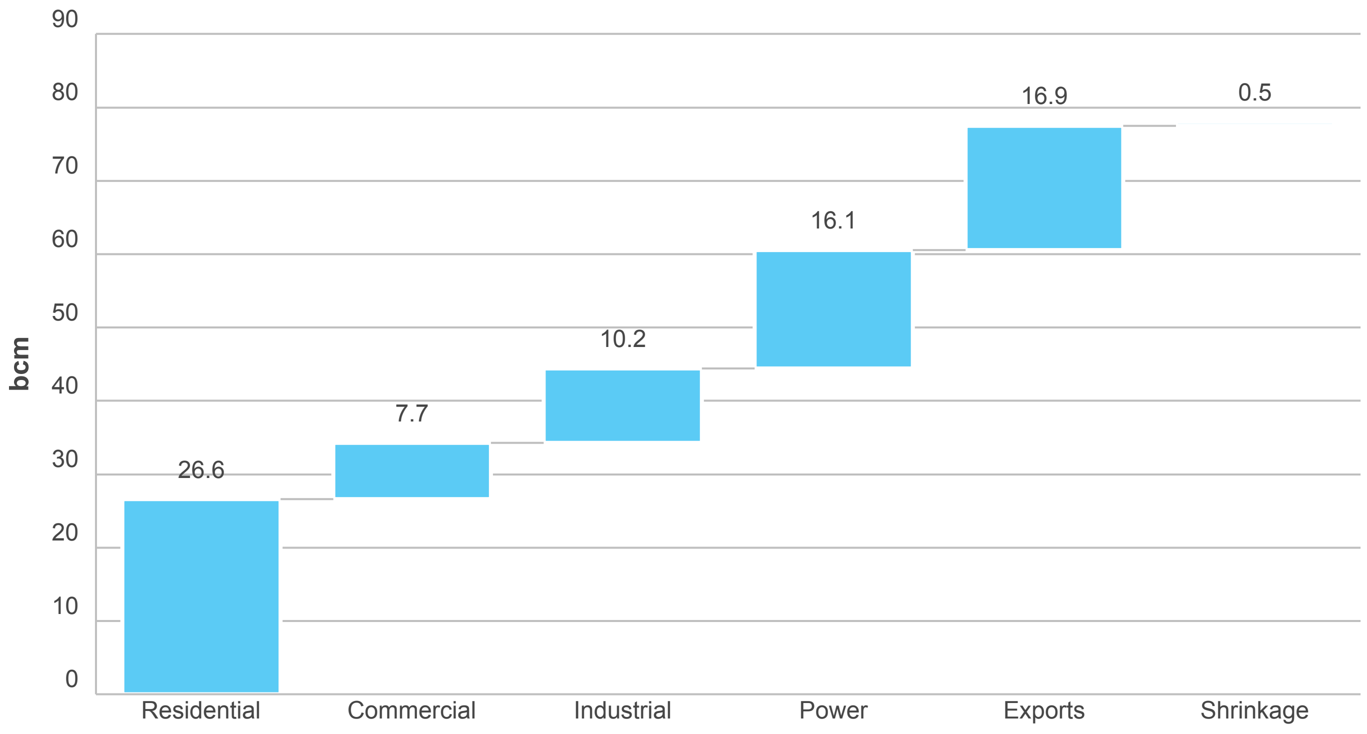


Figure ES.28: Natural gas demand in 2023



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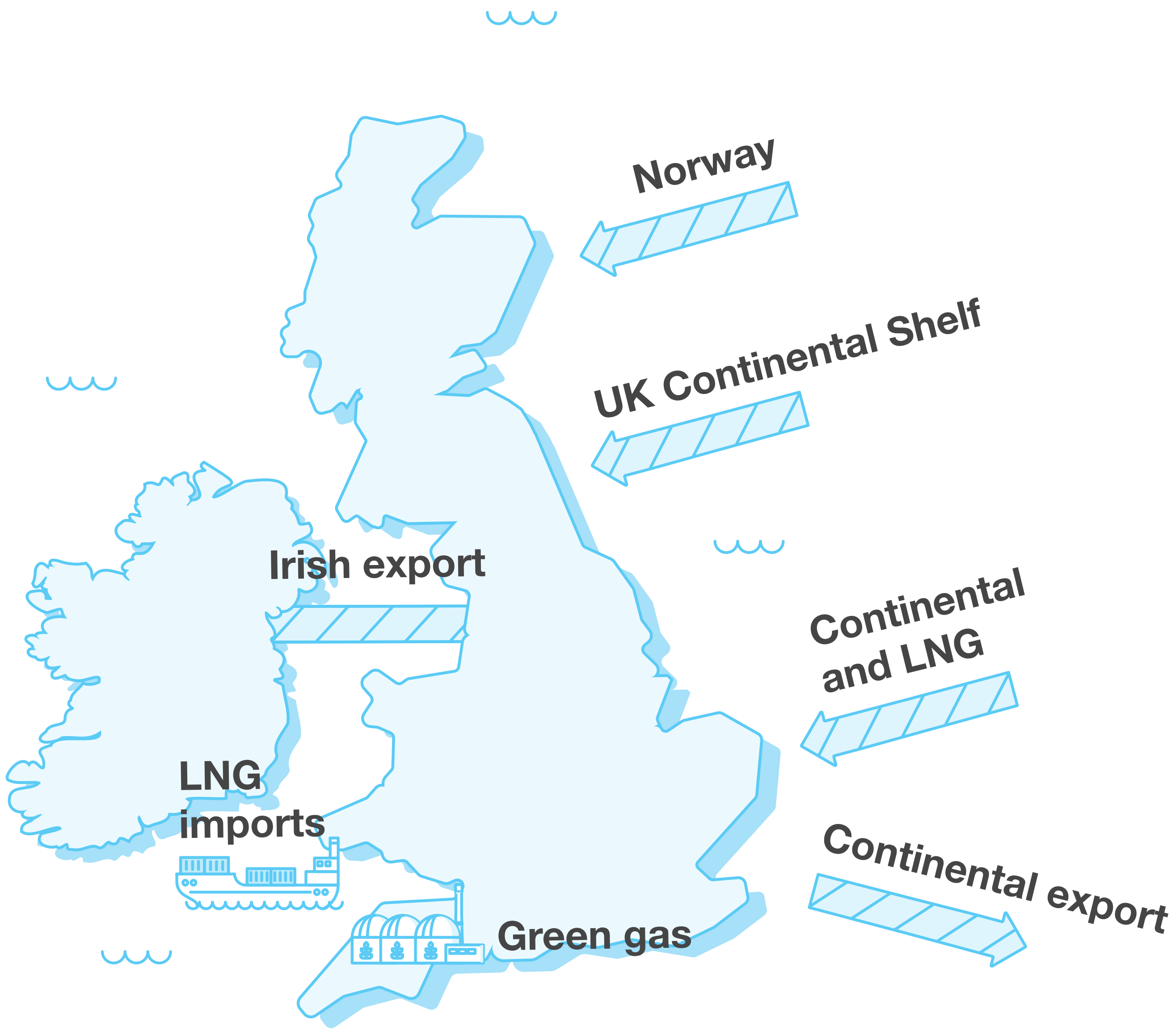
Natural gas



UK Continental Shelf

UKCS production is expected to tail off out to 2050 as fields continue to deplete. However, attempts to push back the decline mean the initial reduction in output is gradual.

Norway

Supply from Norway is traditionally more flexible than the UKCS and greater reserves mean it is expected to produce natural gas for considerably longer.

Green gas

Production of green gas is expected to grow in the short term. The proposed introduction of the Green Gas Levy could support this. However, the increasing value of bioresources for negative emissions and meeting demand in sectors that are hard-to-decarbonise, means there is limited availability for green gas in the long term.

Liquefied natural gas

Over the next few years, the LNG market is expected to rebalance as global demand increases. However, new LNG projects could bring a ‘second wave’ of supply to the market. Global LNG price influences flows across the interconnectors with continental Europe. In the longer term, other markets may transition to hydrogen from natural gas.

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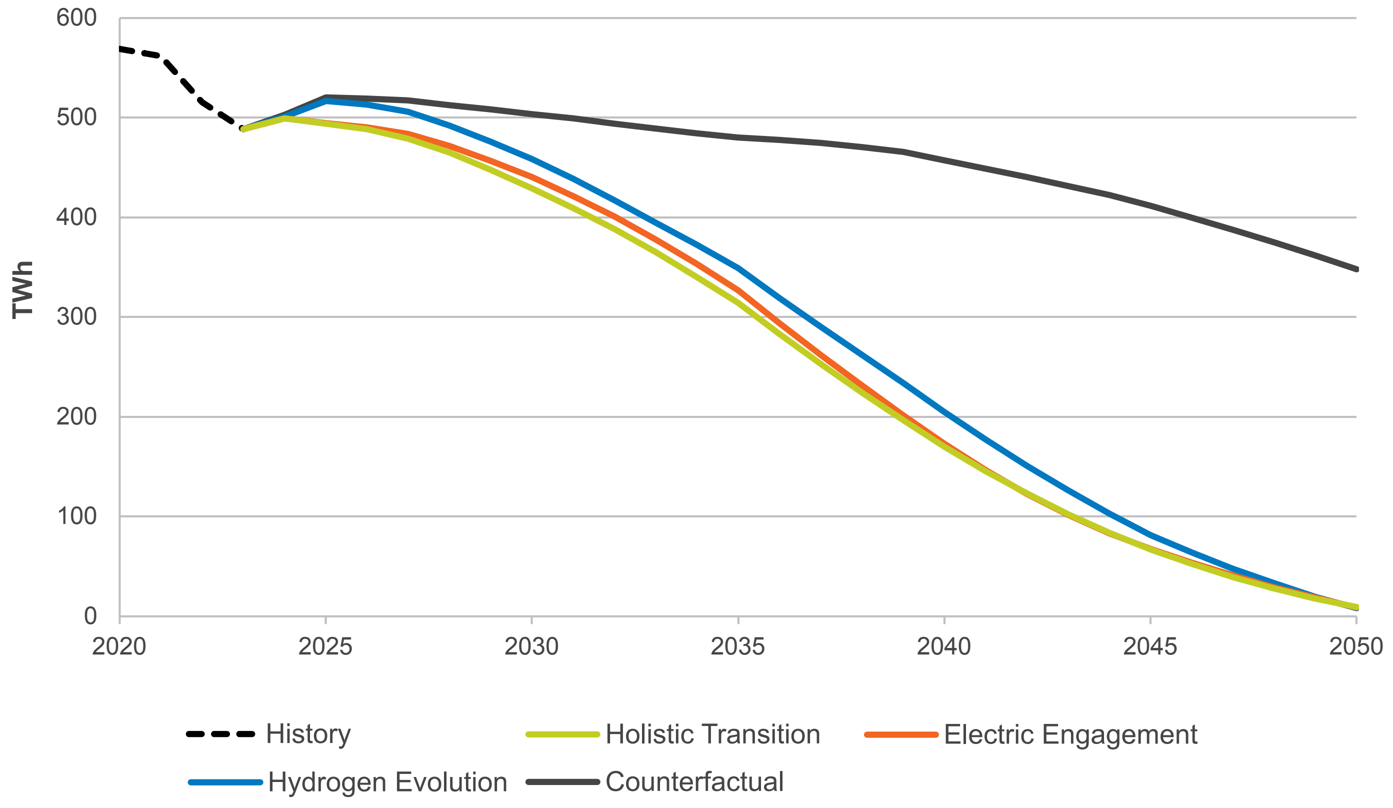
Consumer natural gas demand

While gas consumption will reduce, gas will have an evolving role to play by 2050, such as producing hydrogen through reformation of natural gas with CCS. Further detail on sector demand for gas can be found in The Energy Consumer chapter *(page 80)*.

All net zero pathways see consumer natural gas demand (excluding power, hydrogen and non-FES sectors) reduce by at least 50% before 2039 from today's level of 488 TWh. Fuel switching drives a significant proportion of gas demand reduction, with additional minor gas demand reductions from energy efficiency improvements in the near term.

The **Counterfactual** sees consumer gas demand (excluding power, hydrogen and non-FES sectors) remain at around 70% of today's current demand due to a lack of decarbonisation progress across all sectors.

Figure ES.29: Total annual consumer gas demand (excluding power, hydrogen and non-FES sectors)



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Natural gas supply

Across all net zero pathways and the Counterfactual, there is sufficient supply of gas out to 2050 due to reduced total gas demand and a diverse range of import sources. However, without whole energy system market reform, consumers will continue to be exposed to price fluctuations in global energy markets while gas remains in demand for heat, power and industrial processes.

Our pathways see Great Britain maintain a diverse range of gas supply sources. Gas will continue to be supplied from UKCS, green gas, LNG, and imports from Norway and continental Europe. Additionally, the North Sea Transition Authority (NSTA) has recently awarded 31 new oil and gas licences in UK waters.

The pace at which the current gas demand for power generation, heat and industrial processes will decline remains uncertain. This continued uncertainty also leaves the UK exposed to price fluctuations from global energy markets. It is important that the transition to alternative low carbon sources is managed with minimal disruption and lowest cost to consumers.

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Natural gas

Figure ES.30: Annual gas supply and import dependency in Holistic Transition

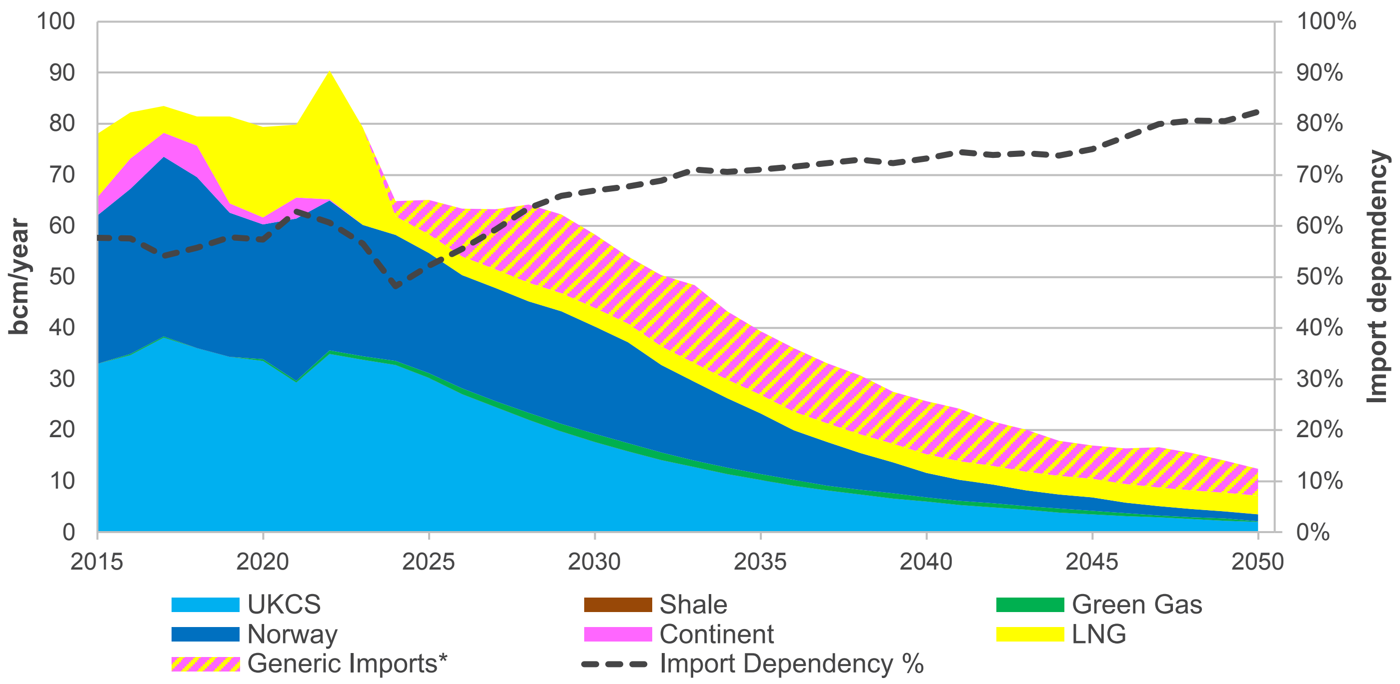
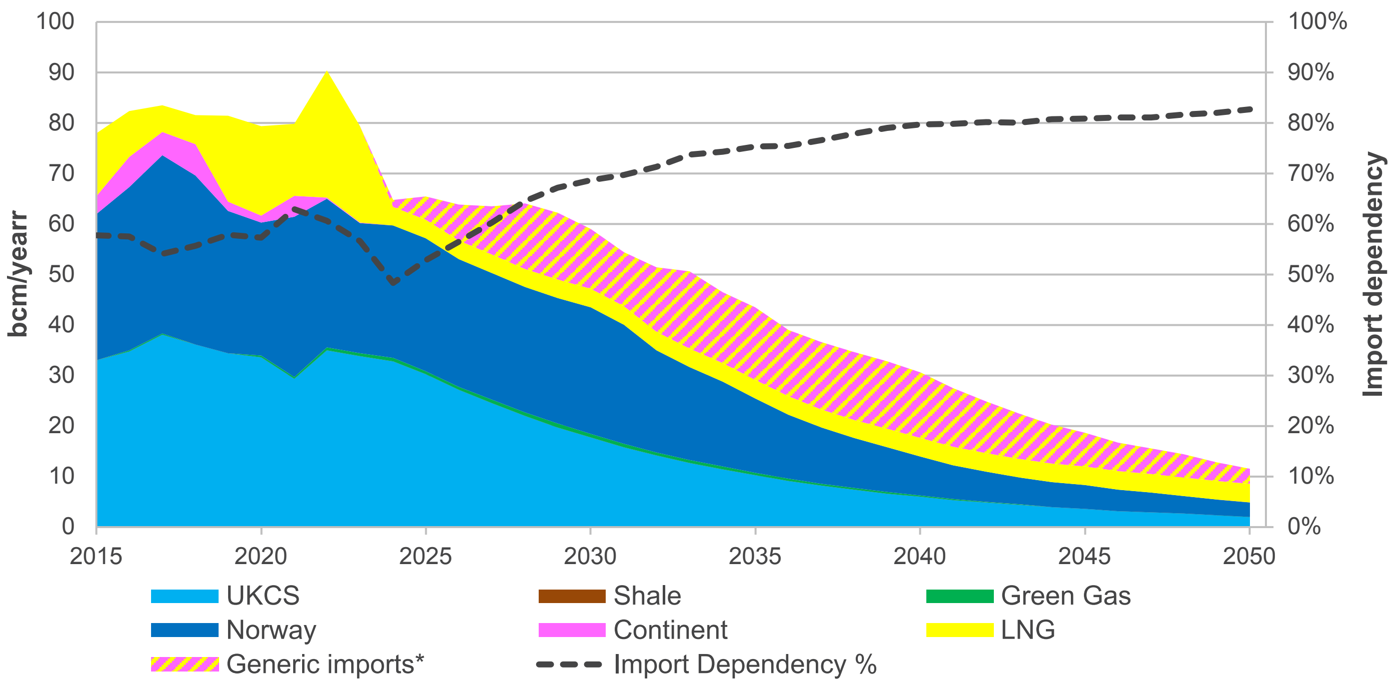


Figure ES.31: Annual gas supply and import dependency in Electric Engagement



Holistic Transition sees annual gas supply decline steadily from the late 2020s onwards. Import dependency remains stable at around 70–75% until the mid–2040s, at which point it increases, reaching 82% in 2050. Natural gas supply is 13 bcm/year in 2050, down from 79 bcm/year in 2050.

Electric Engagement has the lowest gas supply in 2050 out of our net zero pathways (12 bcm/year), although this is only marginally less than Holistic Transition. The proportionate mix of supply sources is similar to Holistic Transition, albeit with a slightly higher import dependency from the late 2030s onwards.

**Generic imports refers only to LNG and/or pipeline imports from the continent.*

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Natural gas

Figure ES.32: Annual gas supply and import dependency in Hydrogen Evolution

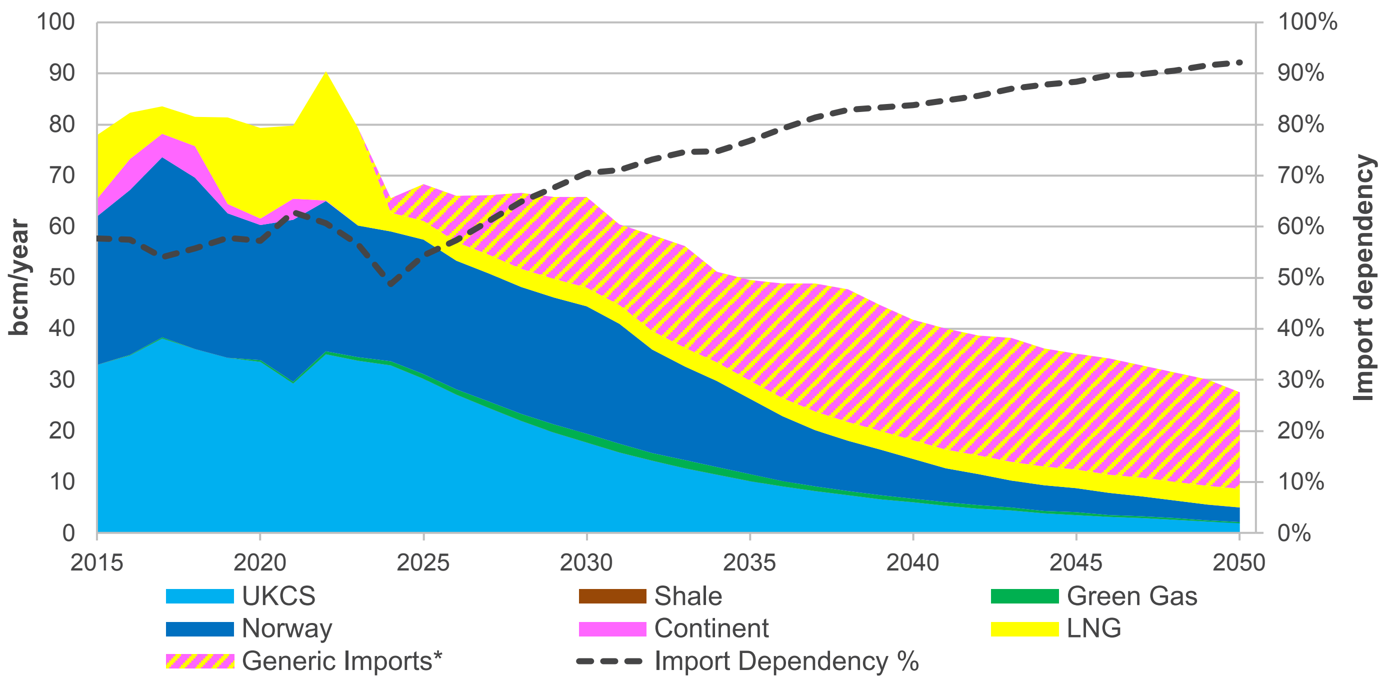
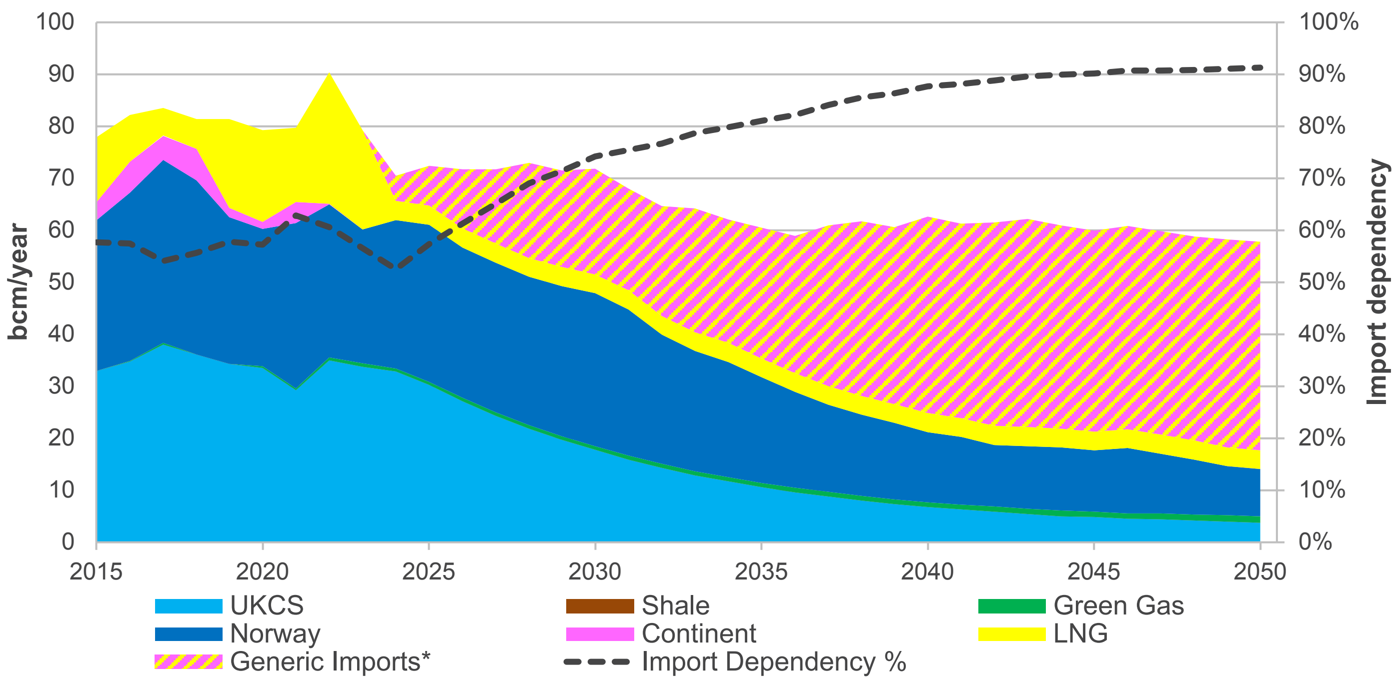


Figure ES.33: Annual gas supply and import dependency in the Counterfactual



Hydrogen Evolution has the highest natural gas supply of our net zero pathways in 2050 at 28 bcm/year. This is driven by higher use of natural gas for blue hydrogen production, with this pathway heavily utilising hydrogen for fuel switching. Import dependency continues to increase from today to 2050.

The **Counterfactual** sees a far less substantial decline in natural gas supply versus current levels, with supply 58 bcm/year in 2050. This is due to limited reduction in gas demand, and less progress towards decarbonisation. Import dependency continuously increases from present day to 2050.

**Generic imports refers only to LNG and/or pipeline imports from the continent.*

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Gas import dependency

Reducing gas import dependency can enhance energy security and help protect from supply disruptions, geopolitical tensions or price fluctuations in international markets.

With UKCS supplies in decline, security of supply must be underpinned by long-term contracts from reliable suppliers. This poses a challenge due to the uncertainty of future gas demand.

Over the past two years, Great Britain has been a key player in the import and onward supply of LNG to Europe due to established import and re-gasification infrastructure. While we can continue to support European security of supply in this way, this role is expected to reduce due to the development of new LNG infrastructure throughout Europe.

All net zero pathways see gas imports increase until 2030 due to the decline in UKCS supplies surpassing the decline in natural gas demand. After 2030, gas imports fall to between 15-56% of 2023 imports, mostly supplied by LNG, but the exact split will depend on market dynamics. The levels of LNG and continental supply are based on minimum technical limits and any additional supplies from these sources would be included in 'generic imports'.

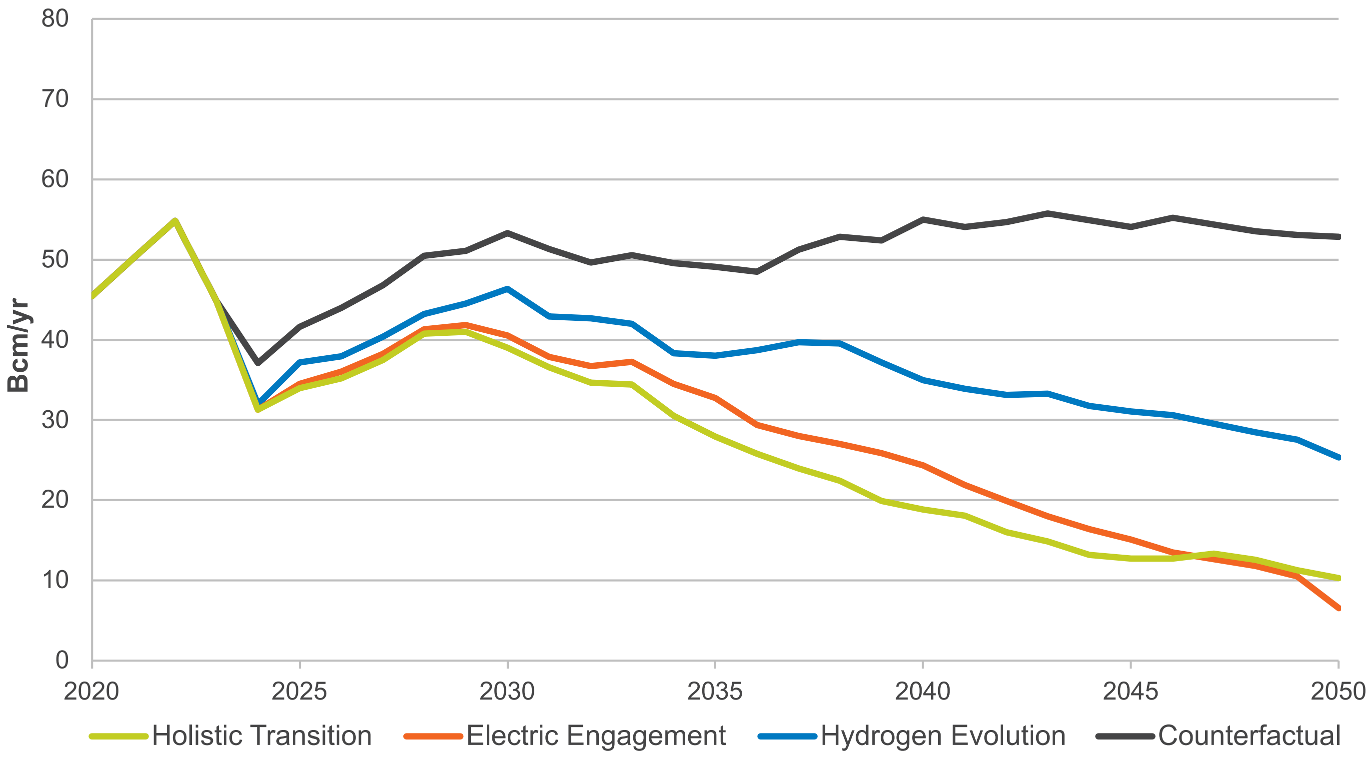
Holistic Transition sees an accelerated move away from a reliance on imported gas between 2030 and 2046 due to faster reduction in gas demand. UKCS still supplies a small amount of the residual annual demand in 2050, meaning that the UK can still meet around 20% of annual demand from domestic sources in 2050.

Electric Engagement sees the lowest imports by volume in 2050 with only 7 bcm/year. Similar to Holistic Transition, import dependency reaches around 80% due to gas usage for flexibility purposes, such as low carbon dispatchable power.

Hydrogen Evolution sees the highest imported volumes of gas across the net zero pathways with 25 bcm/year in 2050. Import dependency is highest, at over 90%.

The **Counterfactual** sees imported gas volumes increase by 8 bcm/year to 54 bcm/year in 2050. This compares to 45 bcm/year today due to limited reduction in gas demand and reducing UKCS supplies out to 2050. More than 90% of supply is imported.

Figure ES.34: Imported gas volumes out to 2050



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Gas networks and storage

Flexibility

Gas is an important flexibility factor in today's energy mix. Through both real-time storage in the gas network and seasonal storage in salt caverns and depleted gas fields.

Great Britain currently has approximately 35 TWh of gas storage, with approximately 80% of this in salt caverns and the remainder in depleted gas fields. This is in addition to the linepack storage available in the existing gas pipeline network.

Many gas storage sites are considering future conversion to hydrogen storage. More certainty is needed on the role of hydrogen as well as the development of transport and storage business models.

Due to the ongoing role of natural gas combined with CCS in 2050, both gas and hydrogen infrastructure will be required. Any conversion of infrastructure to hydrogen must consider the ongoing role of natural gas.

It is important to ensure an orderly transition and that the ongoing costs associated with lower utilisation of assets are considered alongside security of supply.

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Natural gas

The route to net zero

Natural gas has a role in the future energy system across all our net zero pathways. Clarity is needed on how this role will be maintained alongside supplying low carbon hydrogen.

Key Actions 1&8

The scale of the transition to low carbon gas infrastructure is huge and includes repurposing of the existing gas network, blending and reuse of the network for alternative fuels. Significant investment and careful phasing is essential to make sure no consumers are left behind and to minimise the risk of stranded assets. Greater clarity on this will assist the gas supply chain in planning for both gas and hydrogen networks and the repurposing of existing assets.

Industrial processes and power currently rely heavily on natural gas. Adapting to alternatives while managing cost and disruption, without compromising security of supply, will remain a challenge throughout the transition.

Key Action 2

There are challenges around assisting and incentivising consumers to adopt alternative fuels and technologies. Cross-sector market reform is needed to ensure market actors are working effectively together to deliver the best outcomes for consumers.

Utilising the UKCS can contribute to domestic energy security and exploring diverse energy imports can offer enhanced energy resilience and flexibility.

Shocks to the European gas market in recent years have underlined the benefits of a diverse range of sources for energy security. While total gas demand will decline, maintaining a mix of sources will remain important.

Investing in the production of green gases such as biomethane could provide a route for sustainable energy development.

Increased green gas supply could help improve security of supply and resilience and could represent a larger proportion of supply in the future as total demand begins to decline.

Great Britain is well placed to benefit from significant existing assets and expertise in the field of gas transportation and storage through change-of-use to low carbon hydrogen.

Key Action 3

The need for low carbon hydrogen in the energy transition presents an opportunity for the gas industry to pivot to low carbon gas production and for Great Britain to become a leader in hydrogen development.

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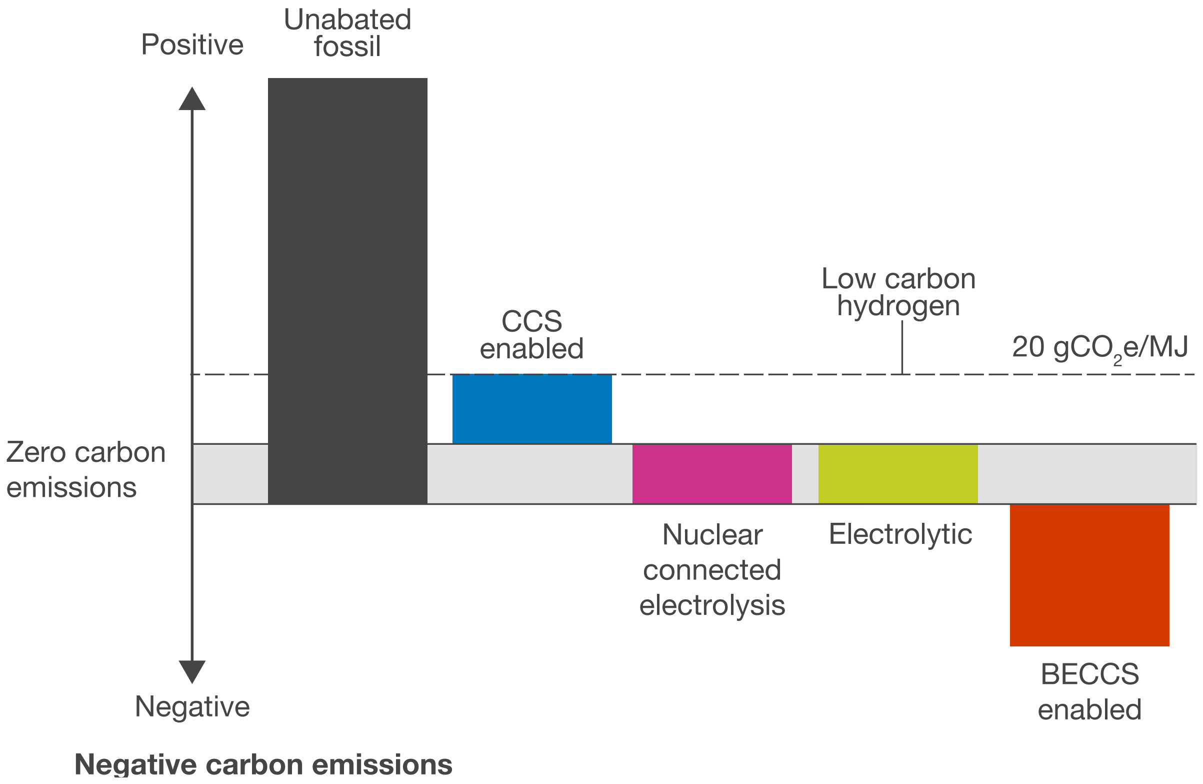
Low carbon hydrogen

Low carbon hydrogen will be an important source of energy, both as an energy carrier and as a source of flexibility.

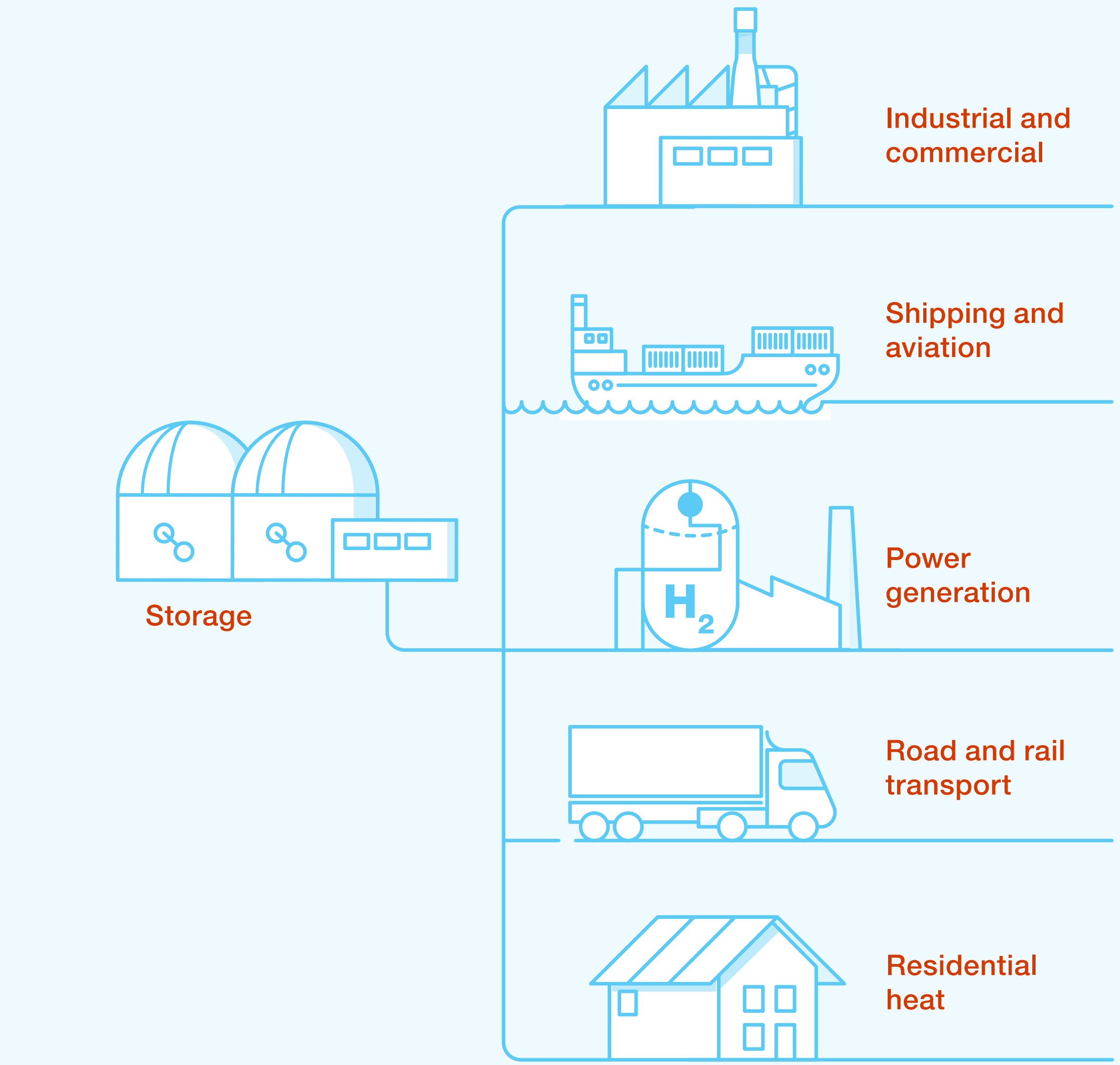
Low carbon hydrogen can replace natural gas in many cases, become a key component of synthetic fuels for aviation and replace the carbon-intensive hydrogen currently used in the production of ammonia and petrochemicals.

The Low Carbon Hydrogen Standard sets a threshold of 20 gCO_2e/MJ for hydrogen to be considered low carbon and eligible for a production subsidy.

Different types of hydrogen and their carbon emissions



Potential uses of low carbon hydrogen



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Low carbon hydrogen

Unabated fossil hydrogen

Hydrogen made by methane reformation without any means to capture emissions or through gasification of coal. Sometimes referred to as grey hydrogen.

Electrolytic hydrogen

The process of using electricity to split water into hydrogen and oxygen. If the electricity used to power the process is renewable, this is sometimes referred to as green hydrogen.

Naturally occurring hydrogen

Sometimes referred to as white hydrogen, geologic hydrogen or gold hydrogen. This is formed by natural processes and recovered rather than produced.

Note that we do not currently include natural hydrogen in the FES hydrogen supply mix.

Nuclear connected electrolysis

Similar to electrolytic hydrogen but, instead, electricity generated by nuclear is used to power the process. In FES 2024, we have focused on low-temperature electrolysis, which can be combined with large or small nuclear reactors as this has the greatest commercial and technical readiness levels of all the options. Other potential ways of pairing nuclear technologies with hydrogen production include high-temperature electrolysis, such as solid oxide electrolysis (using heat as well as electricity from a nuclear power plant) or thermochemical production (using high-temperature chemical reactions and heat from the nuclear plant). Sometimes referred to as pink hydrogen.

Carbon capture and storage enabled hydrogen

Works in the same way as unabated fossil fuel hydrogen but, instead, up to 97% of carbon emissions are captured and either stored or used. It still involves the extraction of fossil fuels and the associated emissions this brings and its status as low carbon technology is dependent on the effectiveness of carbon capture. Sometimes referred to as blue hydrogen.

Bioenergy with carbon capture and storage enabled hydrogen

Biomass can be used to produce hydrogen through gasification. When this is combined with carbon capture, the CO_2 produced as a by-product is stored, making the overall process negative in terms of carbon emissions.

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Low carbon hydrogen supply

Great Britain has the potential to become a world leader in the production of low carbon hydrogen through delivery of hydrogen production projects and establishment of the supply chain. While there is already an established global hydrogen supply chain, this must now transition to low carbon production methods and must be substantially scaled up.

Progress is being seen on the development of hydrogen supply, with the announcement of successful Track 2 clusters and Hydrogen Allocation Round 1 (HAR1). HAR1 awarded support for 125 MW of electrolytic capacity at the end of 2023, with these anticipated to come online in 2025. However, these projects have not yet reached final investment decision (FID). HAR2 will aim to support up to 875 MW of green electrolytic hydrogen production.

We have seen progress through these announcements but a clear strategy is now needed for delivery of projects beyond those included in the first industrial clusters and funding rounds. At present, most hydrogen supply projects are still in development and are yet to receive planning permission or project funding.

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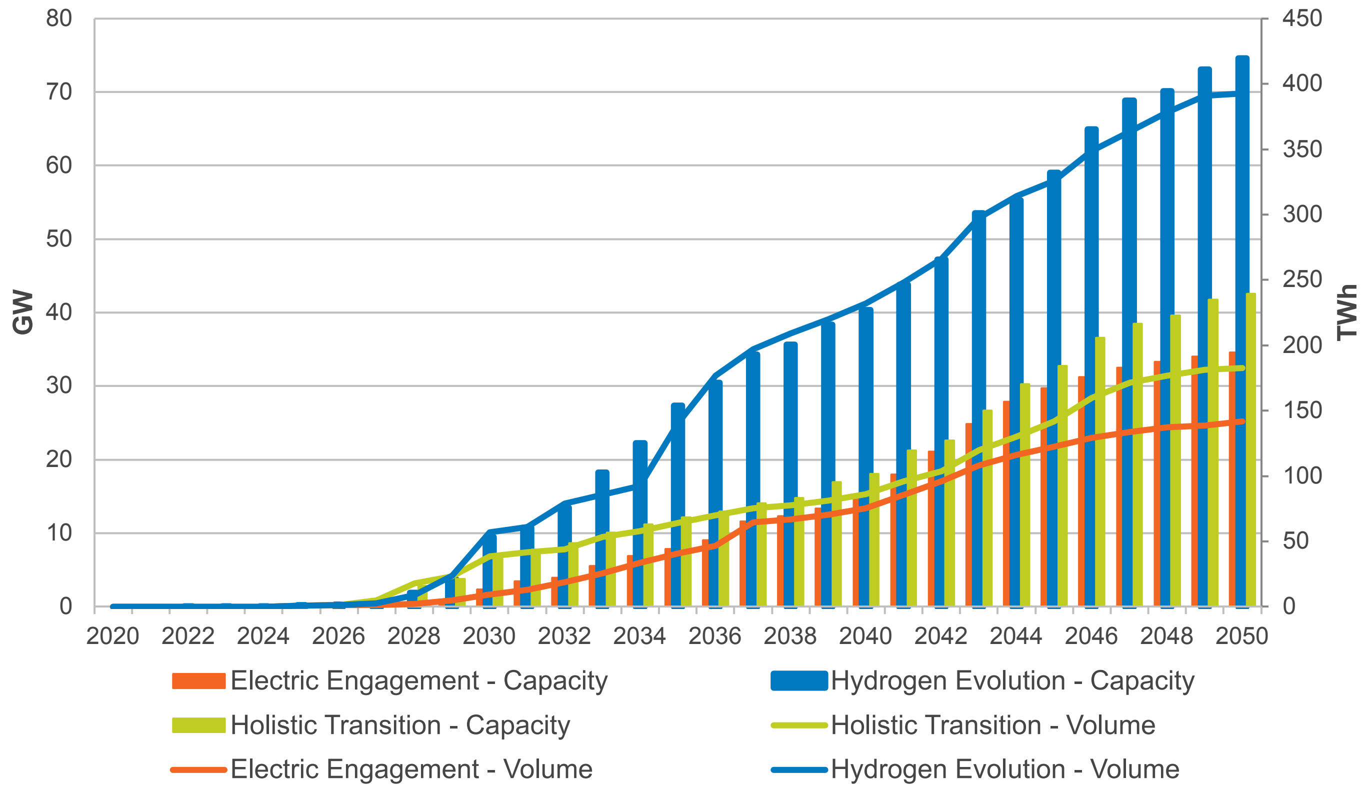
Low carbon hydrogen

Holistic Transition sees hydrogen supply at 183 TWh in 2050, equivalent to almost two thirds of present-day electricity demand in the UK (299 TWh in 2023). Installed capacity is just over 12 GW in 2035, around 60% of which is electrolytic hydrogen. After this point capacity then expands, with the vast majority through the addition of more electrolytic hydrogen capacity.

Electric Engagement sees the lowest overall hydrogen supply of 142 TWh in 2050, due to extensive electrification and, consequently, lower hydrogen demand. Most scaling of supply takes place in the 2040s, with supply doubling in this decade. By 2050, most capacity is from electrolysis. CCS enabled hydrogen accounts for 4 GW of capacity, more than half of which is built by 2035.

Hydrogen Evolution has by far the highest hydrogen supply at 393 TWh in 2050, larger than present-day electricity demand in Great Britain. In this pathway, there is a rapid and substantial build-out of all hydrogen production technologies: electrolytic capacity, methane reforming with CCS, hydrogen BECCS and nuclear-connected hydrogen. In 2035, more than 9 GW of methane reforming with CCS is online and close to 1.5 GW of hydrogen BECCS. By 2050, this more than doubles again to 19 GW and 3 GW respectively. The electrolytic hydrogen capacity increase is more substantial at almost 17 GW in 2035, increasing to 52 GW in 2050. The mix of production technologies is necessary both to scale up to this capacity and to offer security of supply given the importance of hydrogen in this pathway.

Figure ES.35: Hydrogen capacity and supply by pathway



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Low carbon hydrogen

Hydrogen supply by technology

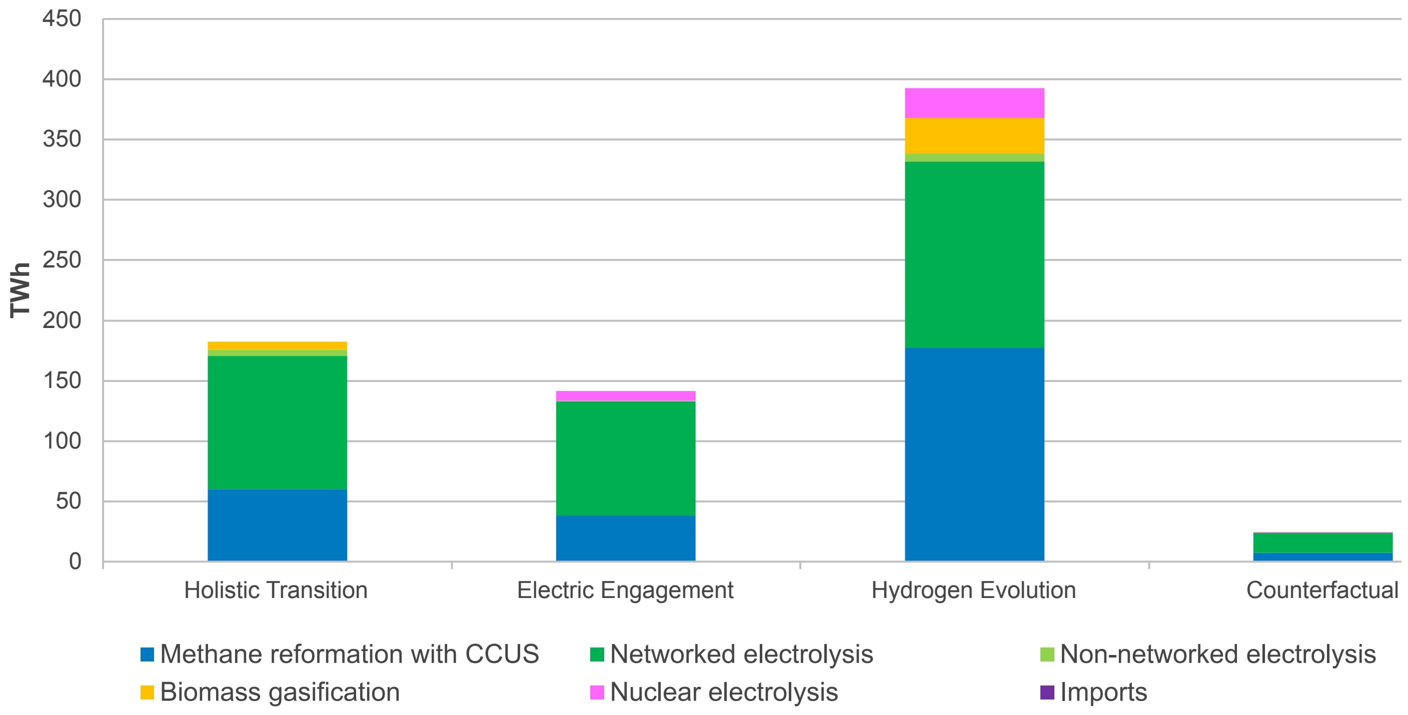
The level of industrial hydrogen fuel switch required to meet the Sixth Carbon Budget requires large volumes of low carbon hydrogen to be delivered at pace, with some stability of supply. Industrial clusters continue to provide this opportunity. A mix of low carbon hydrogen supply technologies will be needed for the range of applications.

Load factors vary based on the feedstock for hydrogen production - some production types will require a transport and storage network. Additionally, there is some regional variability in load factors, reflecting the different outputs from wind and solar used in electrolytic hydrogen production.

Location of low carbon hydrogen production is an important consideration and we are seeing positive levels of proposed electrolysis projects in Scotland.

A coherent strategy is required to ensure that large electricity demand users, such as electrolysis, are located where they will offer the biggest benefit to consumers and the whole energy system.

Figure ES.36: Hydrogen supply by technology in 2050



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Low carbon hydrogen storage

Flexibility

Hydrogen storage can provide significant flexibility benefits across the whole energy system. It's needed to replace some of the flexibility currently provided by natural gas, but is reliant upon either the development of new hydrogen storage and transportation networks or the transition of existing natural gas transportation and storage networks to hydrogen.

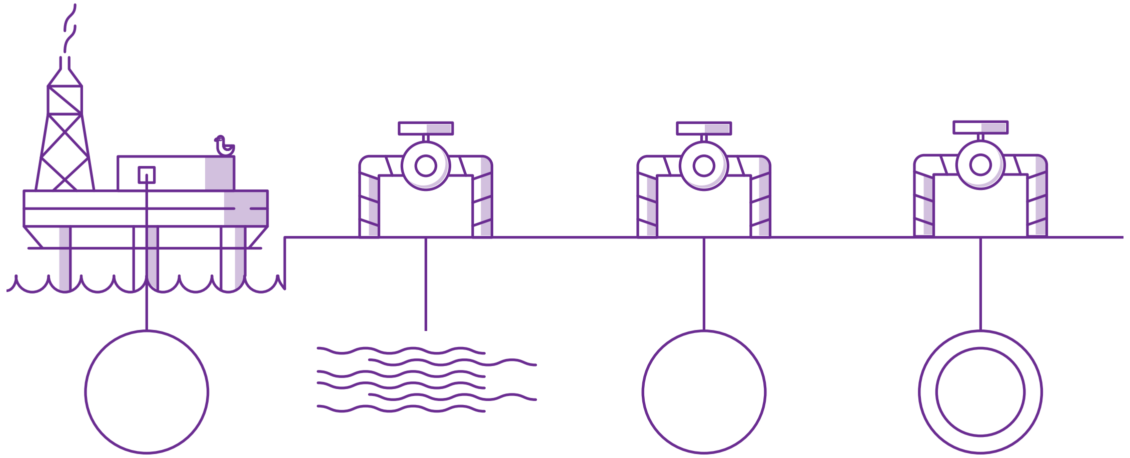
The availability of sufficient quantities of hydrogen storage will be important in helping ensure security of supply. It can also accommodate efficient use of excess wind and solar for electrolytic hydrogen production as a form of long-duration energy storage with both whole system emissions and cost benefits[14].

Salt caverns are currently used to store hydrogen and this is the preferred option across our pathways. A salt cavern hydrogen storage facility has been in operation in Teesside since the 1970s, storing 25 GWh of hydrogen. However, this represents less than 0.2% of the 2050 hydrogen storage in any of our pathways.

The British Geological Survey and academic researchers have estimated approximately 2,150 TWh of potential geological storage capacity for hydrogen in the UK[15] in the East Yorkshire basin region, as well as some in the Cheshire and Wessex regions. However, this estimate is based upon a specific size of salt cavern and total capacity may be lower if this size varies.

Stored hydrogen can also be used during peak electricity demand in hydrogen turbines. Round-trip efficiency of power-to-hydrogen to storage-to-power is low but this must be balanced against the whole system benefits of reducing curtailment and ensuring low carbon security of supply.

Hydrogen storage capacity requirements



	Depleted field	Aquifer	Salt cavern	Lined rock cavern
Availability in Great Britain	✓	✓	✓	✓
Suitability for hydrogen	✓ <10% blend proven; Pure hydrogen under study	Under study	✓	✓
Technology readiness	3-6	3	8	5-6

14 [Scenario Deployment Analysis for Long-Duration Electricity Storage - Page 120]
15 [Journal of Energy Storage]

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Low carbon hydrogen

All net zero pathways see significant availability of onshore hydrogen salt cavern capacity from the mid-2030s onwards. Given that it can take 10–12 years to develop a salt cavern and fill it with cushion gas, this suggests that salt cavern development for hydrogen storage needs to begin immediately. Our pathways show that aiming for 5 TWh of hydrogen storage by 2035 would be a low regret option – all pathways require at least this amount by 2040. Alternatives to salt cavern storage could be explored, such as re-purposing existing natural gas storage, but this must be weighed against the future role of gas and need for gas storage seen across our pathways.

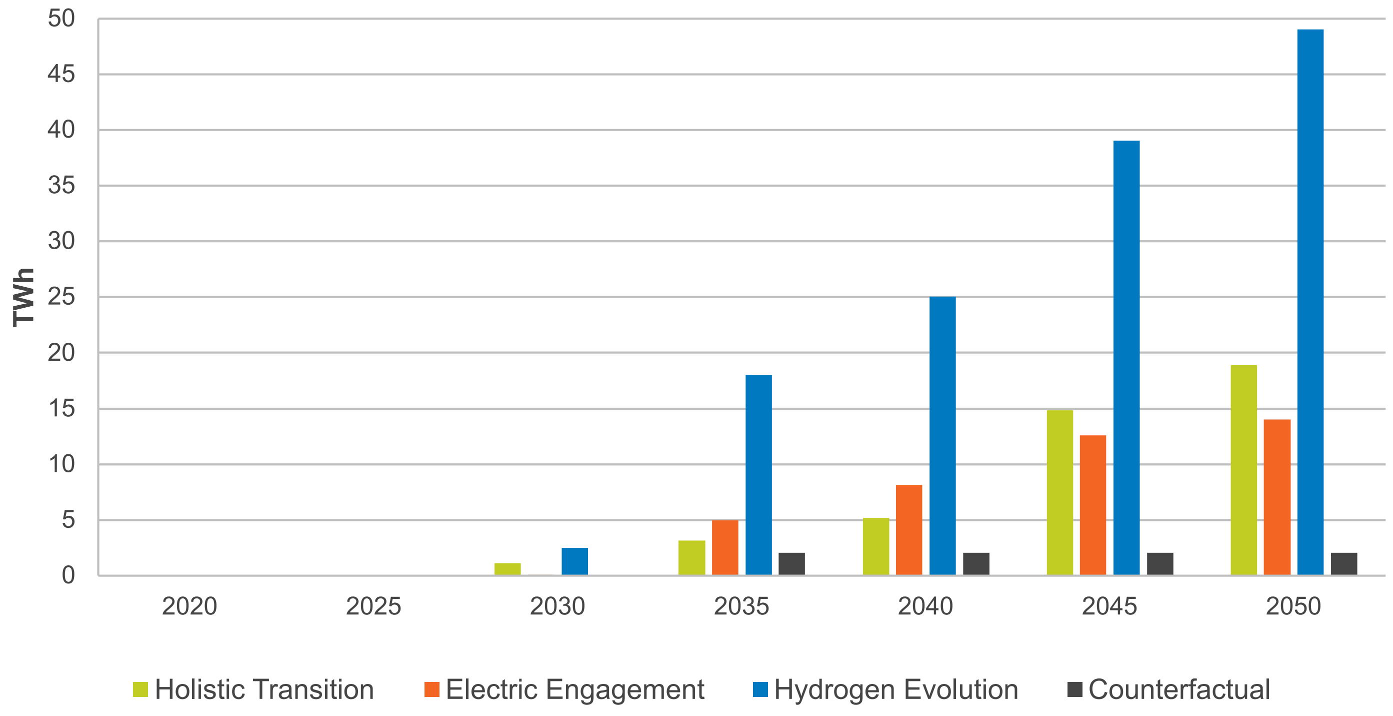
It should be noted that these are the working storage volumes and total volumes are approximately 40% higher when including cushion gas.

Holistic Transition has 3 TWh of salt cavern storage available in 2035, rising to 5 TWh in 2040. This pathway has 19 TWh of hydrogen storage in 2050.

Electric Engagement has 5 TWh of salt cavern storage in 2035, increasing to 8 TWh in 2040. This pathway has 14 TWh of hydrogen storage in 2050.

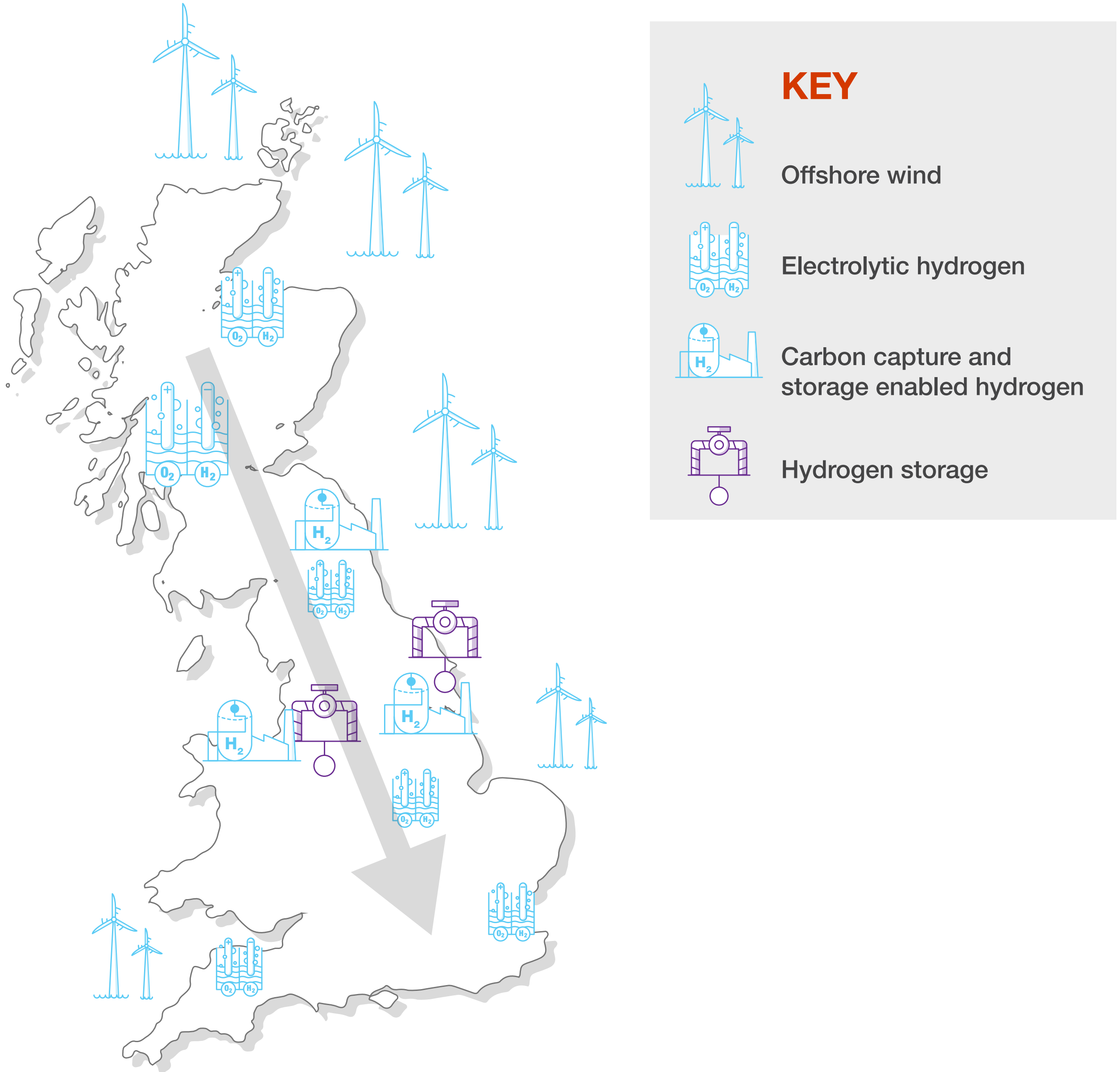
Hydrogen Evolution has 18 TWh of storage in 2035, which more than doubles to 49 TWh in 2050. In this pathway, hydrogen is heavily utilised, particularly for peak power demand which drives up storage needs.

Figure ES.37: Hydrogen storage capacity requirements



Low carbon hydrogen

Hydrogen transmission flows



As renewable energy sources continue to grow, the need for effective energy transmission, storage and distribution will be crucial. The development of a hydrogen network will begin around regional clusters and must be balanced with continued support for consumers still using gas. At present, there is a lack of clarity over how hydrogen pipeline networks will both develop and exist alongside natural gas networks, particularly if natural gas infrastructure is being repurposed for hydrogen.

Figure ES.38: Hydrogen daily stock profile level in 2050 for Holistic Transition

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Low carbon hydrogen blending

The blending of hydrogen into the existing gas network is a transitionary opportunity to provide more certainty for hydrogen producers, helping address the initial mismatch of supply and demand as developers look to achieve economies of scale benefits. This increase in certainty for investors must be balanced against prioritising end-use of hydrogen.

In December 2023, UK Government took a strategic policy decision to support blending of up to 20% hydrogen by volume into Great Britain's gas distribution networks, subject to the outcomes of industry trials and safety assessment. A decision will then be made on whether to enable blending. This assessment should consider the challenges of injection at transmission and distribution level as well as the impact on users of the gas network.

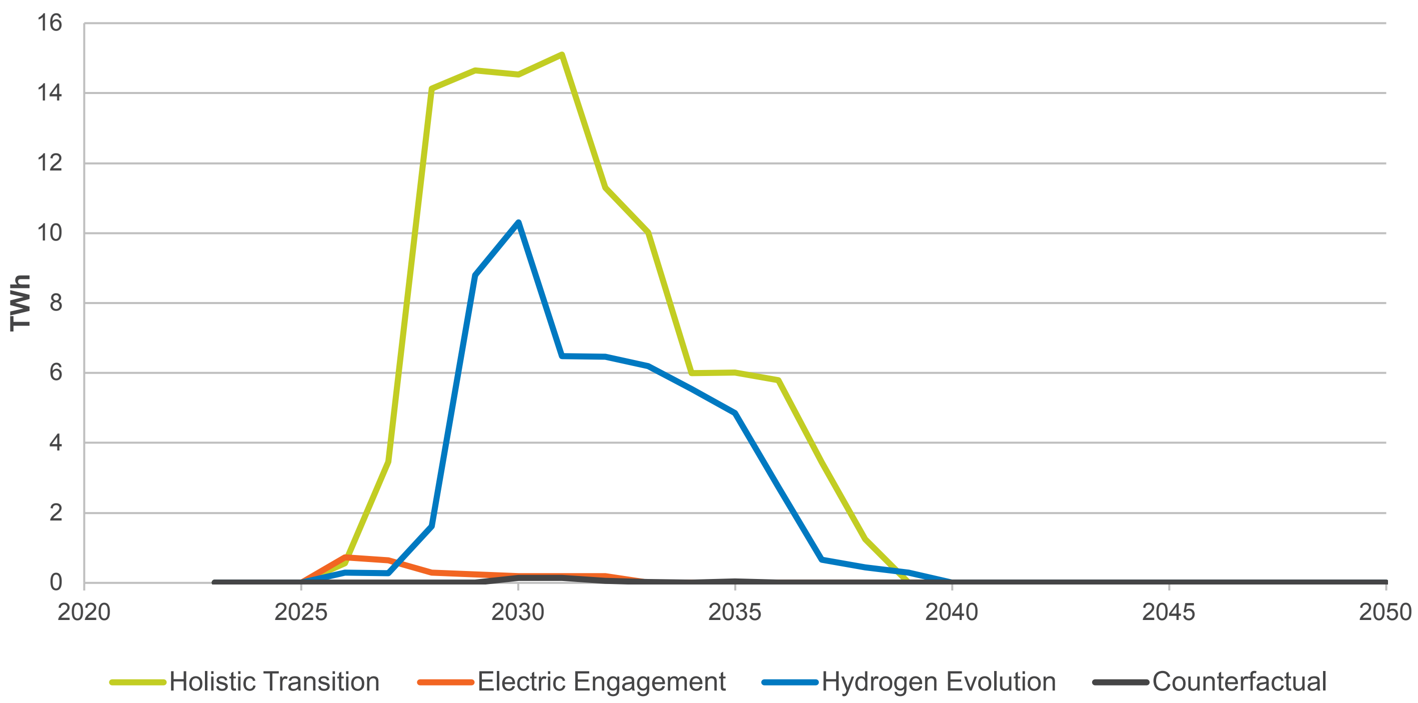
However, blending into the gas network at these levels has a limited impact on reducing emissions. A large 20% blend, for instance, results in a 7% emissions reduction. The impact on consumers must be considered.

All net zero pathways assume no hydrogen blending before 2026, taking into account the likely timescales for blending on a commercial scale.

Holistic Transition and **Hydrogen Evolution** see blending largely taking place from the late 2020s to early 2030s. The maximum amount of blending reaches 15 TWh in 2030 in Holistic Transition and 10 TWh in 2030 in Hydrogen Evolution. Blending is minimal by the late 2030s in these pathways.

Electric Engagement sees smaller amounts of blending.

Figure ES.39: Blending demand for hydrogen by pathway



Low carbon hydrogen

The route to net zero

The whole system benefits of hydrogen can only be realised through investment in hydrogen transport networks and storage. Prioritisation of the use of hydrogen for hard-to-electrify applications is needed.

Key Actions 1&3

Low carbon hydrogen will be a high value energy carrier. Without a hydrogen transportation network, consumers will only be able to access low carbon hydrogen if there is a funded project nearby. A clear plan for the delivery of hydrogen supply projects beyond the delivery of industrial clusters is needed.

Developing hydrogen infrastructure and markets in the UK requires significant investment, supportive regulatory frameworks and a strategy for the repurposing of existing gas networks where necessary.

Clarity is needed on how hydrogen pipeline networks will be developed and how existing gas infrastructure will be repurposed.

Hydrogen transmission networks move hydrogen from areas of lower cost production to end users or storage facilities and are essential across all our pathways. There is still a lack of clarity as to how, where and when these networks will develop and this will limit developments elsewhere in the hydrogen value chain. A limited view of the repurposing of gas networks for hydrogen also still remains. This is made more complex given that natural gas will remain part of the energy system in 2050 across all our pathways.

Hydrogen production from hydrogen BECCS could be a high priority use of sustainable biomass resources.

The Government's Hydrogen BECCS Innovation Programme[16] is aimed at accelerating the development of the technology. In our pathways, hydrogen BECCS is deployed at scale when there is a need for significant amounts of hydrogen production. Ensuring the availability of this technology can help enhance the security of hydrogen production options into the future.

Accelerating the development of below-ground hydrogen storage facilities is required for security of supply in the future.

All pathways see significant amounts of hydrogen storage available from the mid-2030s onwards. The long project timescales of developing large-scale hydrogen storage creates the risk of delays for others in the hydrogen value chain to develop production facilities, build transportation networks or switch fuels. Accelerating the development of large-scale hydrogen storage facilities is now essential.

16 Hydrogen BECCS Innovation Programme

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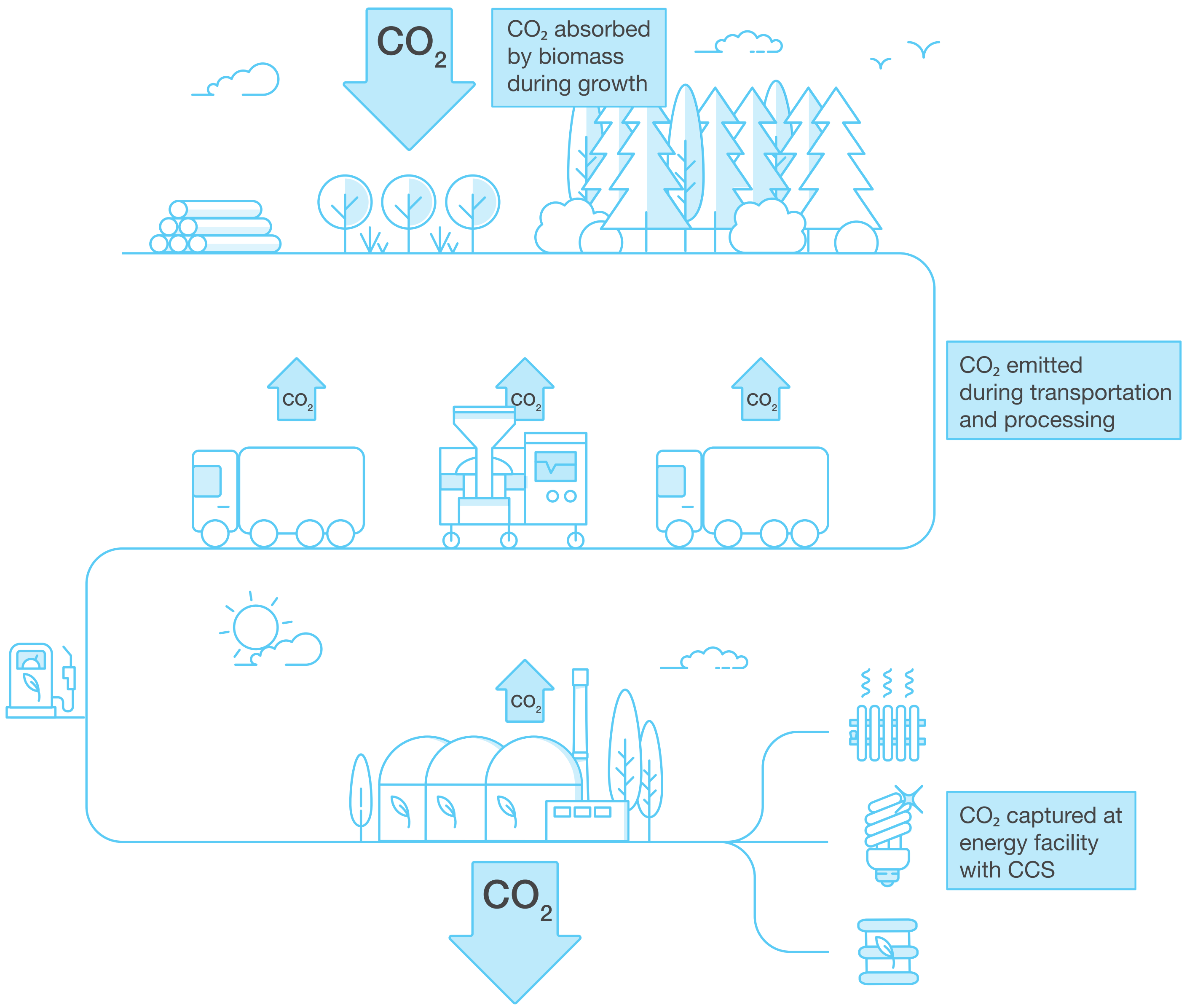
Bioenergy

Bioenergy in Great Britain is currently used for electricity generation, transportation fuels and heating. BECCS technologies could act as a source of net negative emissions and bioenergy could have an important role to play in the future energy system if the biomass value chain is sustainable.

A handful of power BECCS projects are in commercial development across Europe. However, other bioenergy technologies are also needed to meet net zero, such as hydrogen BECCS or Sustainable Aviation Fuels (SAFs). These need further development and demonstration to be proven at commercial scale.

Bioenergy could supply several energy vectors, including:

- Electricity (power BECCS)
- Carbon negative hydrogen production via biomass gasification with carbon capture and storage (hydrogen BECCS)
- Heat via combustion boilers or combined heat and power stations
- Sustainable aviation fuels (SAFs)
- A variety of other liquid or gaseous fuels, through either gasification or fermentation routes. The production of biogas by anaerobic digestion, for instance, serves as a valuable waste management technology, a flexible fuel source and creates a valuable fertiliser by-product.



Bioenergy

Biomass feedstock

Bioenergy can deliver a significant proportion of Great Britain's net negative emission needs through BECCS technologies. BECCS is the only negative emission technology that can provide both a usable energy source and a source of emissions removal. However, efforts are required to realise this potential.

All net zero pathways see biomass sourced from a variety of feedstock options, such as forestry residues, waste wood, energy crops, agricultural residues and municipal solid waste and imports. Different relative amounts of imports have been used across the pathways, as taken from the Sixth Carbon Budget. A greater reliance on imports may impact security of supply and reduce transparency regarding sustainability in the supply chain. A greater reliance on domestic feedstocks, however, would necessitate swift action on energy crop planting and feedstock sourcing in general.

Holistic Transition and **Electric Engagement** primarily use biomass for power BECCS, SAFs and heat in 2050. Liquid bioethanol, currently used for road transport, is no longer required in 2050 due to the decarbonisation of road transport.

Hydrogen Evolution sees power BECCS and SAFs primarily using biomass in 2050. Production of hydrogen (hydrogen BECCS) uses a similar amount of biomass feedstock as is used in the production of SAFs. Note that one future route of SAF production from biomass is via the same biomass gasification technology as is used in hydrogen BECCS.

Biomass feedstocks could be used to decarbonise other sectors of the UK economy as a sustainable source of carbon used for net carbon removal without the production of an energy vector, known as Biomass with Carbon Removal and Storage (BiCRS). Additionally, the increased use of timber in construction could act as a medium-term store of carbon and could lead to additional sawmill residue feedstock for bioenergy facilities. Similarly, the use of biomass to produce biobased plastics and materials could create waste by-products useful for bioenergy processes. These wider uses of biomass were noted in the Government's 2023 Biomass Strategy[17].

17 gov.uk/government/publications/biomass-strategy

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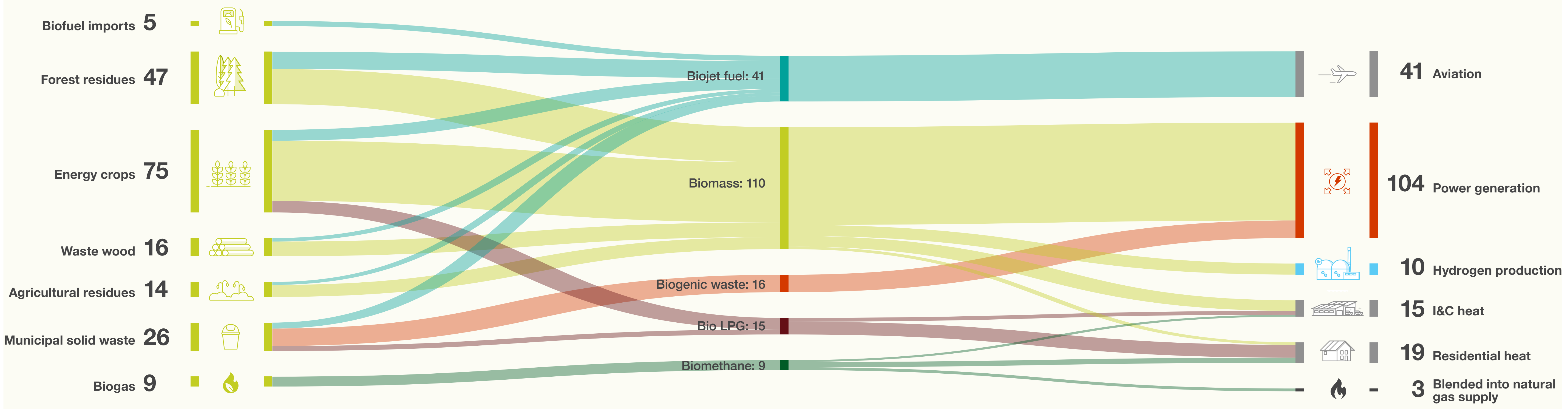
Bioenergy

Figure ES.40: Biomass supply and demand in Holistic Transition



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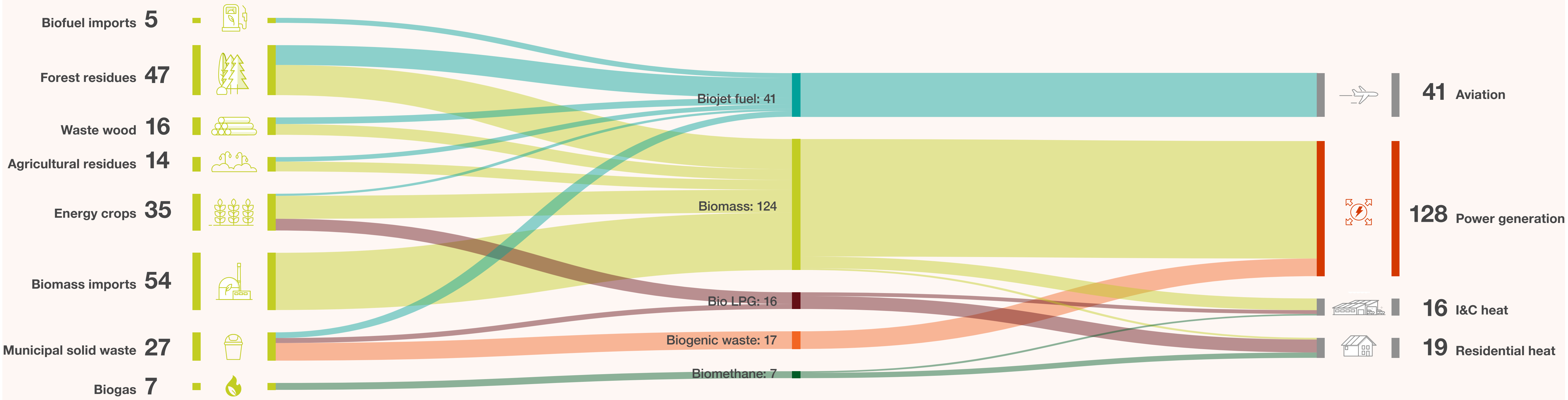
Bioenergy

Figure ES.41: Biomass supply and demand in Electric Engagement



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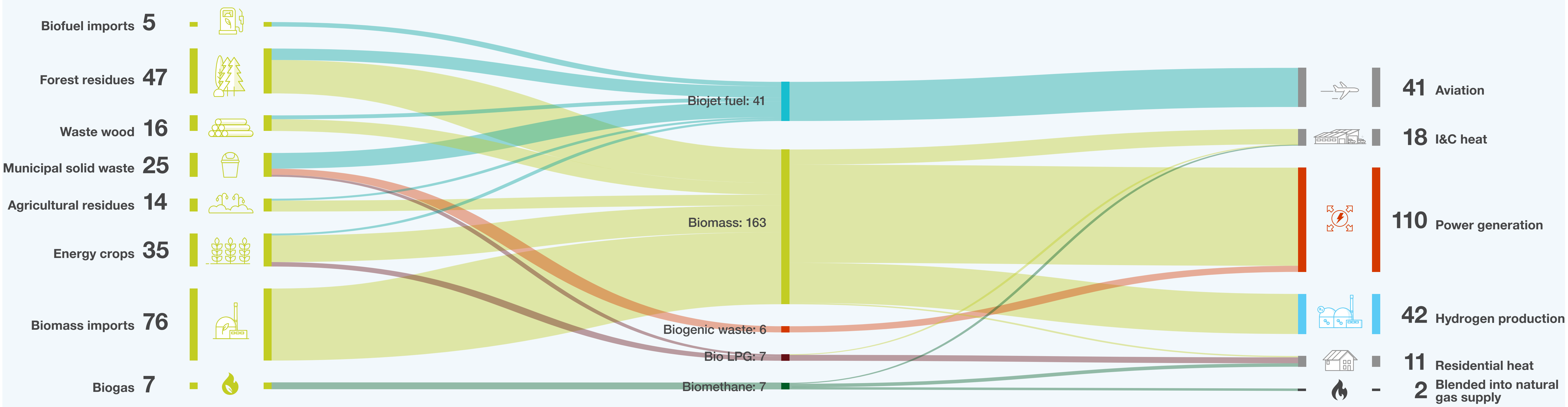
Bioenergy

Figure ES.42: Biomass supply and demand in Hydrogen Evolution



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The route to net zero

As sustainable resources are limited, end uses of bioenergy must be prioritised where they can have the biggest whole system benefit.

The best use of each biomass feedstock and the quantities required for each purpose must be understood. Biomass may also be used elsewhere for decarbonisation (for example, timber in construction or biobased materials). This could have a positive impact on biomass supply for bioenergy (for example, quicker maturation of supply chains or increased waste/residue by-product supply for energy) or could, on the other hand, lead to increased competition for feedstocks. These broader interactions should be investigated.

Clear and robust sustainability criteria are required for biomass feedstocks.

This will provide certainty that biomass is sourced responsibly. In addition, robust emissions accounting standards, consistent across sectors, will ensure investor and public confidence in a negative emissions market made possible through the use of BECCS technologies.

The supply of sustainable domestic biomass resources needs to be scaled up rapidly. Availability of domestic and international feedstocks should be assessed regularly.

A significant expansion of domestic and imported biomass feedstock will be required to meet 2050 feedstock needs. However, no significant perennial energy crop planting has occurred to date in the UK[18]. If we are to align with the CCC's Balanced Pathway, at least 30,000 hectares per year of energy crop need to be planted by 2035. Any scaling up of biomass feedstock supply must be combined with robust and transparent sustainability criteria.

Progressing business models for BECCS will reduce investor uncertainty and could deliver the negative emissions required to meet net zero.

Key Actions 2&3

DESNZ has consulted with stakeholders to develop a power BECCS business model[19]. This should now be developed at pace, given that the UK biomass power sector is well positioned to be one of the first global movers on large-scale power BECCS and that existing subsidy support for biomass power stations is likely to end soon.

Continued innovation and development efforts are required to ensure bioenergy and BECCS technologies are deployable when required.

The future of bioenergy will be heavily focused on BECCS technologies (both power BECCS and hydrogen BECCS), alongside the production of other low carbon fuels for hard-to-decarbonise sectors. These technologies have not yet been deployed commercially at scale and some (notably biomass gasification) have experienced significant challenges during previous commercialisation attempts.

Expansion of domestic biomass feedstock production could provide additional revenue streams and economic benefits for rural communities.

Future large-scale BECCS facilities will require large quantities of feedstock and will need to be located in proximity to CO_2 storage networks. The expansion of domestic biomass feedstock production should be targeted within close proximity of these facilities to minimise transportation costs and the need for high degrees of densification (pelletisation). Action is needed to fully understand where biomass feedstocks should be planted and the potential impacts on farmers, land owners and rural communities.

18 gov.uk/government/statistics/bioenergy-crops-in-england-and-the-uk-2008-2023/bioenergy-crops-in-england-and-the-uk-2008-2023
19 gov.uk/government/consultations/business-model-for-power-bioenergy-with-carbon-capture-and-storage-power-beccs

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Emerging technologies

Our modelling considers fully established or newly developed technologies that can play a role in decarbonising our energy system. However, the scale and pace of innovation in the energy sector is rapidly accelerating, and we continuously monitor emerging technologies that may unlock new potential in Great Britain's journey to net zero.

If you know of a new and innovative technology that could be considered in the modelling of our pathways, please contact fes@nationalgrideso.com.

We've summarised some of the latest technologies currently in development.

Nuclear fusion

A combination of hydrogen gases are heated to extremely high temperatures to form a helium nucleus and a neutron. A tiny fraction of this mass is converted into fusion energy. This reaction releases enormous amounts of energy, which is then captured and converted into useful electricity. Creating the temperature and pressure conditions required to initiate this reaction is a great scientific and technological challenge. Conceptual designs have, to date, been too expensive to compete with other forms of generation. However, the development of enabling technologies has allowed fusion to break new barriers, leading to a wave of programmes in the private and public sectors.

Artificial photosynthesis

Natural photosynthesis is a process in which green plants, algae and certain bacteria convert light energy into chemical energy in the form of glucose. Artificial photosynthesis attempts to mimic this natural process to create an efficient, clean and cost-effective way to convert sunlight into storable energy forms, usually hydrogen or other solar fuels. This is typically performed by developing photo-electrochemical cells that absorb light and split water into hydrogen and oxygen or by using solar energy to drive the reduction of carbon dioxide into carbon-based fuels. The technology to catalyse these reactions at a reasonable cost and with a high level of efficiency is currently still in development.

Space-based solar

Satellites at sufficiently high orbits are illuminated by the sun for more than 99% of the time with a solar flow. Space-based solar power is the concept of collecting this abundant solar power in orbit and beaming it securely to a fixed point on earth. Its main advantage over other forms of renewable energy is its ability to deliver energy day and night throughout the year and in all weathers.

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Emerging technologies

Enhanced geothermal systems

Geothermal energy is energy stored in the form of heat beneath the surface of the solid earth. A naturally occurring geothermal system, or hydrothermal system, requires heat, fluid and permeability to generate electricity. In many areas, however, there may not be enough natural permeability or fluids present. An enhanced geothermal system (EGS) can be used to create a human-made reservoir to tap that heat for energy. Fluid is injected deep underground, causing pre-existing fractures to re-open and creating permeability. Increased permeability allows fluid to circulate, becoming hot as it does so. The hot water is then pumped up to the surface, where it generates electricity. EGS could facilitate geothermal development beyond traditional hydrothermal regions, potentially extending geothermal energy production across Great Britain.

Tandem photovoltaics

Today's silicon-based photovoltaics convert only a small range of longer wavelengths of sunlight into electricity. Perovskite is a lightweight, low-cost semiconductor compound and can be 'tuned' to absorb the shorter wavelengths of light that a silicon solar cell would miss. An ultrathin layer of perovskite on top of a silicon solar cell can convert more sunlight into usable electrical energy than either cell alone. The perovskite layer uses the entire wavelength range of visible light and converts it into electric current. Near-infrared light penetrates the perovskite layer, hits the silicon cell underneath and is converted into electrical energy. By working in tandem, the solar cell duo increases its power-conversion efficiency to more than 30%.

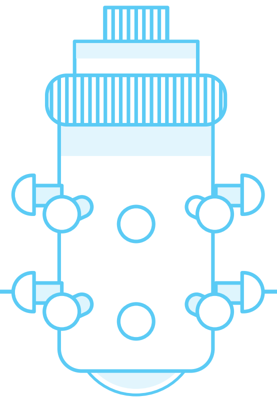
Wave energy

Wave energy converters (WECs) harness the energy contained in the movement of waves. WECs can be deployed on or near the shoreline or at distances of more than 100 metres from the shore. A range of innovative wave device design concepts are in testing globally and a wide variety of different designs could be successful, given the broad spectrum of feasible ways to harness energy from waves.

Advanced fission technologies

Advanced Nuclear Technologies (ANTs) encompass a wide range of nuclear reactor technologies under development. These technologies are smaller than conventional nuclear power station reactors and designed so that much of the plant can be fabricated in a factory environment and transported to site, reducing construction risk and reducing capital cost. Advanced nuclear technologies fall into one of two groups: generation III water-cooled Small Modular Reactors (SMRs), similar to existing nuclear power station reactors but on a smaller scale, and Advanced Modular Reactors (AMRs), the next generation of nuclear reactors (sometimes referred to as Generation IV).

Some designs have the potential to provide high-temperature heat which can be used for a number of applications beyond electricity production, including hydrogen production, district and industrial heating.



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Glossary

Acronym	Description
5YF	Five Year Forecast
ACS	Average Cold Spell
AMR	Advanced Modular Reactor
ASHP	Air Source Heat Pump
AV	Autonomous vehicles
BCF	Billion Cubic Feet
BCM	Billions Cubic Metres
BECCS	Bioenergy with Carbon Capture and Storage
BESS	Battery Energy Storage Systems
BEV	Battery Electric Vehicle
BiCRS	Biomass with Carbon Removal and Storage
BUS	Boiler Upgrade Scheme
CAES	Compressed Air Energy Storage
CB6	Sixth Carbon Budget
CBAM	Carbon Border Adjustment Mechanism
CCC	Climate Change Committee
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CEM	Capacity Expansion Model
CfD	Contract for Difference
CfE	Call for Evidence

Acronym	Description
CH4	Methane
CHMM	Clean Heat Market Mechanism
CHP	Combined Heat and Power
CM	Capacity Market
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CPAs	Construction Planning Assumptions
CSNP	Centralised Strategic Network Plan
DACCS	Direct Air Carbon Capture and Storage
DCC	Data Communications Company
DESNZ	Department of Energy Security and Net Zero
DFES	Distribution Future Energy Scenarios
DFS	Demand Flexibility Service
DNO	Distributed Network Operator
DPA	Dispatchable Power Agreement
DSF	Demand Side Flexibility
DSR	Demand Side Response
EBD	Energy Background Document
ECM	Electricity Capacity Market
EGS	Enhanced Geothermal System

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Glossary

Acronym	Description
EMR	Electricity Market Reform
EPG	Energy Price Guarantee
ESO	Electricity System Operator
ETYS	Electricity Ten Year Statement
EU ETS	EU Emissions Trading Scheme
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FEED	Front End Engineering Design
FES	Future Energy Scenarios
FHS	Future Homes Standard
FID	Final Investment Decision
FIT	Feed-In Tariff
FSO	Future System Operator
GB	Great Britain
GDP	Gross Domestic Product
GGL	Green Gas Levy
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
GW	Gigawatt
GWh	Gigawatt Hour

Acronym	Description
HAR	Hydrogen Allocation Round
HGV	Heavy Goods Vehicle
HND	Holistic Network Design
HPBM	Hydrogen Production Business Model
I&C	Industrial & Commercial
IAS	International Aviation and Shipping
ICE	Internal Combustion Engine
IEA	International Energy Agency
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IT	Information Technology
kWh	Kilowatt Hour
LA	Local Authority
LAES	Liquid Air Energy Storage
LCT	Low Carbon Technology
LDES	Long Duration Energy Storage
LDZ	Local Distribution Zones
LED	Light Emitting Diode
LEVI	Local Electric Vehicle Infrastructure
LNG	Liquefied Natural Gas
LOLE	Loss of Load Expectation

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Acronym	Description
LPG	Liquefied Petroleum Gas
LSOA	Lower Super Output Area
LULUCF	Land Use, Land-Use Change and Forestry
mcm	Million Cubic Metres
MCS	Microgeneration Certification Scheme
MHHS	Market-wide Half-hourly Settlement
MJ	Mega Joule
MPIs	Multi Purpose Interconnectors
$MtCO_2e$	Million Tonnes of CO_2 Equivalent
MW	Megawatt
MWh	Megawatt Hour
N_20	Nitrous Oxide
NDC	Nationally Determined Contributions
NESO	National Energy System Operator
NET	Negative Emissions Technologies
NGET	National Grid Electricity Transmission
NOA	Network Options Assessment
NSTA	North Sea Transition Authority
NTS	National Transmission System
NTV	Near Threshold Voltage
NZHF	Net Zero Hydrogen Funding

Acronym	Description
NZMR	ESO's Net Zero Market Reform
NZS	New Zealand Energy Strategy
OHA	Offshore Hybrid Assets
PHEVs	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydro Storage
Power BECCS	BECCS for Power Generation
PV	Photovoltaic
R&D	Research & Development
RCF	Rapid Charging Fund
REMA	Review of Electricity Market Arrangements
RESP	Regional Energy Strategic Planner
SAF	Sustainable Aviation Fuel
SCOP	Seasonal Coefficient of Performance
SERL	Smart Energy Research Lab
SHET	Scottish Hydro Electricity Transmission
SMR	Small Modular Reactor
SO	System Owners
SoC	State of Charge
SoS	Security of Supply
SPT	Scottish Power Transmission
SSEP	Strategic Spatial Energy Plan

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Glossary

Acronym	Description
SSF	Supply Side Flexibility
TEC	Transmission Entry Capacity
TO	Transmission Owners
TOUT	Time-of-Use Tariff
TWh	Terawatt Hour
UK	United Kingdom of Great Britain and Northern Ireland
UKCS	UK Continental Shelf
UN	United Nations
V2G	Vehicle-to-Grid
WEC	Wave Energy Converter
ZEV	Zero Emission Vehicle

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Continuing the conversation

Thanks for reading, we hope you found Future Energy Scenarios: ESO Pathways to Net Zero insightful and useful

We look forward to continuing the conversation to inform you about our future insights and analysis.

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Get involved in the debate on energy and join our LinkedIn group Future of Energy by National Grid ESO.

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