Government
Office for Science

Net Zero Technology Outlook

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Contents

This is not a statement of government policy

Introduction

The Net Zero Technology Outlook is a futures exercise that sets out a 'best estimate' of the technology mix needed in key emitting sectors to reach net zero by 2050, and identifies the research, development and demonstration (RD&D) needed to get there. The Outlook provides a strategic overview to help orient decision-making across government and the research community in support of the Clean Energy Superpower Mission. The Outlook does not reflect UK government policy or official positions.

To inform our analysis, we conducted over 20 interviews and a peer review exercise involving approximately 45 experts from the research community, as well as policy leads from relevant government departments, during the second half of 2024. We also incorporated relevant material from established scenario modelling, policy documents, industry reports and peer-reviewed literature.

This report covers five major emitting sectors, comprising a total of 18 sub-sectors:

- **Industry:** steel, cement, chemicals, glass and ceramics, and food and drink
- **Transport:** surface transport, maritime and aviation
- **Heat and buildings:** heating and cooling, energy efficiency and building design
- **Agriculture, land use and waste:** agriculture, land use and nature-based solutions, and waste
- **Power:** variable renewables, clean firm power, clean dispatchable power, energy storage and system flexibility, and transmission and distribution

For each sub-sector, we assessed the current technology and market readiness level (TMRL) of technologies that might be part of the mix in 2050.[1] We also assessed the technology certainty level (TCL), which reflects the current confidence that the technology solutions will be part of the final mix. In some sub-sectors, we included 'wildcard' technologies: novel and nascent technologies that are highly uncertain but potentially important. In some cases, the technology may be established in other countries' decarbonisation pathways, but not the UK's.

Technology certainty and readiness for each sector were evaluated using the framework in Table 1. The report also sets out RD&D challenges for three cross-cutting areas: greenhouse gas (GHG) removals and Carbon Capture and Storage (CCS), hydrogen, and biomass.

1 US Department of Energy, Technology-to-market, available at: www.energy.gov/eere/buildings/technology-market

Table 1. Technology certainty and readiness assessment framework

Rating	Low	Medium	High
Technology certainty level (TCL) Confidence that the technology solutions will be part of final mix	Significant optionality in the technology pathway Uncertainty over final technology mix	Some optionality in technology pathway Some uncertainty over final technology mix	Clear technology pathway High consensus over final technology mix
Technology and market readiness level (TMRL) Extent to which these technologies are close to full adoption or scale for the level needed in 2050	Technologies are in the research and development phase TMRL 1 to 4	Technologies are between demonstration to early-stage scale-up TMRL 5 to 9	Technologies have entered the market and are in the deployment phase TMRL 10 to 15 There may still be barriers to market scale-up and technology adoption

RD&D needs for each sector are categorised as follows:

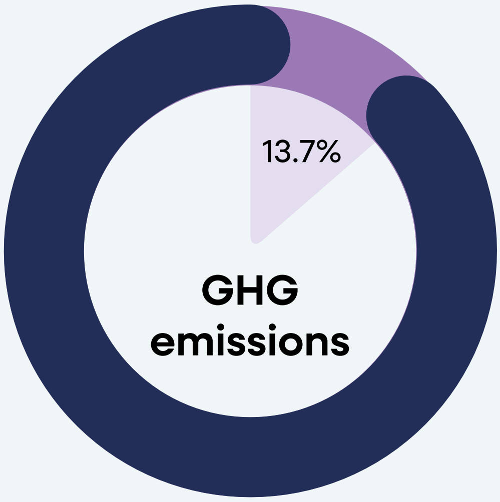
- **RD&D for technology development:** RD&D to develop and innovate earlier-stage technologies to support their scale-up and commercialisation
- **RD&D for decision support:** research and development to support government decisions on technology choice or policy approach as part of the net zero pathway
- **RD&D for delivery:** research and development to support the delivery and implementation of more mature technologies, as well as infrastructure and practices

Emissions data for each sector come from the UK government's 2023 territorial greenhouse gas emissions data. 2050 residual emissions data projections come from the 2021 Net Zero Strategy.

This Outlook is our best estimate of the future, but we recognise that not everything will unfold exactly as expected. Some technologies will progress better than expected, some slower, and some new technologies, challenges and opportunities will emerge.

The report emphasises RD&D measures to support the development of critical technologies for net zero. However, we recognise that other enablers play an important (and in some cases, more important) role in technology development. These include infrastructure, the availability of a skilled workforce, public engagement, supply chains and global market conditions, and policy levers. Broader policy considerations regarding net zero technologies are touched on briefly in the 'non-RD&D enablers' section.

Industry



Sector overview

Foundation industries (steel, cement, chemicals, and glass and ceramics) and the food and drink industry are strategically important to the UK, supporting economic growth and national security.

Sources and drivers of emission levels

- Emissions from fuel combustion for heat and electricity supply
- Industrial process emissions, such as iron ore reduction to make steel and calcium carbonate decomposition to make cement
- Efficient use of resources and energy
- Demand for low-carbon alternative materials

Expected residual emissions in 2050: 3.2-10.2 $MtCO_2e$

Steel

Main solutions

Decarbonise high-temperature heat (over 1,000°C) and process emissions through renewable alternatives to coking coal

- Hydrogen direct reduced iron
- Electrochemical methods of iron production (such as electrowinning and molten oxide electrolysis)

Increase and decarbonise recycled steel production

- Recycle steel in renewably powered electric arc furnaces
- Advanced sorting technologies to improve quality of scrap steel supply

Energy and resource efficiency

- Improving waste heat recovery processes

TCL

Medium/High

TMRL

Medium

Wildcards

- Biochar as coke replacement

Cement

Main solutions

Decarbonise high-temperature heat (over 1,000°C) for clinker production

- Low-carbon fuels: hydrogen, biomass and municipal waste
- Electrification: direct (resistive), indirect (heat pumps) and plasma technologies

Reducing process emissions from cement production

- Carbon Capture, Utilisation and Storage (CCUS)

Low-carbon cement and concrete production

- Low-carbon mixes in concrete production (such as supplementary cementitious materials and silicates, fly ash, blast furnace slag or natural minerals), reducing the clinker-to-binder ratio

Negative emissions potential

- Carbonation (concrete absorption of CO_2 from atmosphere)
- Carbon curing (putting CO_2 into cement which mineralises)
- Adding biochar to concrete

Energy and resource efficiency

- Build design optimisation to reduce concrete and cement demand

Develop concrete alternatives

- Wood
- Alternative composites

TCL

Medium/High

TMRL

Low/Medium

Wildcards

- Advanced modular reactors (AMR) for heat (for processes under 1,000°C)
- Electrochemical cement production (purifies flue gas for higher carbon capture rates)
- Electric arc calciners

Chemicals

Main solutions

Decarbonise medium-temperature (under 1,000°C) heat needed for chemical manufacturing processes

- Electrification
- Biomass or low-carbon hydrogen

Decarbonising chemical pathways that use hydrogen (such as ammonia, methanol and e-fuels)

- Low-carbon hydrogen

Energy and resource efficiency

- Waste heat recovery
- Reaction optimisation
- Better catalysts for improved process efficiency

Defossilise chemical manufacturing (including synthetic fuels) through drop-in replacements that use alternative renewable feedstocks

- Biomass
- Plastic waste
- Captured CO_2

TCL

Medium

TMRL

Medium

Wildcards

- Engineering biology solutions
- Other heat sources: deep geothermal, and AMRs for heat (both for processes over 1,000°C)

Glass and ceramics

Main solutions

Decarbonising high-temperature (over 1,000°C) heat

- Electrification using electric furnaces
- Low-carbon hydrogen, including hybrid melters (such as natural gas, hydrogen and electrodes)
- Biomass and biofuels

Energy and resource efficiency

- Increased use of cullets (recycled glass) via closed-loop glass recycling
- New ceramic product formulations for firing to reduce heat requirements
- Improved automation and process control, efficient drying technologies and heat recovery in product drying stages

Capture process emissions from glass and ceramic manufacturing

- CCUS

TCL

Medium

TMRL

Low/Medium

Food and drink manufacturing

Main solutions

Decarbonising low-temperature (under 500°C) heat – direct and indirect (such as steam, hot water and hot oil)

- Electrification
- Biomass

Energy and resource efficiency

- Improved automation and process control
- Insulation improvements
- Heat recovery and storage
- Sustainable packaging
- Novel heating, pasteurisation and refrigeration technologies

Reduce demand for fossil CO_2 as an input

- Captured CO_2 from other industries and biogenic sources for food and drink products (such as carbonated drinks)

(See the agriculture section for alternative proteins)

TCL

Medium/High

TMRL

Medium/High

Wildcard

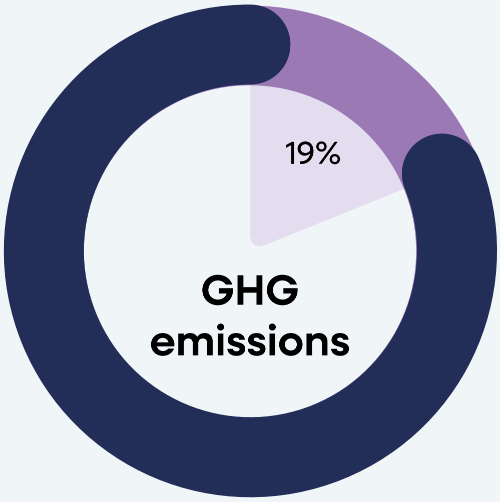
- Other heat sources: deep geothermal

RD&D areas identified

Technology development	• Electrification of high-temperature processes (such as synthetic e-fuel production for chemicals and electric kilns for cement, glass and ceramics) • Hydrogen, biomass, plasma and AMR heat for high-temperature heating across sub-sectors • Advanced separation, sorting and processing of waste (advanced steel scrap sorting technologies) • Lower-emission clinker content, alternative binders and cement formulations • Techniques to optimise and accelerate cement carbonation • Alternative feedstocks for the chemicals industry (such as processing of lignocellulose, chemical recycling and electrocatalysis of CO_2) • New product formulations, material substitution and efficiency measures for glass and ceramics
Decision support	• Demonstrating and comparing feasibility of different high-temperature heating solutions • Emissions accounting to support policy on embodied carbon
Delivery	• UK and global standards, particularly on measuring hydrogen and CO_2 in pipes • Resource efficiency measures, including light-weighting, product redesign and advanced manufacturing • Efficiency measures for food and drink manufacturing

Heat and buildings

Sector overview



The majority of emissions in this sector (67%) come from residential buildings.[2] Most of the UK's current (old and poorly insulated) housing stock will likely remain in 2050. Household demand for space heating may decrease at a national level (assuming improved insulation and energy efficiency of housing stock), while cooling will likely increase towards 2050.

Sources and drivers of emission levels

- Heating (natural gas and other fossil fuel-based technologies)
- Lighting and electric appliances (including battery charging and refrigerants)
- Air conditioning
- Embodied carbon in construction, maintenance and demolition of buildings

For more information on demand side response and flexibility, see 'energy storage and system flexibility' in the power section.

Expected residual emissions in 2050: 0-1.7 $MtCO_2e$

2 For emissions accounting purposes, building emissions relating to embodied carbon and electricity consumption are accounted by industry and power sectors respectively.

Heating and cooling

Main solutions

Low or zero-carbon heating solutions

- Heat pumps for space heating in residential and commercial buildings: mostly air-water, but also ground-water and air-air (the latter offering cooling potential)
- District heating: large heat pumps or exchangers sourcing heat from shallow ground, water (including mine water) and waste heat for densely populated areas and large buildings
- Resistive electric heating technologies and hybrid heat pump systems may play a niche role

Low or zero-carbon cooling solutions (anticipating increased demand)

- Air-to-air heat pumps and energy-efficient air conditioners
- Passive cooling technologies (passive ventilation, shading and heat-reflective materials)
- Refrigerants with low greenhouse-warming potential (gases that maintain cooling efficiency without significantly contributing to global warming): hydrofluoroolefins, CO_2, ammonia and propane

TCL

Medium/High

TMRL

High

Wildcards

- Deep geothermal solutions
- Solid state heat pumps

Energy efficiency and building design

Main solutions

Thermal efficiency and ventilation of building stock

- External and internal insulation materials (such as expanded polystyrene, foam boards, wool, aerogels, phase change materials and vacuum insulated panels)
- Ventilation solutions (such as passive solutions, mechanical ventilation and heat recovery for airtight new builds)
- Building design and materials of new homes (such as passive house design)
- Innovative services for effective retrofit (such as data-driven tools to identify optimal retrofit solutions)
- Smart building management systems (see the power section: energy storage and system flexibility for demand side response technologies)

Reduce embodied carbon from construction and deconstruction

- Low-carbon building materials (such as recycled steel, low-carbon concrete, sustainable timber and engineered wood)
- Optimise building design (such as using fewer materials and extending lifespan)
- Improve construction efficiency (such as prefabrication and modular design)
- Circular deconstruction techniques
- Digital design and construction tools
- Capturing CO_2 in construction materials (see the cement section)

TCL

Medium/High

TMRL

High

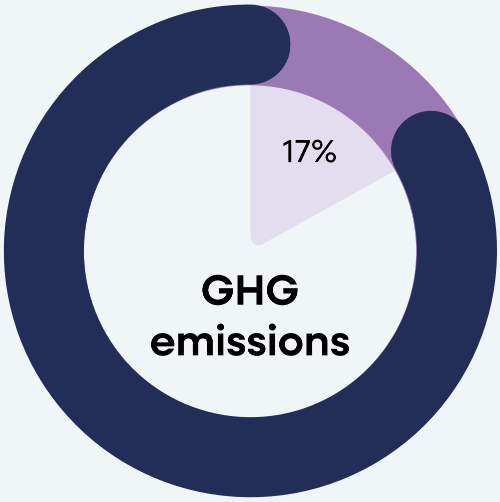
Wildcards

- Recycled and bio-based composite construction materials (such as mycelium)
- Solar windows

RD&D areas identified

Technology development	• Testing and demonstrating emerging low-carbon construction and insulation materials (such as aerogels, phase change materials, vacuum insulated panels and recycled materials like wool)
Decision support	• Understanding drivers of and barriers to technology adoption in buildings: demand side response, heat pumps and insulation • Measuring and assessing embodied carbon across the building lifecycle
Delivery	• Efficiency gains and cost reductions in heat pump manufacturing (such as advanced manufacturing processes and improving component quality) • Heat pump installation improvements (such as integration of hardware and software, and modelling tools) • Reducing role (and risk of leakage) of high-global-warming-potential fluorinated GHG (F-gases) refrigerants in heat pumps and refrigerators • Reducing the cost of retrofit materials and services to make energy upgrades more accessible, especially for older homes • Reducing the cost of heat network infrastructure (such as innovations in heat interface unit and thermal energy storage)

Agriculture, land use and waste



Sector overview

The sector is made up of both GHG emission sources (such as fossil fuel use, degraded peatland, ruminant livestock and fertilisers) and sinks (forestry), but is overall a net emitter. Non-CO_2 emissions form the largest proportion of GHG emissions in this sector (mostly methane, but also nitrous oxide). Technological solutions, alongside system-based and knowledge-based solutions (such as land use change, sustainable farming practices and behaviour change in waste management), will be necessary to reduce emissions in this sector.

Sources and drivers of emission levels

- Methane (CH_4) from livestock (enteric fermentation and slurry) and anaerobic decomposition of organic waste and landfill
- Nitrous oxide (N_2O) from fertiliser breakdown in soil
- Fossil-fuel combustion to power farm machinery and for heating and cooling
- Land use changes affected by competing land use priorities (such as biomass production vs. food vs. nature and nature-based solutions) and economic, social and cultural barriers (such as beliefs and farming traditions) inhibiting emission-reduction potential
- Dietary choices, especially red meat consumption
- Waste management behaviours and processes (such as food waste)

Expected residual emissions in 2050: 27-34 $MtCO_2e$ (also includes F-gas emissions)

Land use and nature-based solutions

Main solutions

Increasing carbon sequestration through nature-based solutions

- Optimal methods for afforestation, peatland restoration and soil carbon capacity
- Data infrastructure and modelling tools for insights into carbon storage capacities, monitoring changes over time, and optimising land use strategies (such as ground-based and remote sensing technologies, and modelling of carbon sequestration potential)
- Lignocellulosic biomass for energy crop production (such as miscanthus and short-rotation coppice) for negative emissions, such as Bioenergy with Carbon Capture and Storage (BECCS) or biochar
- Innovation in business models and policies to establish natural capital markets and bioeconomy

Managing competing demands for land use

- Decision-making optimisation using systems modelling, machine learning and enhanced emissions monitoring
- Improve sustainability and energy efficiency of lignocellulosic crops (such as advanced breeding techniques and genetic improvements)

TCL

Medium/High

TMRL

Medium/High

Wildcards

- Nature-based carbon sequestration solutions (such as enhanced rock weathering, marine carbon solutions including seaweed farming and saltmarshes)
- Other Biomass with Carbon Removal and Storage (BiCRS) solutions (such as bio-oil injection, biomass burying, sinking and slurry fracture injection)
- Engineering biology solutions

Agriculture

Main solutions

Reducing methane emissions from enteric fermentation and slurry

- Methane-suppressing feed additives and vaccines for cattle
- Selective livestock breeding
- Forage crops with improved quality and digestibility
- Adopting low-carbon slurry application and management practices: slurry acidification and nutrient budgeting

Decarbonising farm machinery and operations

- Electrification, and in some cases alternative renewable fuels (such as hydrogen and biomethane)
- Precision agriculture technologies that optimise resource use and have the potential to lower fertiliser application, such as artificial intelligence (AI) for diagnosing and correcting plant, animal and soil health

Cutting nitrous oxide (N_2O) emissions from fertilisers

- Bio-fertilisers (such as fungal and bacterial microbes) and enhanced efficiency fertilisers
- Precision breeding techniques (such as crop genome editing)
- Improved techniques (such as AI and precision agriculture) for soil management, irrigation and fertiliser application
- Practices to protect soil health (see 'sustainable farming practices')

Decarbonise fertiliser production

- Renewable feedstocks for synthetic fertilisers (such as green ammonia – see 'chemicals' in the industry section)
- Switch to bio-based and organic fertilisers

Improved options for lower-carbon diet

- Alternative proteins (plant-based meat, cultivated meat and precision fermentation)

TCL

Medium

TMRL

Medium/High

Sustainable farming practices

- Use of anaerobic digestion (AD) technologies for waste management and biogas production for heat and electricity
- Improve soil health via regenerative agriculture practices (such as crop rotation and reduced tillage) and novel agricultural systems (such as paludiculture, permaculture and vertical farming)
- Low-carbon animal feed (including alternative proteins and waste utilisation)
- Captured biogenic and atmospheric CO_2 used in greenhouses to increase photosynthesis
- Biochar in pig and poultry housing

Wildcards

- Mycelium-based farming
- Electrochemical fertiliser technology
- Methane capture from cattle sheds

Waste

Main solutions

Increase landfill and wastewater emission capture rates

- Advanced AD and methane oxidation technologies (such as biocovers and biowindows)
- Leachate (liquid that drains from a landfill) treatment technologies
- Novel wastewater treatment processes (such as membrane aerated biofilm reactors and alternative ammonia removal processes)
- Energy efficiency improvements of wastewater treatment plants
- Improved data and monitoring infrastructure, enabling better detection and management of emissions

Energy recovery from waste

- Composting facilities and AD plants (organic waste converted into biogas for injection into the grid or combusted for heat and power)
- AD with CCUS to capture biogenic CO_2
- Retrofitting CCUS to energy-from-waste (EfW) incineration plants
- Gasification, pyrolysis and hydrothermal liquefaction technologies for different end uses (electricity, heat, fuel, chemicals and biochar)

To note, this section focuses on 'downstream' solutions to reducing waste emissions, as well as recovering waste once waste is produced. Broader changes will be needed 'upstream' to prevent waste in the first place and increase circularity in the economy. Some of these considerations are reflected in the other sector sections.

TCL

Medium

TMRL

Medium/High

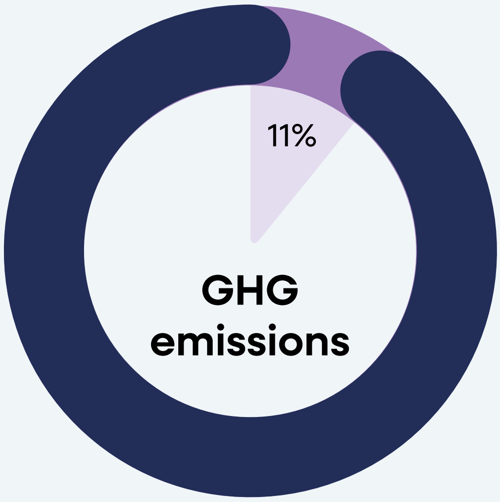
Wildcards

- Advanced thermo-chemical and biological processes (such as plasma gasification and dark fermentation) to convert waste into hydrogen, biofuels and biochar

RD&D areas identified

Technology development	• Low-carbon farming practices, including alternative, low-carbon fertilisers and integrating precision farming techniques • Cost-efficient flexible gasification systems and fully integrated, scaled-up, advanced gasification demonstration plants • Emerging AD and thermo-chemical processes (such as plasma pyrolysis and biohydrogen production)
Decision support	• Assessing behavioural approaches to reduce food waste and developing new approaches to increase lifespan of food products • Assessing impacts of AD technologies on air, water and soil quality • Understanding food choices and drivers of and barriers to alternative protein consumption • Analysis to support monitoring, reporting and verification of carbon sequestration technologies • Understanding drivers of and barriers to technology adoption on farms • Measuring landfill emissions
Delivery	• Improved methods for management and restoration of natural carbon sinks (such as peatland and woodland) • Business model innovation for nature-based solutions • Data and monitoring improvements for wastewater emissions • Improving existing landfill gas capture technology • Scaling EfW CCUS plants (incineration and AD) • Scaling soil additives, including biochar and soil health improvement methods (such as cover cropping and crop rotation)

Power



Sector overview

Emissions originate from combustion of fuel for electricity generation and from the production and supply of fuels. The power sector is central to achieving net zero and the UK government's clean power by 2030 target, supporting decarbonisation and electrification in other sectors. UK demand for electricity is forecast to double by 2050.[3]

Sources and drivers of emission levels

- Combustion of fossil fuels (such as gas) to generate electricity
- Combustion of biomass to generate electricity
- Economy-wide electrification and electricity demand
- Managing supply and demand to optimise use of low-carbon electricity sources and minimise fossil fuel use

Expected residual emissions in 2050: 1.2-3 $MtCO_2e$

Variable renewables

Main solutions

Increased solar and wind capacity:

- Onshore and offshore wind, including floating offshore wind
- Ground-mounted and rooftop solar photovoltaics
- Co-production of renewable power and green hydrogen

Other renewables:

- Tidal stream (has a smaller role, but offers greater predictability than solar and wind)

TCL

High

TMRL

Medium/High

Wildcards

- Novel photovoltaics
- Novel wind turbine designs

3 Climate Change Committee, The Sixth Carbon Budget: Electricity generation, available at: https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Electricity-generation.pdf

Clean firm power

Main solutions

Baseload nuclear capacity

- Gigawatt-size nuclear plants (existing designs)
- Small modular reactors (SMRs)

Sustainably sourced biomass and waste power generation

- BECCS
- EfW combustion with CCS
- Biogas from AD (including with CCS)

Firm renewables

- Pumped or reservoir hydro
- Solar and wind with energy storage

TCL

Medium

TMRL

Medium/High

Wildcards

- Enhanced deep geothermal
- Biomass gasification
- Allam cycle for BECCS
- AMRs
- Space-based solar power

Dispatchable power

Main solutions

- Low-carbon peaking plants
- Natural gas and CCS
- Hydrogen to power (H2P)
- BECCS
- EfW combustion with CCS

Renewables

- Pumped or reservoir hydro

TCL

Medium

TMRL

Medium

Wildcards

- Ammonia-to-power
- Enhanced geothermal
- Biomass gasification

Energy storage and systems flexibility

Main solutions

Short-term storage (seconds to hours)

- Batteries (lithium but also sodium-ion, flow and solid-state batteries)
- Pumped hydro
- Interconnectors for low-carbon electricity imports and exports

Long-term energy storage (hours to weeks)

- Mature solutions: pumped hydro storage
- Emerging solutions: compressed air, liquid air, thermal batteries (for heat storage), iron-air battery and flow batteries

Very long-duration energy storage to balance seasonable variability

- Hydrogen (from electrolysis with renewable or nuclear electricity) stored in salt caverns or other geological formations

Peak-shaving and load-shifting of electricity demand through demand side response solutions

- Energy management systems (analyse and predict consumption patterns, and smart controlling capabilities of cooling, lighting and industrial processes)
- Advanced smart meters
- Vehicle-to-grid
- Energy smart appliances
- Dynamic time-of-use electricity tariffs

TCL

Medium

TMRL

Medium/High

Wildcards

- Virtual power plants
- Enhanced geothermal

Transmission and distribution

Main solutions

Increased transmission efficiency

- High-voltage direct current cables (including for sub-sea cabling) and converter hubs
- Grid-enhancing technologies, such as dynamic line rating, advanced power flow control and reconductoring

Increasing grid flexibility and managing intermittency

- Advanced digital and computing technologies – such as AI, the internet of things (IoT) and digital twinning – to provide real-time grid monitoring, better demand response and predictive maintenance systems
- Grid-forming technologies
- Distributed feeder technologies

Grid resilience

- Microgrids
- Islanded architecture of critical infrastructure

TCL

Medium/High

TMRL

Medium/High

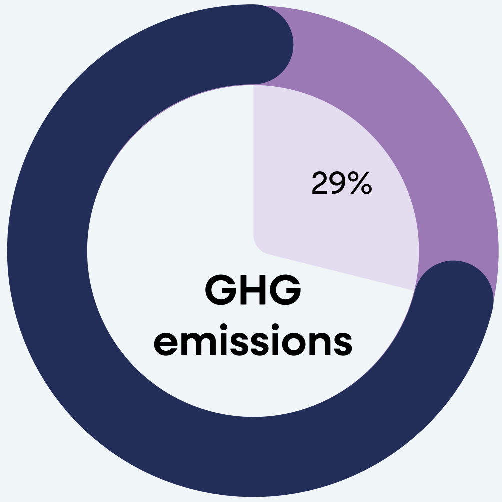
Wildcards

- Second-generation cables (such as use of ultra-high voltage or high-temperature superconducting cables on main transmission lines)
- Wireless power transmission technologies
- Quantum encryption technologies

RD&D areas identified

Area	RD&D areas
Technology development	• Increase sustainability of batteries (such as advancements in cell chemistry, manufacturing techniques and recycling) • Floating offshore wind (designs, mooring lines and dynamic cables) • Advanced nuclear reactors (underpinning design, new fuels and increased flexibility) • Data and digitalisation technologies for the grid (including AI and the IoT to increase optimisation and flexibility) • Advancing earlier-stage and smaller-scale renewables (tidal and geothermal) • Developing next-generation transmission and infrastructure upgrades (such as improved cabling, high-voltage direct current converter hubs and advanced cybersecurity)
Decision support	• Cost-benefit analysis and comparison of well-established and emerging technology • Scenario planning for deployment of long-duration storage
Delivery	• Full-scale, first-of-a-kind for power: CCUS technologies, SMRs, certain forms of geological hydrogen storage, H2P, and offshore wind-generated green hydrogen production • Demonstrating at scale, reducing costs and increasing efficiency of long-duration energy storage solutions and vehicle-to-grid technologies • New processes and materials to reduce costs of renewable energy sources (such as automating turbine production and advanced monitoring) • Increasing sustainability of wind turbine materials (such as life extension solutions, recyclability and decreasing costs of decommissioning) • Mitigating environmental impacts of offshore wind • Reducing the cost of solar technologies, improving efficiency and lifetime • Scale-up of grid-enhancing technologies (such as dynamic line rating, advanced power flow control and reconductoring) • Interoperability between demand side response technologies, the grid and other appliances at a system level and at scale • Standardised and integrated energy management system services for consumers

Transport



Sector overview

Over the past 30 years, domestic transport emissions have decreased by 12%, although emissions have increased from international aviation (84%) and light commercial vehicles (62%).[4] Future transport demand is difficult to predict. Increased, decreased or flat demand scenarios are all plausible.

Sources and drivers of emission levels

- CO_2, N_2O and CH_4 emissions from combustion (all modes)
- Contrails (aviation)
- Congestion (road and air)
- Demand (car ownership, e-commerce, holiday flights and international trade)
- Transport vehicle manufacturing (embedded carbon)

Expected residual emissions in 2050: 26-39 $MtCO_2e$ (mainly in aviation and shipping)

4 Department for Transport (2023), Transport and environment statistics

Main solutions

Surface transport

Main solutions

Heavy goods vehicles (HGVs), buses and coaches

- Battery electrification, with niche use of hydrogen fuel cells possible

Cars, vans and motorcycles

- Advanced battery technologies, supported by fast charging infrastructure
- Electrified micromobility, reducing car miles

Rail

- Overhead electrification, and battery electric (and possibly hydrogen) on thin routes and branch lines

Modal shifts

- Greater use of public transport, car sharing and active travel
- Potential shifts between road, rail and waterborne freight (domestic)

Reduce embodied carbon

- Improved vehicle design and manufacturing using sustainable and recyclable materials and considering the vehicle's end-of-life, such as electric vehicle (EV) battery recycling and reuse

TCL

Medium/High

TMRL

Medium/High

Wildcards

- EV battery swapping
- Electric road systems

Maritime

Main solutions

Long-range shipping fuels

- Ammonia made from green hydrogen
- Methanol made from green hydrogen and CO_2 from CCS or biomass
- Optionality between fuel cell and combustion technologies for ammonia and methanol (fuel cells are more efficient)

Short-range shipping

- Battery electric, hydrogen and ammonia (combustion or fuel cell)

Port operations

- Electrification of operations and for cold ironing (providing the ship power while it is docked at port)
- Automation and digital for multi-modal logistics of seaside and landside operations

TCL

Medium

TMRL

Medium

Wildcards

- Biofuel from algae as a drop-in replacement for bunker fuel

Aviation

Main solutions

Short-haul

- Battery-electric

Long-haul

- First generation sustainable aviation fuels (SAFs) – from waste fats and oils
- Second generation SAFs – from non-food biomass and waste
- Third generation SAFs – from green hydrogen and captured CO_2 (power-to-liquid)
- Hybrid SAFs – combining bio-based and power-to-liquid processes

Airport operations

- Infrastructure for integration of new fuels at airports
- Electrification or SAFs for taxiing, ground support equipment and vehicles

Efficiency gains

- Route optimisation on ground and in airspace
- Energy efficiency and lighter airframes
- Contrail management by optimising flight path by weather and time of day

TCL

Medium

TMRL

Low/Medium

Wildcard

- Hydrogen-fuelled aircraft, but requires extensive engine and airframe redesign

RD&D areas identified

Technology development	• Improvement to energy efficiency in ships • Vessel engine technology that can use low-carbon fuels (such as hydrogen and biofuel) • N_2O reduction technology in maritime (nitrogen oxide emissions are produced from the combustion of fossil fuels and, to a lesser extent, from non-abated emissions from methanol and ammonia fuel) • Improved SAF production, including e-fuels, gasification and waste lipids
Decision support	• Understanding consumer behaviour and choice to support policy decisions to incentivise low-emission travel • Assessing viability of hydrogen-based fuels (including methanol and ammonia) • Safety analysis of new shipping and aviation fuels • Non-CO_2 effects produced by aviation (such as contrails and N_2O emissions)
Delivery	• Demonstration and testing of zero-emission HGVs to support adoption • Lower-cost vehicle charging technology (especially bidirectional EV charging) • Electrification standards, including charging point standards and battery swapping • New infrastructure at ports and airports for ships and aircraft powered by electricity, hydrogen, ammonia and SAF • Increased efficiency of aircraft, airspace and airport operations

Cross-cutting solutions

This section explores three cross-cutting solutions that play a role across the five sectors: hydrogen, biomass, and greenhouse gas removals (GGR) and CCUS. The two tables below set out the role these solutions play in each of the five sectors, as well as RD&D needs for each. These lists are not exhaustive but reflect what has emerged from the Outlook exercise.

Table 1: Cross-cutting technology strands overview

	GGRs & CCUS	Hydrogen	Biomass
Overview	A number of sectors are not expected to be fully decarbonised by 2050 – agriculture, transport (most noticeably aviation and maritime), heavy industry and waste management. Direct air capture and point-source CCUS technologies are therefore necessary in most reasonable decarbonisation pathways to meet net zero.	The primary roles for hydrogen are likely to include: • chemicals, as a feedstock and a reducing agent (especially to make ammonia for fertiliser) • an input into alternative fuels where electrification is difficult (ammonia and methanol for shipping, e-fuels for aviation) • high-temperature heat for industrial processes where electrification is particularly difficult • long-duration energy storage (effectively a source of low-carbon dispatchable energy) Significant reduction of high costs of production, transport, distribution and storage could expand uses.	Biomass covers a wide range of feedstocks from forestry, agriculture and waste. It can be used directly as a fuel, where it can offer negative emission potential if applied with carbon capture technology, or as an input into chemical processes (including for the production of hydrogen). However, potential uses for biomass are likely to exceed available sustainable sources in the UK. Prioritisation will be needed according to the merit order of possible uses and the availability of alternative pathways for the purpose in question (such as power-to-liquid e-fuels vs. biomass-to-liquid biofuels).

	GGRs and CCUS	Hydrogen	Biomass
Industry 	• **Cement, glass and ceramics, and other industries:** point-source CCUS is one option for decarbonising these industries • **Chemicals:** CCUS for blue hydrogen or ammonia production • **Cement:** carbonation and carbon-curing processes can use captured CO_2 • **Food and drink:** captured CO_2 used in place of fossil CO_2 in manufacturing	• **Steel:** hydrogen used in steelmaking by direct reduced iron • **Chemicals:** using green or blue hydrogen for ammonia production • **Steel, chemicals, glass and ceramics, cement:** hydrogen as a high-temperature heat source • **Cross-cutting:** fuel-switching option for off-road mobile machinery alongside battery electrification	• **Industry:** feedstock for industrial heating by direct combustion or use in combined heating and power systems • **Chemicals:** feedstock for bio-based chemicals • **Steel:** biochar used as a partial replacement for coke (wildcard) • **Cement:** biochar added to concrete
Heat and buildings 	• **Building design and energy efficiency:** CO_2 use and storage by embodying CO_2 in construction materials (wood and wood composites, and cement)	• Hydrogen is limited to a very niche role in non-industrial heating	• **Building design and energy efficiency:** sustainable alternative construction materials, insulation, panels and flooring

	GGRs and CCUS	Hydrogen	Biomass
Agriculture, land use and waste 	• **Land use and nature-based solutions:** afforestation, peatland restoration and soil carbon • **Land use and nature-based solutions (wildcards):** marine seawater CO_2 removal, ex-situ and surficial mineralisation (such as enhanced rock weathering) • **Agriculture:** captured CO_2 used in greenhouses, and on-farm methane capture technologies • **Waste:** retrofitting CCUS to EfW incineration plant, and AD with CCS technologies • **See also the biomass section**	• **Agriculture:** potential role as a low-carbon fuel for agricultural machinery	• **Land use and nature-based solutions:** energy crop production for BECCS, biochar application and BiCRS solutions (wildcard) • **Agriculture:** biochar application, biofertilisers, and on-farm EfW solutions. • **Waste:** EfW recovery in different applications

	GGRs and CCUS	Hydrogen	Biomass
Power	• **Firm and dispatchable power:** uses of CCUS include BECCS, and EfW with CCUS • **Dispatchable power:** natural gas-powered plants with retrofit CCUS systems	• **Energy storage, flexibility and dispatchable power:** hydrogen used to generate electricity with gas turbines or fuel cells	• **Firm and dispatchable power:** electricity generation by BECCS, biomass gasification or of biogas (methane) produced by AD (including from landfill)
Transport	• **Maritime and aviation:** captured CO_2 used for production of synthetic fuels (such as methanol or e-fuels)	• **Maritime and aviation:** hydrogen as an input into alternative fuel production (such as methanol, ammonia, e-fuels and SAF) or as a fuel itself • **Surface transport:** hydrogen fuel cells are an option where electrification is not possible (some heavy vehicles or rail routes)	• **Maritime and aviation:** gasification and pyrolysis to produce syngas for fuel production (such as biofuel SAF, hydrogen, methanol and ammonia) • **Surface transport:** bioethanol as a gasoline additive, and other biofuels limited to niche roles in road and rail transport (such as vintage cars) where electrification is not viable

Table 2: RD&D areas of focus

	GGRs and CCUS	Hydrogen	Biomass
Technology development	• **Direct Air Carbon Capture and Storage development:** novel technologies to improve capture performance, modular point-source CCS systems, reduce the energy needed to separate and regenerate CO_2, and integration of large renewable heat sources. • **Testing and demonstration:** continue to develop, test and advance novel GGR technology solutions through demonstration projects and field sites	• **Production:** explore emerging small-scale, low-TMRL production of green or blue hydrogen (biogenic, solid oxides, nuclear and alternative reforming technologies). Researching white (naturally occurring) hydrogen production technologies. • **Storage:** demonstrate alternative, cost-effective, large-scale hydrogen storage solutions that are quicker to deploy and likely to be more widely deployable than salt caverns (such as lined rock caverns).	• **Biomass supply:** RD&D to deliver improved biomass productivity and address environmental and other impacts of aggregating biomass supply chains. • **Emerging conversion technologies:** develop advanced AD and thermo-chemical processes (such as plasma pyrolysis and biohydrogen production), to expand sustainable biomass utilisation options.

	GGRs and CCUS	Hydrogen	Biomass
Decision support	• **Whole-system analysis:** explore the integration of GGR technologies with industrial, energy, land and food systems to understand systemic impact. • **Environmental and societal impact:** assess potential environmental effects and social implications of large-scale GGR deployment, including land use, biodiversity and public acceptance.	• **Whole-system analysis:** to understand interfaces with the broader energy system, utilisation of waste, and RD&D to align hydrogen production and demand, enable supply chain development and improve safe integration into wider energy system. • **Environmental and societal impact:** assess environmental impacts of a hydrogen economy and develop mitigation measures, and ongoing research into consumer attitudes to understand and manage risks. • **Resource prioritisation and viability:** assessing performance and cost-effectiveness of hydrogen-based systems compared to alternative low-carbon technologies.	• **Whole-system analysis:** identify the most cost-effective and GHG-optimal methods of utilising sustainable biomass, including biochar, and the development of BECCS technologies for industrial use. • **Environmental and societal impact:** investigate sustainability concerns related to biomass sourcing, land use and lifecycle emissions, alongside public perceptions. • **Resource prioritisation:** evaluate and prioritise biomass use across sectors (such as bio-based chemical production and low-carbon fertiliser production).

	GGRs and CCUS	Hydrogen	Biomass
Delivery	• **Capture technologies performance:** demonstration of advanced solvents, novel capture methods, and flexible post-carbon capture to match dispatchable power plants. • **Storage:** identify and assess CO_2 storage locations, including geological formations, aquifers and unexplored potential sites. • **Monitoring, reporting and verification:** Develop technology-specific monitoring, reporting and verification frameworks for engineered GGRs, nature-based solutions and CCUS to enable robust carbon accounting and support carbon credit systems. • **Carbon utilisation and lifecycle assessment:** advance the use of captured CO_2 in long-life products, and improve lifecycle assessments to maximise value and reduce costs.	• **Production:** demonstrate large-scale deployment of blue and green hydrogen. Identify cost reduction opportunities (improved electrode design, materials innovation and modularisation), while expanding the scale and efficiency of hydrogen production technologies. • **Transport and storage:** demonstrate low-cost, effective methods of bulk hydrogen transport. Validate end-to-end applications (such as co-location of production, storage and usage) to reduce the need for distribution infrastructure	• **Gasification technologies:** improve the performance and commercial viability of gasification conversion through development of cost-beneficial flexible systems. Advance research to improve efficiency of existing systems, and support innovation to enable a fully integrated, scaled-up, advanced gasification demonstration plant.

Non-RD&D technology enablers

While this report focuses on RD&D needs for the development and scaling of critical technologies to meet net zero, we recognise there are other enablers that also play an important (and in some cases, more important) role than RD&D. These enablers came up during our interview and peer review process and are summarised below.

Cross-cutting enablers

Infrastructure

Efficient planning for infrastructure across the UK will determine the deployment pace and technology mix. For instance, transport will require a widespread network of fast-charging stations for electric vehicles and modified infrastructure for managing new green fuels in aviation and maritime.

Public engagement

Public engagement and awareness are essential for the successful adoption of net zero technologies. When the public is informed, consulted about, and supportive of these technologies, their engagement can drive policy changes, increase adoption rates, and create a favourable environ-ment for innovation.

Policy

RD&D is just one government lever to scale up technologies. Business models, market mechanisms and regulation are essential to de-risk investment and support rapid deployment. Notable examples include the Zero Emission Vehicle Mandate, Future Homes Standard, and Contract for Difference.

Global market forces and supply chain

Technology innovation occurs in a global context, with market forces significantly influencing technology choices and decarbonisation pathways. Countries and regions like the US, China and EU are leaders in certain clean technologies.

The UK needs a stable, imported supply of critical minerals for key net zero technologies, such as for battery technologies.

Skilled workforce

A shortage of trained professionals exists for installing and maintaining energy-efficient and low-carbon technologies. Maintaining relevant sector skills during the low-carbon transition while upskilling workforce to use new technologies at full capacity will be necessary.

Acronym glossary

AD	Anaerobic digestion
AI	Artificial intelligence
AMR	Advanced modular reactor
BECCS	Bioenergy with Carbon Capture and Storage
BiCRS	Biomass with Carbon Removal and Storage
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
EfW	Energy-from-waste
EV	Electric vehicle
GGR	Greenhouse gas removals
GHG	Greenhouse gas
HGV	Heavy goods vehicle
H2P	Hydrogen to power
IoT	Internet of things
$MtCO_2e$	Megatons (or million metric tons) of carbon dioxide equivalent
RD&D	Research, development and demonstration
SAF	Sustainable aviation fuels
SMR	Small modular reactor
TCL	Technology certainty level
TMRL	Technology and market readiness level

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