HM Government

UK Net Zero Research and Innovation Framework

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Contents

Foreword

The UK has made real progress on delivering against our long-term greenhouse gas emissions reduction targets. Between 1990 and 2019, we grew our economy by 78% and cut our emissions by 44%, decarbonising faster than any other G7 country. However, achieving net zero will require profound changes across society and the economy. Greenhouse gases are emitted from every part of the UK economy and sustained, co-ordinated action across government, business, academia and civil society is required to meet our 2050 target. This transition will involve complex interactions between technology, infrastructure, people, data, institutions, policy and the natural environment.

Sir Patrick Vallance

Government Chief Scientific Adviser

As the Government Chief Scientific Adviser and National Technology Advisor, I will lead the newly established Office for Science and Technology Strategy (OSTS) to help the government use science and technology to address the most significant challenges of today and the future, including net zero. Net zero is a whole-system challenge - if tackled in the right way, it could create opportunities for increased prosperity, better social outcomes and a thriving natural world. A systems approach can provide the framework to lead change across both the public and private sectors, and the UK has world-leading capabilities in research and innovation to help inform the approach we might take. This will be supported by the new National Science and Technology Council (NSTC), chaired by the Prime Minister, which will provide direction on the use of science and technology to achieve strategic advantage for the UK.

Research and innovation will be an essential part of the drive to decarbonise. Success will require us to pursue both mature technology implementation and enhancement, together with more rapid pull through of emergent technologies and discovery and invention of new technologies for the longer-term. We can achieve this through a bold, coherent programme of public sector research and innovation investment alongside appropriate policy support, coordinated with industry, to encourage and de-risk technology development and deployment and mobilise private sector investment.

Produced under the guidance of the Government's Net Zero Innovation Board, this Net Zero Research and Innovation Framework represents a first statement of the UK's net zero research and innovation priority areas over the next 5-10 years. It supports delivery of the UK's Net Zero Strategy and carbon budget commitments, drawing on the existing evidence-base and research and innovation work already being undertaken. It identifies the main sectors and their respective challenges for the UK to reach net zero, the key research and innovation needs that should be addressed and the timescales for doing so. Government funded research and innovation, appropriate policy and regulatory support, private sector innovation, investor funding and academic research will all play a key role in delivering these.

This Framework will help to ensure that the UK's public sector net zero research and innovation spending is aligned to agreed UK priorities. It aims to provide a clear signal to the private sector and our academic and research communities about the UK's focus areas as we move towards 2050 and to lay the foundations for a collaborative, whole-systems approach to net zero research and innovation activity. Taken together with the Net Zero Strategy, this provides an initial roadmap for maximising the contribution of innovation towards net zero, understanding the social and economic drivers of change and supporting international science and technology collaboration. It will need to be quickly developed into a detailed plan for delivery against which we can track our progress.

UK Net Zero Research & Innovation Challenges

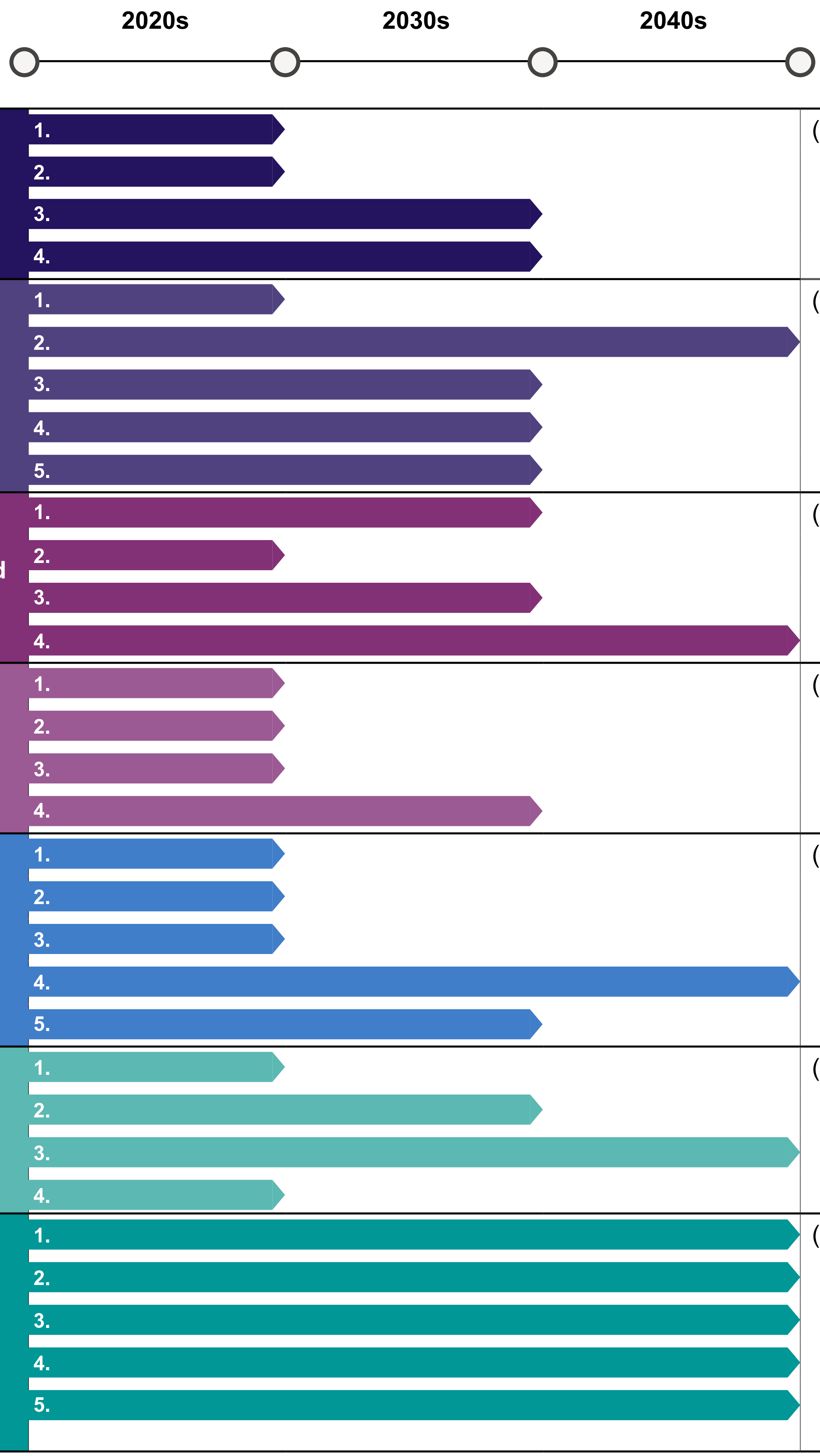
This Net Zero Research and Innovation Framework outlines the research and innovation required to support delivery of the UK's Net Zero Strategy. A wide-ranging portfolio will be needed and this Framework details research and innovation challenges across the Carbon Budget and related sectors[1]:

- Power
- Industry and low-carbon hydrogen supply
- Carbon Capture Utilisation and Storage (CCUS) and Greenhouse Gas Removal (GGR)
- Heat and buildings
- Transport
- Natural resources, waste and F-gases

It also identifies cross-cutting and systems-wide issues and linkages between sectors extending beyond technology to include research and innovation related to systems, processes, business models and the socio-economic and behavioural considerations needed to encourage green choices. Ultimately, both investments to push forward technology development and policy mechanisms to create the conditions to pull innovations to market will be needed to accelerate pathways to net zero.

[1] Chapters have been defined based on the underlying research and innovation challenges. In particular, hydrogen production has been highlighted within the industry chapter and end-uses of hydrogen within their related sector chapter. Similarly, given CCUS's potential impact across the net zero system, it has been highlighted as an area of focus alongside greenhouse gas removal (GGRs) technologies.

Figure 1: Key areas for research and innovation to 2050



Power	(Chapter 4.1, p.34)	1. Improving system integration, flexible demand and energy storage
		2. Continual development of offshore wind (including floating) and earlier stage renewables
		3. Developing nuclear SMRs and AMRs
		4. Utilising bioenergy and BECCS
Industry and low carbon hydrogen supply	(Chapter 4.2, p.50)	1. Improving resource and energy efficiency in industrial applications
		2. Switching to low and zero-carbon fuels and feedstocks
		3. Capturing and storing industrial emissions
		4. Efficient production of low carbon hydrogen at scale
		5. Bulk hydrogen transportation and storage
Carbon Capture Utilisation and Storage (CCUS) and Greenhouse Gas Removals (GGR)	(Chapter 4.3, p.66)	1. Capturing emissions efficiently and at low-cost
		2. Supply chain innovation for CCUS
		3. Developing and improving transportation and storage of CO_2
		4. Developing and demonstrating GGR technologies
Heat and buildings	(Chapter 4.4, p.75)	1. Building retrofit and energy efficiency solutions
		2. Understanding feasibility and safety of hydrogen for heating
		3. Further innovation of heat pumps, including installation and use
		4. Researching and trialling heat networks and non-traditional heat sources
Transport	(Chapter 4.5, p.85)	1. Transport and mobility as a system
		2. Decarbonising roads
		3. Decarbonising railways
		4. Decarbonising aviation
		5. Decarbonising maritime sectors
Natural resources, Waste and F-gases	(Chapter 4.6, p.99)	1. Integrated and dynamic approach to land-use
		2. Sustainably managing forests, peatlands and the marine environment
		3. Sustainable food and biomass production
		4. Reducing and minimising waste and F-gases
Whole systems approach	(Chapter 3, p.26)	1. Understanding optimal net zero pathways
		2. Creating an integrated energy system
		3. Enabling integrated, multi-modal transport systems
		4. Developing digital solutions and unlocking resource and energy efficiency
		5. Researching, understanding, and unlocking sustainable behaviours, business and financial models

In the **Power** sector **(Chapter 4.1)**, renewable energy generation will need to be rapidly deployed with research and innovation driving continual improvements and unlocking new opportunities, such as floating offshore wind, as well as enabling reliable low carbon electricity through nuclear. The wider electricity system must also transform to integrate large-scale and long-term energy storage and maximise the opportunities for matching flexible supply and demand. Innovation is also needed in biomass production, which has potential to aid decarbonisation across several sectors and drive negative emissions through carbon capture and storage.

In the **Industry and low carbon Hydrogen Supply** sectors **(Chapter 4.2)**, continuing innovation to drive resource and energy efficiency alongside proving the feasibility and reducing the cost of low and zero-carbon fuels and feedstocks (e.g. electricity, hydrogen and biomass) will be critical. Residual emissions will need to be captured at source or offset (see chapter 4.3). In addition, hydrogen is expected to be a key energy vector with uses in industry, for heating, for low-carbon fuels and to support flexibility in the energy system. Research and innovation which supports scaling-up the supply and demand for low carbon hydrogen will be required through the 2020s-30s, including developing and demonstrating cost effective production, distribution and storage of low carbon hydrogen at scale.

For **Carbon Capture, Utilisation and Storage (CCUS) and Greenhouse Gas Removals (GGRs) (Chapter 4.3)**, even in ambitious decarbonisation scenarios there are likely to be some residual greenhouse gas (GHG) emissions across the UK in 2050. This means research and innovation is needed to support deployment of industrial-scale CCUS technologies over the 2020s–30s, to develop other greenhouse gas removal solutions such as Direct Air Capture (DAC), for the deployment of CO_2 transport and storage infrastructure, and for using captured CO_2, for example, in the production of synthetic fuels.

In the **Heat and buildings** sector **(Chapter 4.4)**, a key challenge is retrofitting the significant proportion of homes and non-residential buildings that require remedial work to improve efficiency and supply low carbon heat. Innovation in technologies, processes and business models is required to support this as well as research to understand how consumer behaviour affects uptake. Research will also support decisions in the 2020s on the most suitable options for heating our homes, including low carbon hydrogen and heat pumps, as well as the longer term role for heat networks.

In **Transport (Chapter 4.5)**, electrification is expected to be the principal decarbonisation solution for passenger transport. However, other low carbon fuels, particularly low carbon hydrogen, may have an important role to play, for example in heavy goods vehicles, some buses and railways. Research and innovation is also required on refuelling and recharging infrastructure and how to integrate electric vehicles with the wider electricity system. Innovation is critical in aviation and maritime, which are amongst the most difficult to decarbonise sectors. Research is also needed to understand how we can make lives better by changing the journeys people make, bringing behavioural and technological solutions together at scale with an understanding of how we will travel within our communities.

For **Natural resources, waste and F-gases (Chapter 4.6)**, there are multiple demands on land that influence how it is used. Research is needed to understand trade-offs and synergies between food production, forestry and biomass production, habitat and peatland restoration, biodiversity and urban expansion. Research and innovation is needed for methods of sustainably managing forests, peatland and the marine environment to promote carbon sequestration alongside wider environmental benefits; for scaling-up a sustainable bioeconomy, on the resilient supply and demand of agricultural products and promoting sustainable choices; as well as for tackling methane from waste and to develop sustainable alternatives to F-gases.

Underpinning all of this is the need for a **whole systems approach (Chapter 3)**. This includes research to understand the interrelated nature of different sectors and between new technologies, consumer behaviour and business models. Cross-cutting themes and system of systems questions include understanding the optimum use of scarce resources; integration of digital solutions; and the need for broad public support of new technologies as well as the development of viable markets, regulatory arrangements and supply chains.

This Framework supports an **integrated approach to net zero research and innovation planning within Government (Chapter 5)** and aims to provide businesses and the research community with a tool for their own research and innovation agendas. We intend to publish a follow-up detailed Delivery Plan to show which aspects of this Framework government investment is prioritising based on three factors: its impact on decarbonisation, potential economic opportunities for the UK and keeping open credible pathways to net zero.

1. Innovating for net zero

Innovation to enable net zero

In 2019 the UK became the first major economy to legislate to reduce greenhouse gas emissions to net zero by 2050. The Net Zero Strategy sets out the UK's current pathways to net zero and to delivering Carbon Budget 6, which requires greenhouse gas emissions to reduce by 78% from 1990 levels by 2035. Achieving these goals will require strong coordination across the UK, the accelerated development and deployment of green technologies and increased energy and resource efficiency, the creation of new industries and business models, supportive policy and regulatory interventions and encouraging a shift to more sustainable green choices.

Research and innovation including investment in skills, infrastructure, technologies, knowledge generation and sharing, and stakeholder engagement will play an essential role in making this happen. Innovation and related policy support have helped the UK to decarbonise faster than any other major economy over the past two decades. The success of the offshore wind sector in the UK demonstrates what can be achieved through partnership between government and industry and by combining technology innovation with targeted incentives and policies for market deployment. As outlined in the Net Zero Strategy, research and innovation will further enable many of the changes needed to continue cutting emissions whilst maximising jobs, export opportunities and environmental benefits.

However, the scale of transformation is profound. Whatever the ultimate route, net zero will involve some combination of the following:

- Transitioning away from fossil fuels, with continued decarbonisation of our energy system, including electricity supply, heating and transport as well as growth in other low carbon fuels such as hydrogen, alongside large-scale and long-term storage to achieve increased system flexibility;
- Improving energy and resource efficiency across the economy, including moving to a circular economy approach "reduce, reuse, repair, recycle", to reduce increasing demand for energy and carbon-intensive resources whilst delivering wider environmental benefits;
- Greenhouse gas removals at scale, through natural methods (e.g. tree planting) and through engineered technologies (e.g. direct air carbon capture and storage). Carbon Capture and Storage technologies are an urgent and essential component for all realistic pathways to net zero;
- Changes in land use to support carbon sequestration and clean energy, alongside sustainable food production, thriving biodiversity and climate change adaptation;
- Green choices and practices, including supporting people and businesses to use lower carbon products and services wherever possible.

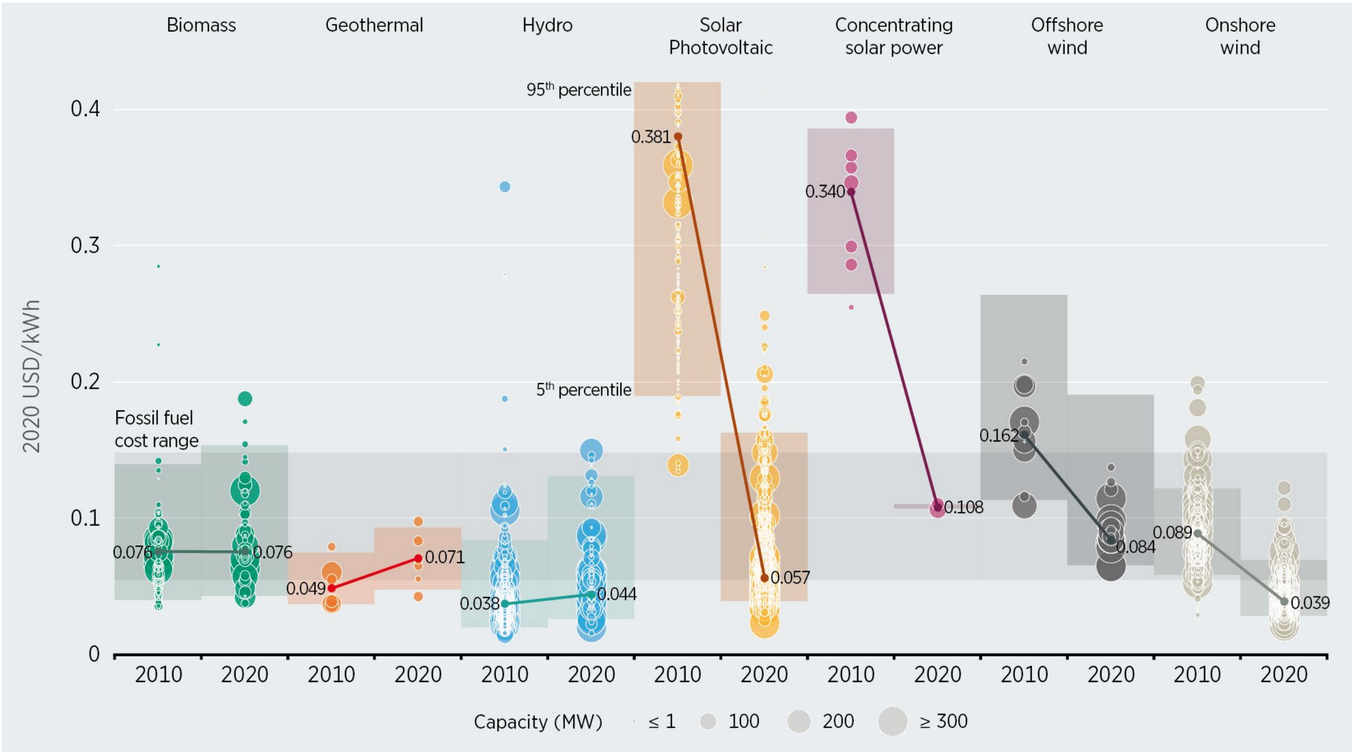
This transition will involve complex interactions between technology, infrastructure, people, data, institutions, policy, and the natural environment. By taking a 'systems approach' Government can help to navigate this complexity. Research and innovation will be needed in the technological, socio-economic and environmental spheres recognising that changes to one area can directly or indirectly impact others. Both investments to push forward technology development and supportive policy mechanisms to create the necessary conditions to pull innovation to market will be needed, engaging with both current providers of products and services and new entrants. It will be important to properly engage with end-users to ensure effective product and service design and to remain alert to any unintended consequences from introducing new technologies.

Benefits of innovation

Research and innovation can significantly reduce the cost of the net zero transition, nurture the development of better products and new business models, and remove barriers to adoption. Innovation has been key to many of the carbon savings seen to date and the cost of renewable energy technologies continues to fall (see examples in Figure 2). However, technologies needed to deliver almost half of the CO_2 reductions required to reach net zero by 2050 are still in prototype phases[2] and will require continued investment in research and innovation to pilot, scale-up and commercialise cost-effective solutions. Estimates suggest that public R&D investment in key technologies could deliver between £54bn and £115bn of cumulative UK energy systems savings from 2019 to 2050[3].

Figure 2: Global Levelised Cost of Electricity (LCOE) from newly commissioned utility-scale renewable power generation technologies, 2010-2020

Source: IRENA (2021) Renewable Power Generation Costs in 2020, International Renewable energy Agency, Abu Dhabi. ISBN 978-92-9260-348-9



Note: This data is for the year of commissioning. The thick lines are the global weighted-average LCOE value derived from the individual plants commissioned in each year. The project-level LCOE is calculated with a real weighted average cost of capital (WACC) of 7.5% for OECD countries and China in 2010, declining to 5% in 2020; and 10% in 2010 for the rest of the world, declining to 7.5% in 2020. The singl band represents the fossil fuel-fired power generation cost range, while the bands for each technology and year represent the 5th and 95th percentile bands for renewable projects.

Working back from 2050, major research and innovation challenges must be tackled **this decade** to keep the UK on track for achieving net zero and to remain globally competitive. Fast tracking carbon reduction requires gaining acceptance for and deploying at scale those technologies that are ready; accelerating the development of those that are not; and researching solutions to problems that do not yet have solutions. Appropriate policy support will help near-to-market innovations drive progress on emissions reductions and attract private sector investment. Investment in discovery research, as well as development and scaling-up of current prototypes, will increase the chances that new technologies not yet ready for commercial deployment, will be available in the future.

The UK has an opportunity to be a leader in certain low carbon technologies, services and systems that will be needed globally, with the Government's plan to Build Back Better focussing on the three pillars of infrastructure, skills and innovation. Innovation across key technology areas could contribute £60 billion in GVA through domestic and export activity annually in 2050[4]. Given the geographical distribution of the required activity, this in turn will help to level-up the country and mitigate the risks to jobs and the economy associated with moving away from current high-carbon sectors and help to build back better after the COVID-19 pandemic.

The global market for low carbon goods and services could be worth up to £1.8tn by 2030[5] and, within that, there is an opportunity for UK export sales of £60bn - £170bn[6], in areas such as electric vehicle manufacturing and supplying components for the wider electrification of transport, green finance, precision agriculture, renewables such as wind and heat pump technologies, sustainable construction and sustainable infrastructure including waste and water. There are other clear areas where, due to the UK's current academic and business strengths, we could secure a leadership position in technologies if we act effectively including: advanced battery technologies, advanced photovoltaics, biomass and bioenergy, CCUS, floating offshore wind, fuel cell technologies, low carbon hydrogen/ammonia, machines and drives, power electronics and advanced nuclear reactor technologies.

International trade and investment are key to the promotion, growth and diffusion of UK green innovation at a global scale and for stimulating targeted inward investment to the UK from overseas. They also help to speed-up technological development, scale-up and dispersion, and drive down costs by enabling access to critical resources and increasing the returns to innovation by allowing access to larger markets. Research and innovation should aim to prioritise the scaling of commercial and exportable propositions for the UK alongside delivering carbon emissions reductions.

Prioritisation framework

Delivering net zero will require a wide-ranging portfolio of research and innovation support across the public sector, private sector and research communities. This Framework identifies the main challenges and key timelines over the next 5-10 years across each Carbon Budget and related sector as well as cross-cutting and systems-wide issues and linkages between sectors. It extends beyond technology to include research and innovation related to systems, processes, business models and the socio-economic considerations needed to encourage green choices. It will set the direction for publicly funded research and innovation towards net zero and aims to signal areas where new ideas, products and services have a potential market, to build confidence and catalyse research and investment from business, researchers and entrepreneurs. This research and innovation activity will start to narrow down options and ensure that we can invest at scale in the areas where this is needed for widespread deployment.

For Government investment, we will prioritise spend based on:

- **Expected contribution to delivering the UK's carbon budgets and major decarbonisation** – accelerating delivery of greenhouse gas emissions reductions by increasing certainty of technologies / solutions, including by taking into account the current state of technologies and the potential for research and innovation to make rapid progress;
- **Building and maximising UK comparative advantage globally** – focussing on areas with the highest potential for UK business and jobs. Developing and commercialising technologies, processes and business models for the energy transition can provide business opportunities and enhance economic competitiveness; and
- **Retaining optionality of different net zero pathways** – investing in a portfolio of solutions, and tolerating some failure, including novel technologies for areas such as greenhouse gas removals.

Both public research and innovation spending to push technology development and market-pull mechanisms such as policy, regulatory and financial frameworks will be needed for success.

We intend to subsequently publish a Delivery Plan which will show how these prioritisation principles have been applied and the current Government programmes prioritised from this framework. Based on current understanding of technologies and solutions, the likely low regrets measures for investment over the next 5-10 years are:

Figure 3: Key low regrets areas for UK investment

Major decarbonisation opportunities
Floating offshore wind
Energy storage at scale and system flexibility - enablers of high renewables system
Hydrogen - enabler of industrial fuel switching, heat and some negative emissions
Carbon capture, utilisation and storage for industry - critical for hard to abate areas
Buildings decarbonisation
Land transport, including zero emission road vehicles, rail, light rail and active travel
Aviation and maritime
Agriculture and food
Nature-based carbon removals, e.g. afforestation, domestic perennial energy crops, short rotation forestry, biochar, etc.

Major business opportunities
Transport - aviation, automotive, maritime
Energy storage at scale
Hydrogen
Nuclear - Small Modular Reactors, Advanced Modular Reactors and advanced fuel cycle, particularly in export
Offshore wind - with floating offshore wind potential new area for export and domestic deployment

Creates optionality in net zero pathways
Energy efficiency
Carbon capture, utilisation and storage - major enabler for industry, hydrogen and bioenegry with carbon capture and storage (BECCS)
Innovation within industrial energy sectors - hard to abate and cannot be substituted by other technologies
Sustainable land-use
Negative emissions technologies including Direct Air Capture

The Framework will need to adapt and change over time given the current uncertainty on pathways to net zero and we will need to continue to invest in research for the longer-term solutions. We have not attempted to plan all the research and innovation needs over the next 30 years. Breakthrough technologies could revolutionise our understanding and approaches in some areas, although the time to develop and deploy new technologies across an economy means that the next decade – and the technologies we have available over that timescale – must not be wasted. Government, as well as business, will need to be agile and able to pivot plans in the future.

2. Funding for research and innovation

Publicly funded R&D

The International Energy Agency (IEA) 'Net Zero by 2050' report recommended that globally, government research and innovation spending needs to be increased and reprioritised. Technology areas, such as bioenergy, CCUS, electrification of buildings, industry and transport, and low carbon hydrogen, receive markedly less funding globally, in comparison to more established low carbon electricity generation and energy reduction and efficiency technologies.

The UK's Innovation Strategy makes clear that the Government continues to be committed to increasing direct public expenditure on research and innovation to a record £22bn per year and a key part of this will be net zero related. UK public funding for clean energy research and innovation has been on an upwards trajectory over the last decade as illustrated in Figure 4. Whilst this puts the UK in the top ten OECD countries in terms of spend, it equates to just over 0.03% of GDP compared to countries such as France, Canada and Japan which are spending close to 0.05%[7] or above. Comparisons of spending levels and relative prioritisation of technologies by different countries can be seen in Figure 5.

Figure 4: UK Government expenditure on energy innovation by technology group (£m)

Source: IEA R, D&D spending database

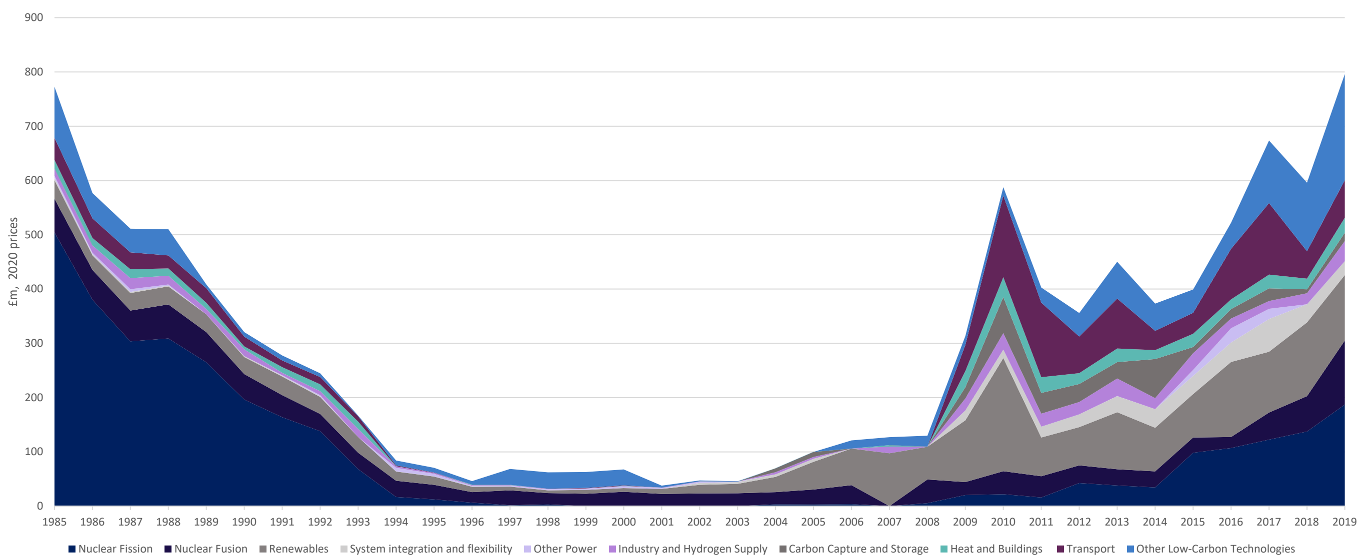
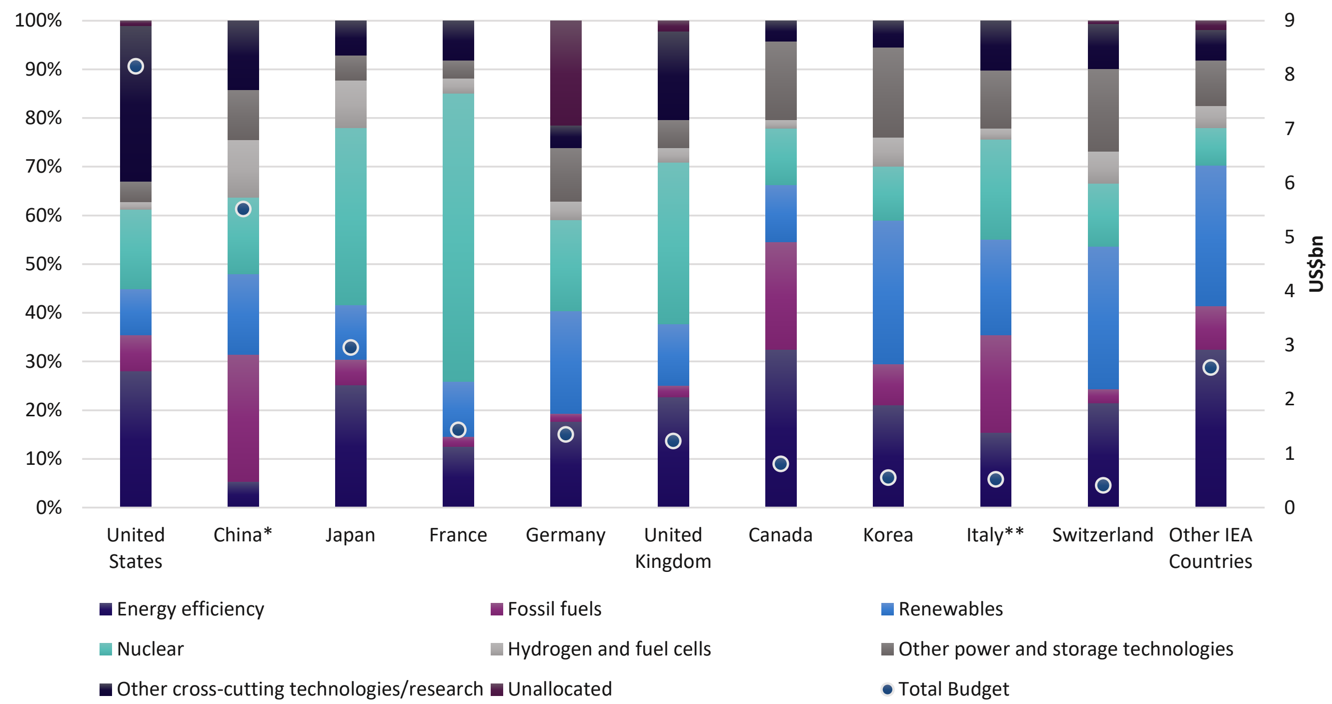


Figure 5: Total energy innovation and % spend by technology

Sources: IEA R,D&D Budget Database - data reflects 2019 R&D budgets, using 2020 prices; Mission Innovation Country Summaries



*China is not an IEA member - data is from Mission Innovation (2019)
**2018 IEA data is used

A greater proportion of funding is now needed for demonstrating and accelerating the commercialisation of technologies. The IEA estimates that technologies needed to deliver almost half of the CO_2 reductions required to reach net zero by 2050 are still in prototype phases[8]. Given the urgency of delivering key new technologies and solutions to market, funding across early-stage discovery research, development of technologies and solutions and demonstration will need to increase. Within this the proportion focussed on demonstration is expected to significantly increase over the next 5-10 years as spend is rebalanced towards scaling-up technologies which will be needed to meet Carbon Budget 6.

Private sector R&D

Publicly funded R&D will not be sufficient on its own to deliver the step change in innovation needed. Private sector investment in research and innovation is essential and will help UK businesses to compete internationally and accelerate UK growth.

The UK has a vibrant ecosystem of innovative start-ups, with more 'unicorns' (start-ups that have grown to be valued $1 billion or more) than any other country in Europe[9] including a number operating in the energy sector. The Innovation Strategy sets out steps to foster this ecosystem including ensuring our research, development and innovation institutions serve the needs of businesses and places across the UK. This means ensuring firms can access the right private finance at the right stage, creating policy and regulatory frameworks which incentivise innovation, supporting businesses to commercialise new ideas, providing targeted public support where there are gaps in private markets and using government procurement as a lever to pull through innovation from idea to market.

Different green technologies and infrastructure will require different types of financial support depending on their maturity (see figures 6 and 7). We must engage all types of capital from early-stage grant and angel investment through to institutional finance like pension fund investors and inward investors from overseas.

Public funds will be used strategically to support new technologies, as well as emerging sectors, as they move from the research and innovation stage through to commercialisation and deployment. Early-stage research and innovation is supported by various government schemes, while later-stages can benefit from funds such as the Clean Growth Fund or support from the British Business Bank (BBB) in addition to other private investment sources.

For larger scale infrastructure finance, the Government launched the UK Infrastructure Bank in June 2021. A combination of capital, government guarantees and private investment will enable more than £40bn of investment in areas most prone to market failure and to help deliver on its dual policy focus to tackle climate change and support regional and local economic growth.

Figure 6: Public Finance interventions across the different stages of commercialisation

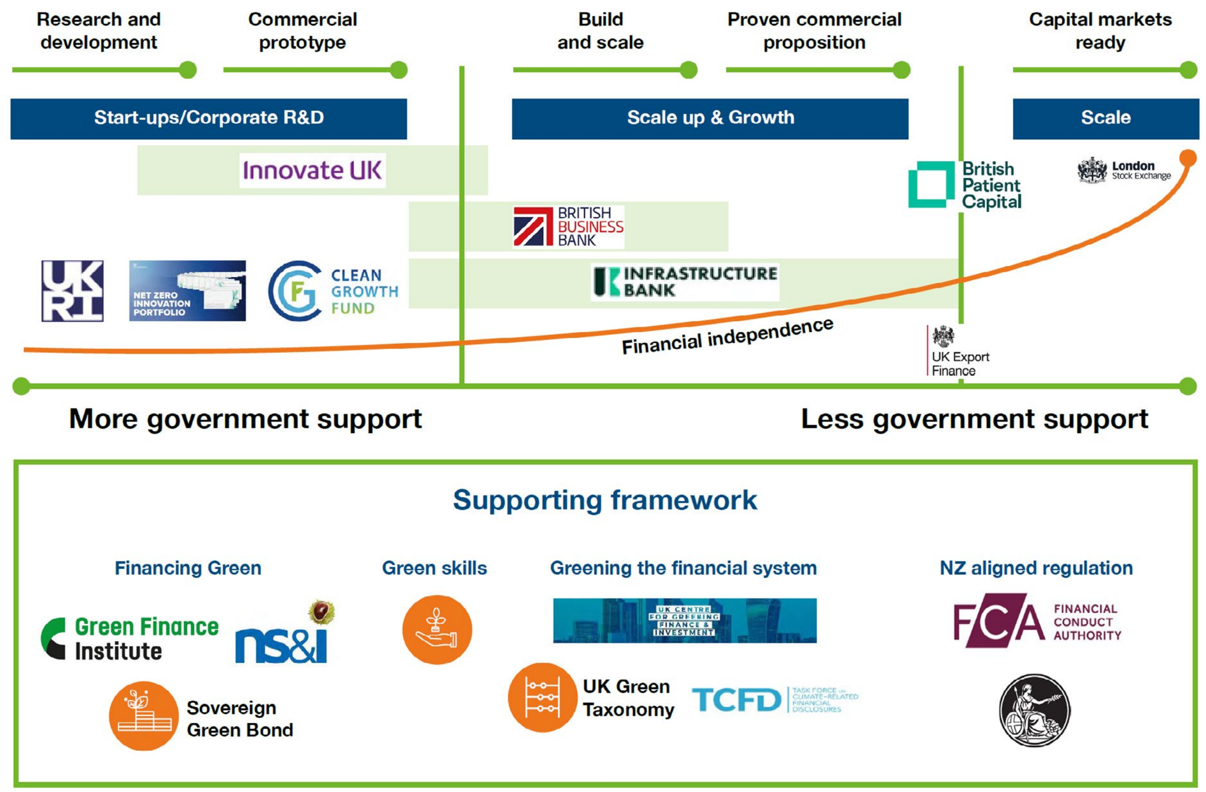
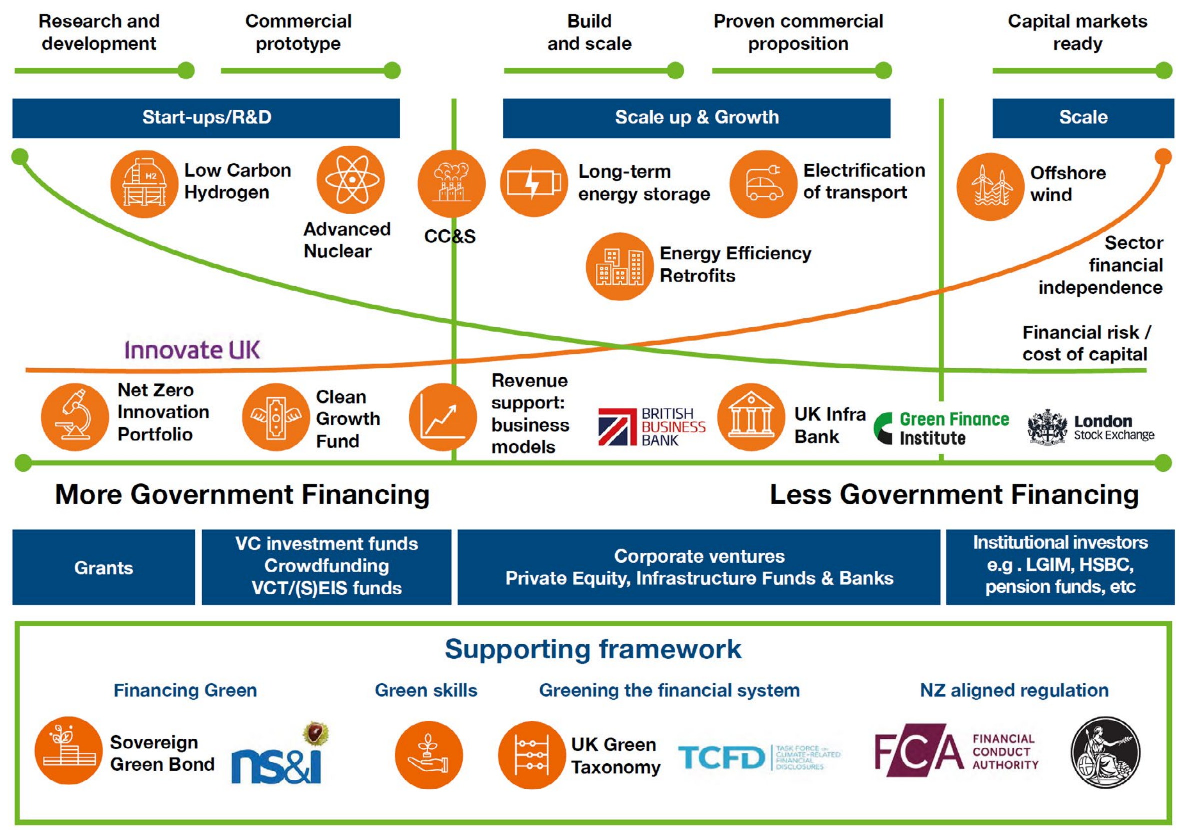


Figure 7: Low carbon sectors commercial maturity and associated capital requirements.



International R&D Collaboration

International co-operation and collaboration, including access to research and innovation infrastructure, the sharing of experience and lessons learned and input to standards setting will also support the UK's ability to meet its net zero target. Different countries have capabilities in different areas of the energy system and technology development and decisions on which areas of research and innovation to prioritise within the UK should consider whether the UK is best placed to "lead, collaborate or access".

Mission Innovation is the primary international forum to strengthen cooperation on clean energy technology development, aiming to deliver a decade of innovation to make clean energy affordable and accessible for all. Combined, its members represent over 90% of global public sector investment in clean energy research and innovation. Now into its second phase, Mission Innovation 2.0 includes new international Missions, public-private innovation alliances aiming to accelerate tipping points in the cost and scale of clean energy solutions. The UK is co-lead for the Clean Hydrogen and Green Powered Future Missions and is a core member of the Zero Emission Shipping Mission. The UK also intends to associate to the Horizon Europe research and innovation funding programme which, along with participation in International Energy Agency Technology Collaboration Programmes, offers significant opportunities for knowledge sharing, network building and involvement in the development of future supply chain and market building.

The majority of emissions growth globally in the coming decades to 2050 is expected to be in developing and emerging economies as they raise standards of living. This is a key reason why the UK is also a major contributor to International Climate Finance, helping countries adopt low carbon pathways to meeting the energy needs of their populations and industries, as well as managing natural resources and adapting transport systems. Innovation plays a key role and the UK's £1bn Ayrton Fund commitment aims to help drive forward the clean energy transition in developing countries by developing, testing and demonstrating innovative technologies and the business models to commercialise them. This will focus on the transformation of the whole energy system and work with developing countries on a series of priority challenges including industrial decarbonisation, sustainable cooling, efficient end-use appliances, modern cooking, smart energy, energy storage, next generation solar, and inclusive energy leaving no-one behind.

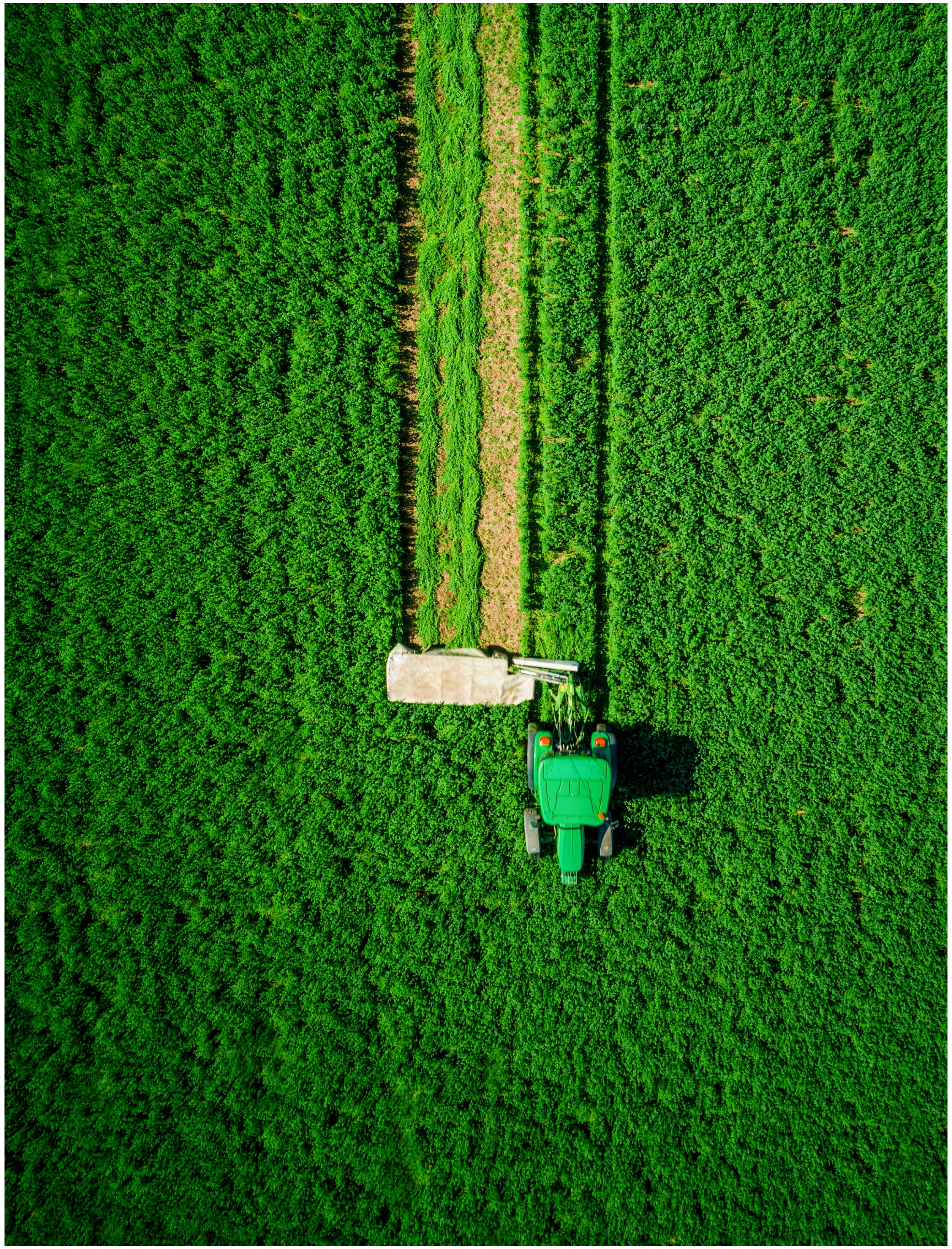
UK action on net zero innovation at home is critical if our 2050 target is to be met, but we also need to support action internationally if we are to pursue efforts to limit global temperature rises to 1.5°C. This Framework will support our on-going role in international initiatives and fora based on a clear outline of UK domestic net zero research and innovation interests, while our wider UK offer internationally also responds to the needs and opportunities of international markets and emerging economies.

3. A whole systems approach

An economy-wide transformation is required to reach net zero and a whole systems approach considers the interrelated nature of different sectors and between new technologies, consumer behaviour and business models. It considers the order in which different actions are required, and their cumulative impacts, and allows decision makers to assess interactions between different parts of the system and how these can combine to affect an outcome. New technologies, products and processes have the potential to influence other environmental outcomes, both positively and negatively. A systems approach can therefore help to identify potential co-benefits or tensions, manage uncertainty, target points of greatest leverage, mitigate unintended consequences, identify highest value and minimum cost pathways, maximise benefits and ensure an agile and dynamic approach to decision-making over time.

This Framework is a step towards implementing a whole systems approach to net zero research and innovation. Each chapter draws out the linkages between decarbonisation challenges and solutions in other sectors of the economy and identifies research and innovation needs that address system level issues. It considers both technological innovation and research into how people will respond to new technologies, services and business models. Research and innovation will also be needed to tackle key cross-cutting themes and system of systems questions. These will be important across many or all sectors and are developed in the table below.

These should be achieved whilst leaving the environment in a better state by improving biodiversity, air quality, water quality and availability, natural capital and resilience to climate change. Innovation to mitigate any wider environmental impacts of decarbonisation policies and proposals and harness any co-benefits from the transition will be important for wider government objectives. Improvements to measuring progress across the whole system will need to be developed. Looking beyond 2050, research into climate repair may become increasingly important, but is not considered further in this Framework which is focussed on activities that must happen now.



Research and innovation: whole-system challenges and needs

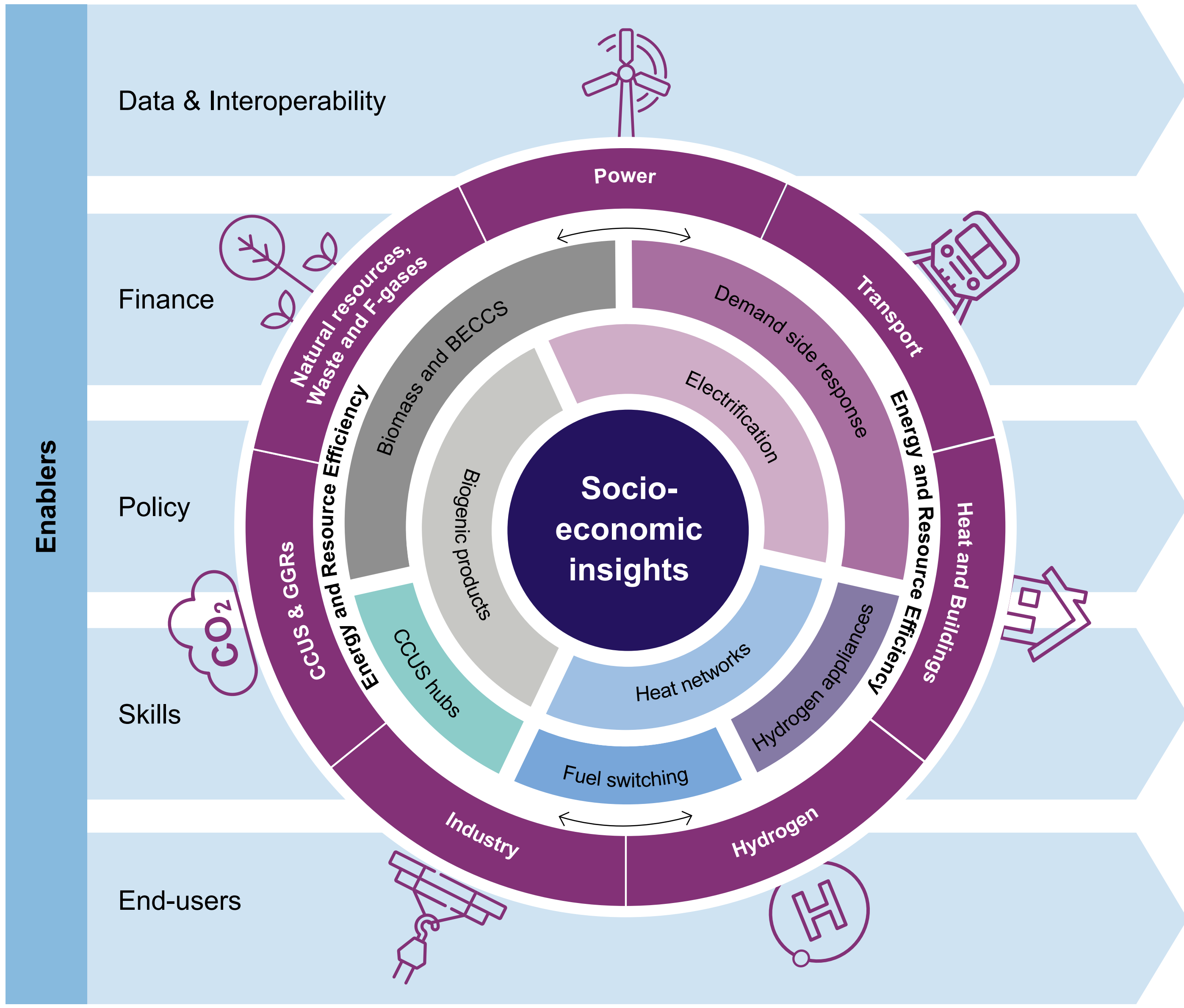
Challenge	Key research and innovation needs
Navigating pathways to achieving net zero	*Whole systems analysis is needed to understand net zero pathways and to address interdependencies and trade-offs across physical, natural, social and digital systems (including via deployment of technology, policies and processes).* • Cross-cutting research and a wide range of analytical tools, systems models and other systems-based approaches to explore the system dynamics and interactions between sectors in the transition to net zero. • Assess the systemic effects of net zero interventions on GHG emissions and other environmental, social and economic outcomes. Develop tools and models to explore the broad, systemic impacts of alternative trajectories to net zero under different future scenarios including scenarios in which embedding resilience can mitigate the risk climate change poses to achieving net zero, e.g. where disruptions to natural systems may reduce GHG sequestration potential[10]. • Modelling to optimise the roles of different energy vectors. • Systems research on the use of land for food production, biomass, and afforestation, among others, including analysis of interdependencies and trade-offs between multiple environmental outcomes and commitments, and economic and social goals. • Feasibility and efficacy of large-scale GGR, including how this may inform decarbonisation pathways across sectors and where best to intervene. • How decarbonisation interventions can deliver wider co-benefits in terms of environment and ecosystem services including air and water quality, noise, and health.
Managing socio-economic and behavioural impacts	*Complex interactions between societal behaviours and new technology / policies need an understanding of system dynamics and how norms and green choices can both impact and be impacted by a net zero transition, and how more sustainable choices can be supported and incentivised.* • Attitudes towards low carbon technologies (e.g. hydrogen, CCUS, and GGRs) and measures to build consumer confidence and acceptance. • Adoption of, and interaction with, smart technologies, including home energy use, electric vehicle charging and mobility services. • Choices on purchasing and consuming more or less carbon-intensive goods e.g. building materials and practices. • How needs and preferences may change over time and in response to incentives, e.g. shifts to more active forms of travel. • Innovation necessary for vulnerable end-users to participate in and benefit from the net zero transition. • Role of advice in empowering end-users and tackling low levels of awareness and acceptance for low carbon interventions, e.g. energy reduction and efficiency.

Challenge	Key research and innovation needs
Developing an enabling environment for net zero through new business models and finance	*To support innovation across the economy, there is a need to develop new types of business models and financial mechanisms alongside clear standards to unlock the value of innovation, manage risk and enable faster uptake of low carbon solutions.* • New business models, standards and market arrangements to facilitate uptake of solutions, e.g. energy as a service and time-of-use tariffs. • Green finance options to support new products and services. • Economic models for new or significantly scaled-up commodities, e.g. hydrogen, CCUS and GGRs.
Taking a place-based approach	*A successful net zero transition will be driven by locally and regionally appropriate solutions that vary across the UK. Cities, towns and neighbourhoods will be the locations where integrated cross-sector net zero solutions are delivered. Research and innovation is needed to support these objectives.* • Living-labs and local testbeds, including public / local engagement and participation in decision making into solutions, taking into account skills, employment, impacts, trade-offs and co-benefits to provide equitable and sustainable solutions. • Design and retrofit buildings and the built environment, including towns and cities, to support more sustainable choices, including low carbon forms of travel. • Optimise solutions at the local level, e.g. hydrogen heating where there is a local supply of low carbon hydrogen, distributed electricity generation / smart local energy systems, opportunities for making climate resilient homes / infrastructure as part net zero retrofits, etc.
Mobilising digital solutions and data and the shift to Industry 4.0	*Digital solutions and technologies, alongside adequate cyber and physical security, can support cross-sector integration, enable systems-level understanding and joined-up action and unlock resource and energy efficiency.* • Digital technologies to reduce energy and resource demand across sectors, e.g. reducing journey length or the need to travel. • Availability and interoperability of data, including through standards and possibly blockchain based platforms, to enable active data flows throughout the energy and transport systems. • Novel digital technologies, such as digital twins, to identify potential issues and inefficiencies and improve the cost effectiveness, efficiency, and flexibility of industry, buildings, and transport. • Identify how and where digital technologies may increase energy demand, and measures to reduce energy requirements.

Challenge	Key research and innovation needs

Developing an integrated energy system	*The transition to net zero is driving fundamental changes to energy supply, demand, transmission, distribution, storage and use; trends that will be compounded by interlinkages between energy vectors and across different sectors of the economy. Research and innovation are needed to manage and integrate net zero energy systems.*
	• Enabling, and preparing for, flexibility across the energy value chain:
	  • Changes and opportunities that arise from a larger capacity, more dynamic electricity system, involving variable renewables alongside large-scale and long-term storage.
	  • Demand side response to increase system efficiencies.
	  • Interoperable smart appliances and flexibility services offering effective energy management / balancing, at building / home, local area and national levels.
	  • Market platforms across vectors to efficiently coordinate flexible and decentralised supply and demand.
	• Identify energy needs across sectors and optimise existing and new infrastructure (including re-purposing where practical) to deliver energy in the most efficient ways:
	  • Energy vectors to promote system-wide efficiency.
	  • Impact of large-scale electrification of transport and buildings on the power system.
	  • Integration of transport and industry into local and national decarbonised energy system planning.
	  • Interactions between transport modes with wider systems and infrastructure.
	  • Optimising cogeneration potential and re-use of waste energy resources, for example using Combined Heat and Power (CHP) technology to minimise waste heat from power generation and other industrial processes.
	  • Research into appropriate economic, finance and business models to support delivery and identification of co-benefits.
	• Demonstrating integrated energy-systems as well as technology-specific demonstrations.

Figure 8: An integrated approach to net zero: Simplified illustration of key system and sector interlinkages for the net zero transition



The following chapters include graphics centred on each sector, which further develop key sector interlinkages.

4. Research and innovation challenges

4.1 Power

Context

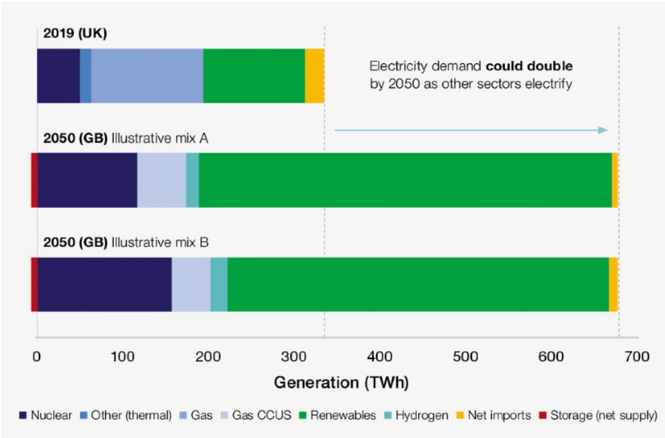
The power sector has led the UK's efforts to reduce greenhouse gas emissions. In 1990, electricity generation accounted for 25% of UK GHG emissions, by 2019 this share had reduced to 13%[11]. In 1990, fossil fuels provided nearly 80% of electricity supply. Today, over half the UK's electricity comes from low carbon sources and the average carbon intensity has fallen by more than 50% from 1998 levels[12].

This rapid decarbonisation will need to accelerate if the UK is to reach net zero by 2050. The Energy White Paper sets out the Government's policies and commitments for achieving net zero in the energy sector with the ambition now updated to have decarbonised the UK electricity system by 2035. This includes 40GW of offshore wind by 2030 (a quadrupling of current capacity that is estimated to support 60,000 jobs), supporting the development of the next generation of nuclear technology, building world-leading digital infrastructure for the energy system, and a commitment to assess market changes that may be required to facilitate and encourage the development and uptake of innovative tariffs and products.[13]

Substantial electrification of surface transport and heat for buildings means that electricity demand is likely to at least double by 2050[14] (see Figure 9). In future, it is likely that the majority of UK electricity generation will come from wind and solar, with the remainder from a mix of nuclear, bioenergy with carbon capture & storage (BECCS), gas with CCS (see sections 4.3), hydrogen (see sections 4.2) and other renewables such as hydro and tidal power.

Figure 9: Electricity mix today and illustrative 2050 electricity mixes

Source: Energy Trends, table 5.1 and 6.1; BEIS analysis

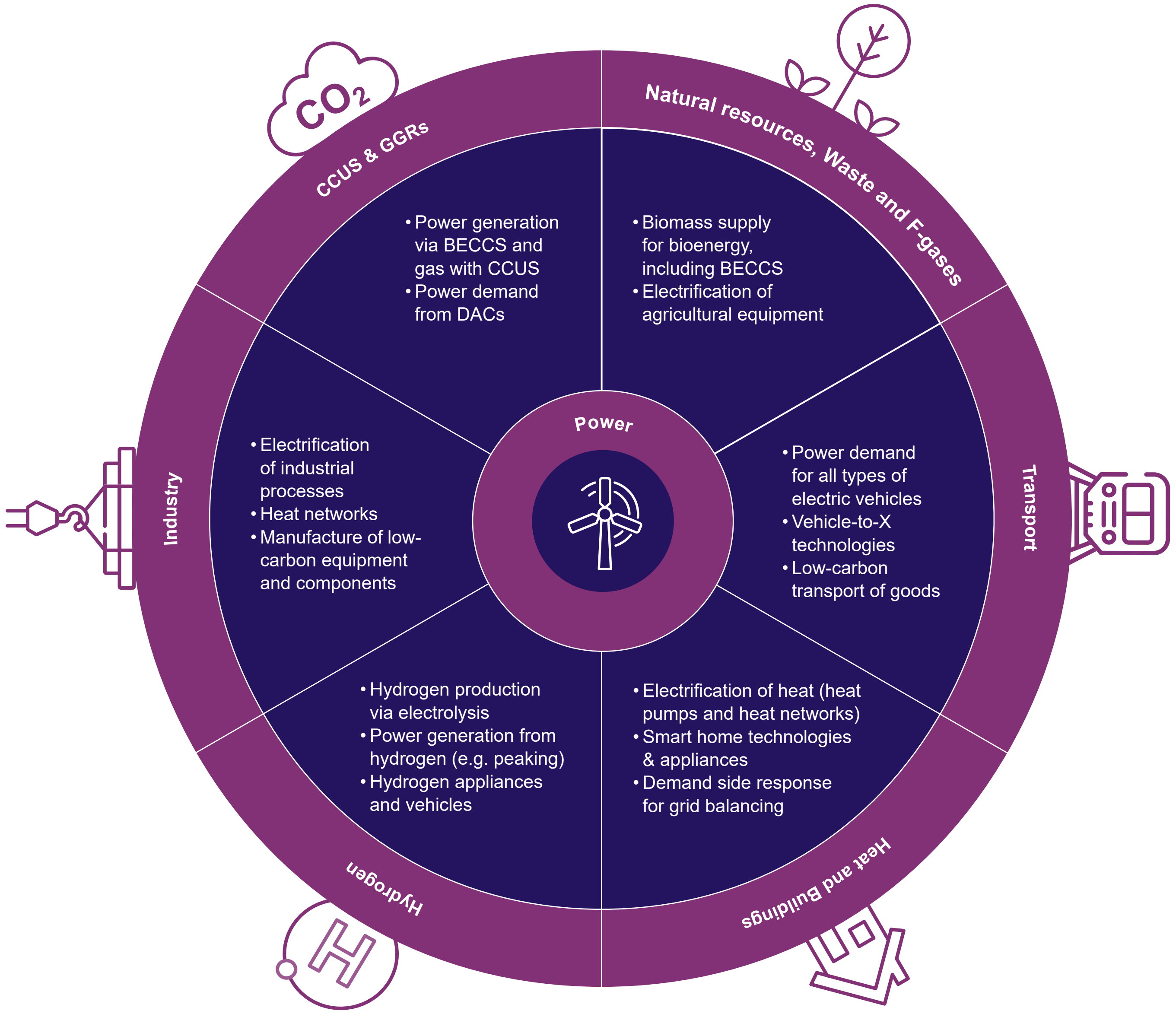


As variable and distributed technologies take up an increasing share of supply, the wider electricity system must undergo a parallel transformation with supporting policy changes and infrastructure improvements. Energy sector and other companies will need to invest in transmission and distribution system innovation (including interconnection), long-duration storage, demand reduction and demand-side response - all whilst keeping costs to end-users as low as possible and maximising energy efficiency.

Research and innovation in the power sector also presents significant opportunities for international collaboration and UK leadership. The UK is co-leading the Green Powered Future Mission[15] which aims to demonstrate cost-efficient integration of up to 100% variable renewable energy and is leading efforts to create standardised data systems and digital platforms that enable interoperability and cross-sectoral flexibility to deliver fully integrated power systems across the world.

Business opportunities for UK companies exist in a number of areas, including developing business models for flexible markets, billing services and engagement models. The UK also has one of the largest markets for offshore wind and is at the leading edge of global development in areas such as new nuclear, smart technologies and tidal. Opportunities exist to continue to develop expertise and reduce costs across these sectors, to supply both domestic and export markets and integrate UK companies into international supply chains.

Figure 10: System interlinkages between Power and other sectors



4.1.1 System integration and flexibility

Research and Innovation: challenges and needs

A flexible energy system is essential for integrating high volumes of low carbon power, heat and transport. The Smart Systems and Flexibility Plan 2021 sets out how Government and industry will transition to a smart, flexible, decarbonised energy system[16]. Technologies such as energy storage, smart charging of electric vehicles, flexible heating systems and interconnection could save up to £10 billion per year by 2050[17] by reducing the amount of generation and network infrastructure needed to decarbonise. To date, power system flexibility has largely been provided by fossil fuels, as we turn up or turn down coal or gas fired power stations. In the future, we need an energy system that matches new sources of demand to renewable generation by using low carbon flexibility across the system underpinned by smart, secure, data-enabled technologies to ensure reliability and interoperability.

Research and innovation can help inform policy and regulation in this context, for example through market arrangements to align price signals with the actual cost of generation at a given point in time, which will help to unlock the potential of flexible technologies. New business models and smart technologies, informed by behavioural research, will give end-users the opportunity to match consumption patterns to times of cheap low carbon electricity and gain greater control over their energy usage. Customer-focussed innovation across the supply chain, including industrial energy users as well as domestic consumers, will be key to this transformation.

Demonstrating flexibility at scale in the domestic market and effectively leveraging strengths in information technology, artificial intelligence, financial settlement, aggregation, and advisory services can help to strengthen UK leadership in system integration and flexibility.

Challenge	Key research and innovation needs
Accelerating the transition to an interoperable, digitalised, cyber-secure system	Develop solutions to increase grid operators' visibility and awareness of energy assets (such as electric vehicles (EVs), EV charge points and heat pumps) - leading to faster, more complete, more accurate registration data available to energy networks. Increase in availability and interoperability of data, including through standards to enable active data flows throughout the system, building on existing infrastructure including smart metering capability, while providing adequate data privacy and security. Improve interoperability and cyber security of smart appliances and flexibility services for end-users, including through standards to enable technology types to interact and operate with service providers.
Understanding, enabling and demonstrating flexible demand	Develop information and communication technology platforms capable of coordinating Demand Side Response across distributed assets, including through standards for interoperability. Demonstrate the flexible operation of various smart technologies in buildings of all scales. Develop intelligent and/or autonomous devices and approaches for end-users to deliver flexibility. Facilitate and encourage consumer uptake of flexibility services, including: • Developing compelling and effective solutions (including products, services, and business models) for a diverse range of end-users including vulnerable end-users. • Developing and enabling energy suppliers to develop products and services which use intelligence and automation to improve and simplify the consumer experience of engaging with flexibility services. • Improve understanding of consumer behaviour and willingness to shift electricity use (including EV charging, vehicle to grid and smart appliance use) in response to dynamic time-of-use tariffs, price signals and other incentives through the use of smart technologies, such as smart meters. • Investigate the impact of exported energy-based tariff adjustments, incentivising behaviour that facilitates system optimisation.

Challenge	Key research and innovation needs
Enabling, developing and demonstrating energy storage particularly at large scales	Improve energy storage performance and cost, including: • Stationary battery technology where improvements will not be driven by EV uptake, with particular focus on battery management and manufacture. • Immature bulk storage options (e.g. sodium ion battery technologies). • Develop Vehicle-to-X energy technologies. • Research, development and demonstration of novel energy storage solutions for a range of durations and at appropriate storage and power capacity. This could include large-scale hydrogen storage, hydrogen fuel cells, gravitational solutions, compressed air storage, flywheels and other mechanical storage systems, supercapacitors, thermal and chemical options (including molten salts, green ammonia, etc.). • Develop strategies for integrating various types of storage into the grid, including understanding whether storage is best at the edge or centre of networks.
Developing and demonstrating flexible platforms for smarter markets	Develop market platforms to efficiently coordinate flexible and decentralised supply and demand i.e., enabling multiple buyers (suppliers, networks, system operators) and multiple sellers (end-users, aggregators, local communities) to participate across markets, driving an optimised energy system, innovation, competition and maximising consumer participation. Demonstrate platforms at multiple levels of aggregation including improved interaction between transmission and distribution system operators and linking to other energy vectors as well as secondary trading of flexibility.
Prepare networks for the energy system transformation and integration	Understand and develop collaborative solutions to manage the changes that arise from a larger capacity, more dynamic system with high penetration of variable renewable energy, including: • Solutions that manage network or system peaks and allow better utilisation from a variety of assets such as grid-connected low carbon technologies and in-home flexible use of heating and EV smart charging. • Lower-cost innovative options for increasing the capacity of the low voltage distribution network to meet increased electricity demand, this includes low voltage smart load management and control systems as well as demand side options. • Whole systems integration for future energy provisions around heat, power and transport and improve coordination between networks and other system participants and ancillary services across local, national and international scales.

4.1.2 Renewables

Research and Innovation: challenges and needs

Renewable generation will need to be rapidly deployed to reach net zero. The offshore wind industry has developed quickly in the last decade. Large-scale deployment, supported through the government's Contracts for Difference (CfD) scheme, has driven innovation across the supply chain. For this trajectory to continue and expand globally, innovation must enable turbines to be deployed in deeper waters and floating offshore wind is likely to be key to unlocking these locations. Innovations in fixed bottom offshore wind will also be important including in wind turbine foundation design, as well those that decrease the costs of foundation manufacture and installations.

Other renewables, such as solar photovoltaics (PV) at domestic and community scales, are expected to make contributions to our energy mix. UK companies could be at the forefront of technological advancements that will drive up panel efficiencies and integrate with other products and services. This research and innovation will be delivered predominantly through private sector investment, although support for next generation solar photovoltaics at earlier technology readiness levels (TRLs) will be needed. Research and innovation can also help unlock new opportunities in other early stage TRL technologies, such as tidal and wave generation.

Challenge	Key research and innovation needs
Accelerating the deployment of offshore wind capacity	Contribute to global development of next generation turbines by focussing on key areas of potential UK competitive advantage including gearboxes, drive trains, generators, new materials and foundation design. Further innovation to: • Improve grid integration to smooth the variability of wind energy and decrease the costs of transmission, including long distance AC transmission, high voltage DC transmission, novel methods of power transmission, and advanced wind modelling. • Reduce costs via larger turbines, robotics and artificial intelligence. • Improve cable burial and repair, logistics, installation, and smart and remote operations and maintenance. • Improve power conversion technologies for offshore grid networks.

Challenge	Key research and innovation needs
Unlocking deep water offshore wind sites deeper than 50 meters	Research and innovation to improve floating offshore wind technology including: • Foundations. • Dynamic cable design / modelling. • Novel installation and mooring systems and logistics. • Offshore operations. Further improve fixed bottom offshore wind to decrease the costs of foundation manufacture and installation.
Mitigating the wider impacts from wind turbine installation and operation (both fixed and floating)	Maintain the effective surveillance of airspace by developing technologies that will allow co-existence of radar and offshore wind farms. Develop technological solutions for mitigation and compensation for cumulative environmental effects, including underwater noise effects on marine mammals, the effects of cabling on benthic habitats, the effects of bird collision and displacement and end of life recycling of structures.
Developing and demonstrating earlier-stage renewables including next generation PV, tidal and other lower TRL technologies	Develop and demonstrate that solar technologies can operate reliably, at scale, and at competitive cost through research and innovation in the following areas: • Next-generation solar PV including new or modified cell chemistries; inverters with increased efficiency and lifetimes. • Building Integrated PV (BIPV) working with construction sector. Research and innovation for more speculative solar technologies and conversion processes. Demonstrate the potential for tidal and wave technologies to operate reliably, at scale, and at competitive cost through research and innovation in the following areas: • Turbine blades, including material innovation (such as concrete and polymers) and novel structure design. • Power take-off and control technologies, foundations, moorings, operations and maintenance. • Understanding wave and tidal energy resource through resource modelling innovation. Research and innovation for more speculative renewable technologies and conversion processes.

4.1.3 Nuclear

Research and Innovation: challenges and needs

Nuclear fission technologies can deliver reliable low carbon electricity to compensate for the variable output of renewables. Most technology development is centred around two broad technology categories - Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs). Innovation is also required in the way that nuclear technologies convert their energy into usable applications of reliable low carbon electricity, low carbon hydrogen, and heat.

SMRs are usually based on proven water-cooled reactors similar to current nuclear power station reactors, but on a smaller scale. Components can be manufactured in factories using innovative techniques and then transported to site to be assembled. AMRs are next generation reactors which use novel cooling systems or fuels and may offer new functionalities (such as high temperature heat that could be used to decarbonise industrial processes). These reactors could operate at over 800°C and unlock efficient production of low carbon hydrogen and synthetic fuels.

There is a related policy need to assure investors and developers that nuclear technologies and developments are investable and that credible routes to market will exist.

Challenge	Key research and innovation needs
Develop Small Modular Reactors (SMRs)	Develop first of a kind SMR by the 2030s. Deliver and demonstrate innovative engineering design, materials, manufacturing and deployment methods to reduce costs and risk to SMRs supporting decarbonisation in all technical and economically viable ways.
Develop and demonstrate Advanced Modular Reactors (AMRs)	Demonstrate AMR technology in the UK by early 2030s. Identify optimum operating temperature to maximise the value of AMRs in a decarbonised energy system. Deliver AMR design and supporting research and development needs including materials, modelling and simulation validation, modular and factory build, and advanced joining and construction. Develop and deliver AMR fuel by developing the design, demonstrating its performance and proving the fuel cycle.
Integrate advanced nuclear with other technologies to support a flexible energy system	Demonstrate the system integration of nuclear to support a flexible energy system, including understanding and demonstrating: • Electricity supply either through directly varying electrical output (potentially alongside cogeneration by diverting energy output to other activities) or via energy storage in the form of hydrogen and heat storage systems. • Process heat to decarbonise industry. • Feasibility of heat use for direct air capture of carbon dioxide. • Nuclear potential for district heating.
Driving continual improvement in large-scale nuclear	Demonstrate the role of Accident Tolerant Fuel to enhance safety margins of existing technology. Innovation in project delivery models to reduce risk and cost of new deployment. Demonstrate ability of large scale nuclear to support flexible electricity, hydrogen and heat provision, complementing other energy technologies and supporting wider integrated energy system decarbonisation. Demonstrate the cost reduction potential through repeatability of design and application of digital and advanced manufacturing and modular approaches.
Research and development in nuclear fusion with a view to options beyond 2050	Design and build a prototype fusion power demonstrator in the UK by the 2040s to demonstrate the commercial viability of fusion.
Improving processes for decommissioning and waste	Research and development aligned to possible future fuel cycle scenarios.

4.1.4 Bioenergy and BECCS

Research and Innovation: challenges and needs

Sustainable biomass has a range of applications as a substitute for fossil-fuel based products and activities. Coupling bioenergy with CCS to deliver negative emissions (BECCS) also makes biomass an option for reaching net zero emissions. Biomass already plays a prominent role in the UK energy mix. The conversion of biomass and other organic wastes and residues into fuels met around 10.5% of primary energy demand in 2020[18]. The versatility of biomass means that it has the potential to provide decarbonisation options in most sectors of the economy including hydrogen production, industry, renewable transport fuels for aviation and surface transport (addressed in respective chapters) and power generation with CCS.

The UK will need significant amounts of bioenergy to achieve net zero[19]. The sustainable sourcing of biomass feedstocks from forestry, agriculture and waste is critical and raises economic, environmental, social, and land-use challenges, all of which require research if the UK is to increase the use of imported or domestic and home-grown biomass (see also section 4.6.3).

Challenge	Key research and innovation needs
Whole systems approach to bioenergy	Identify the most cost effective and GHG-optimal methods of utilising sustainable biomass to meet net zero, taking into account technical limitations for different biomass feedstocks, where the energy vectors will be needed, where the biomass materials will be sourced, and compare with counterfactual production routes.
Creating and securing a sustainable and reliable supply of quality biomass *Note that biomass production is covered in section 4.6.3*	Address environmental and other impacts (e.g. GHG, air quality, biodiversity, water use) of aggregating and scaling up sustainable biomass supply chains, for both imported and domestic biomass. Improvements in biomass productivity, through breeding, planting, cultivating, harvesting and pre-processing.
Improving the performance and commercial viability of gasification conversion technologies	Research into flexible gasification systems that can handle various feedstocks and understand the potential domestic biomass resource that is suitable for gasification. Research into flexible gasification systems that can efficiently produce various end products (e.g. sustainable aviation fuel, hydrogen, biomethane). Improve syngas treatment / clean-up technologies to improve gasification plant availability at various scales. Support innovation to enable a fully integrated, scaled-up advanced gasification demonstration plant. Enable full integration of advanced gasification flowsheet through a first of a kind plant. This is to demonstrate performance and provide investor assurance for commercialisation.
Exploring routes to deploy BECCS *(See also sections 4.2.1, 4.3 and 4.6.3)*	Research into suitable sustainable feedstocks and pre-processing technologies that deliver the greatest decarbonisation and negative emission potential in different end uses (e.g. power, transport, industry, etc). Research to assess the environmental and public health consequences of these approaches, such as for air quality, and mitigation options to address these.

Figure 11: Power research and innovation needs timeline

System integration and flexibility

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Accelerating the transition to an interoperable, digitalised, cyber-secure system	Develop solutions to increase grid operators' visibility and awareness of energy assets (such as EVs, EV chargepoints and heat pumps)			
	Increase availability and interoperability of data, including through standards to enable active data flows throughout the system			
	Improve interoperability and cyber security of smart appliances and flexibility services for end-users, including through standards			
Understanding, enabling and demonstrating flexible demand	Develop information and communication technology platforms capable of coordinating DSR across distributed assets			
	Demonstrate the flexible operation of various smart technologies in buildings of all scales			
	Develop sophisticated, intelligent and / or autonomous devices and approaches for end-users to deliver flexibility			
	Develop compelling and effective solutions (products, services, business models) for a diverse range of end-users, including low income / vulnerable end-users			
	Develop and enable energy suppliers to develop products and services which use intelligence and automation to improve and simplify the consumer experience			
	Improve understanding of consumer behaviour and willingness to shift electricity use in response to time-of-use tariffs, price signals or other incentives through the use of smart technologies			
	Investigate the impact of exported energy-based tariff adjustments, incentivising behaviour that facilitates system optimisation			
Enabling, developing and demonstrating energy storage, particularly at large-scale	Improve energy storage performance and cost, including for stationary battery technology, with particular focus on battery management and manufacture			
	Improve energy storage performance and cost for immature bulk storage options (e.g. sodium ion battery technologies)			
	Develop vehicle-to-X energy technologies			
	Research, development and demonstration of novel energy to electricity storage solutions for a range of durations and at appropriate storage and power capacity (such as electrolytic hydrogen, hydrogen fuel cells, gravitational solutions etc)			
	Develop strategies for integrating various types of storage in the grid, including whether storage is best at the edge or centre of the network			
Developing and demonstrating flexible platforms for smarter markets	Develop market platforms to efficiently coordinate flexible and decentralised supply and demand			
	Demonstrate platforms at multiple levels of aggregation (including improved interaction between transmission and distribution system operators) and linking to other energy vectors as well as secondary trading of flexibility			
Prepare networks for the energy system transformation and integration	Understand and develop solutions to manage changes from a larger capacity, more dynamic system with high penetration of variable renewable energy			
	Innovations for solutions that manage network or system peaks and allow better utilisation from a variety of assets			
	Lower-cost innovative options for increasing the capacity of the low voltage distribution network to meet increased electricity demands			
	Research into whole systems integration for future energy provisions around heat, power and transport and improve coordination between networks and other system participants across local, national and international systems			
Policy Ambitions	40GW of offshore wind by 2030, including 1GW floating offshore wind			
	Advanced Modular Reactors demonstrator by the early 2030s			
	Prototype fusion power demonstrator by the 2040s			
	Deploy at least one operational power CCUS project by 2030			
	Deploy first of a kind SMR by the 2030s			
	By 2022, publish Biomass Strategy to establish the role of BECCS			

Renewables

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Accelerating the deployment of offshore wind capacity	Develop next generation turbines, focussing on areas of UK advantage including gearboxes, drive trains, generators, new materials and foundation design			
	Innovation to improve grid integration to smooth the variability of wind energy and decrease the costs of transmission (including long distance AC transmission, high voltage DC transmission)			
	Innovation to reduce costs via larger turbines, robotics and Artificial Intelligence			
	Innovation to improve cable burial and repair, logistics, installation, and smart and remote operations and maintenance			
	Innovation to improve power conversion technologies for offshore grid networks			
Unlocking deep water offshore wind sites deeper than 50 meters	Research and innovation to improve floating offshore wind technology including:			
	• Foundations			
	• Dynamic cable design/modelling			
	• Novel installation and mooring systems and logistics			
	• Offshore operations			
	Further improve fixed bottom offshore wind to decrease the costs of foundation manufacture and installation			
Mitigating wider impacts from wind turbines (fixed and floating)	Maintain effective surveillance of airspace by developing technologies that will allow co-existence of radar and offshore wind farms			
	Development of technological solutions for mitigation and compensation for cumulative environmental effects			
Developing and demonstrating earlier-stage renewables including next generation PV, tidal and lower TRL technologies	Solar Technologies: research and innovation in next-generation solar PV including new or modified cell chemistries; inverters with increases in efficiency and lifetimes			
	Solar Technologies: research and innovation in Building Integrated PV (BIPV) working with construction sector			
	Research and innovation for more speculative solar technologies and conversion processes			
	Tidal technologies: innovation to improve turbine blades, material innovation and novel structure design			
	Tidal technologies: improve power take-off and control technologies, foundations, moorings, operations and maintenance			
	Improve understanding of wave and tidal energy resource through resource modelling innovation			
	Other and lower TRL technologies: Research and innovation for more speculative renewable technologies and conversion processes			

Nuclear

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Develop Small Modular Reactors (SMRs)	Develop first-of-a-kind SMR by the 2030s			
	Deliver and demonstrate innovative engineering design, materials, manufacturing and deployment methods to reduce costs and risk to SMRs supporting decarbonisation			
Develop and demonstrate Advanced Modular Reactors (AMRs)	Demonstrate AMR technology in the UK by early 2030's			
	Identify optimum operating temperature to maximise the value of AMRs in a decarbonised energy system			
	Deliver AMR design and supporting research and development needs, including materials, modelling and simulation validation, modular and factory build, advanced joining and construction			
	Develop and deliver AMR fuel by developing the design, demonstrating its performance and proving the fuel cycle			
Integrate advanced nuclear with other technologies to support a flexible energy system	Demonstrate the system integration of nuclear to support a flexible energy system, including understanding and demonstrating: electricity supply either through directly varying electrical output (potentially alongside cogeneration) or via energy storage in the form of hydrogen and heat storage systems			
	Develop and demonstrate the technologies for nuclear process heat to decarbonise industry including sustainable fuel manufacture, ammonia production, direct air capture systems and traditional manufacture of carbon intensive industries such as paper, steel and glass			
	Demonstrate and underpin the role for nuclear heat to energise zero carbon district heating systems			
Driving continual improvement in large-scale nuclear	Demonstrate the role of Accident Tolerant Fuel to enhance safety margins of existing technology			
	Innovation in project delivery models to reduce risk and cost of new deployment			
	Demonstrate ability of large scale nuclear to support flexible electricity, hydrogen and heat provision			
	Demonstrate the cost reduction potential through repeatability of design and application of digital and advanced manufacturing and modular approaches			
Research and development in nuclear fusion with a view to options beyond 2050	Design and build a prototype fusion power demonstrator in the UK by the 2040s to demonstrate the commercial viability of fusion			
Improving processes for decommissioning and waste	Research and development aligned to possible future fuel cycle scenarios			

Bioenergy and BECCS

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Whole systems approach to bioenergy in meeting net zero	Identify the most cost effective and GHG-optimal methods of utilising sustainable biomass to meet net zero			
Creating and securing a sustainable and reliable supply of quality biomass	Address environmental (greenhouse gas, air quality, biodiversity, water use) and other challenges of aggregating and scaling up sustainable biomass supply chains, for both imported and domestic biomass			
	Improvements in biomass production and pre-processing, including woody biomass, agricultural residues, waste, perennial energy crops and marine feedstocks to make them suitable for a greater variety of end uses, reduce supply chain losses and maximise their GHG emission reduction potential			
Improving the performance and commercial viability of gasification conversion technologies.	Research into flexible gasification systems that can handle various feedstocks, and understand the potential domestic biomass resource that is suitable for gasification			
	Research into flexible gasification systems that can efficiently produce various end products (e.g. sustainable aviation fuel, hydrogen, biomethane)			
	Improve syngas treatment / clean-up technologies to improve gasification plant availability at various scales			
	Support innovation to enable a fully integrated, scale-up advanced gasification demonstration plant			
	Enable full integration of advanced gasification flowsheet through a first of a kind plant			
Exploring routes to deploy BECCS	Research into suitable sustainable feedstocks and pre-processing technologies that deliver greatest decarbonisation and negative emission potential in different end uses (e.g. power, transport, industry, etc)			
	Research to assess the environmental and public health consequences of these approaches, such as for air quality, and mitigation options to address these			

4.2 Industry and low carbon hydrogen supply

4.2.1 Transitioning to a net zero industrial base

Context

Industry contributes £180bn per year to the UK economy, accounting for 8% of UK GDP and providing 2.5m direct jobs[20] as well as 5m jobs across the value chain[21]. It is, however, also a major source of CO_2 and other GHGs, and high emitting sectors include iron and steel, chemicals, petrochemicals (plastics) and cement and lime. In 2019, direct emissions from manufacturing and refineries accounted for around 16% (71 $MtCO_2e$) of total UK GHG emissions[22]. Over half of these come from the UK's six major heavy industry 'clusters' – Grangemouth, Humberside, Merseyside, Southampton, South Wales and Teesside. The bulk of industry emissions result from direct fossil fuel combustion for heat, but process emissions from chemical reactions (e.g. to produce cement or iron) also contribute.

Since 1990, total UK Industry emissions have more than halved mainly due to the changing structure of the UK's manufacturing sector, improved energy efficiency and a shift to lower carbon fuels. However, despite this progress, the overall pace of reduction is slowing and critical technologies required for further emissions reductions, such as electrification, low carbon hydrogen, bioenergy and Carbon Capture, Utilisation and Storage (CCUS), remain globally underfunded in comparison to more established low carbon electricity generation and energy reduction and efficiency technologies[23]. Heavy industry is one of the hardest-to-abate sectors and many technologies to reduce emissions are still at an early stage of development.

By 2050, emissions from industry need to fall by at least 90% with all remaining emissions offset by GHG removals (see section 4.3). The Industrial Decarbonisation Strategy[24] and the Net Zero Strategy set out a framework for how government and industry can work together to achieve decarbonisation targets whilst also capitalising on clean growth opportunities. They highlight the following key milestones and targets:

- Connecting two of the UK's major industrial clusters to CCS decarbonisation infrastructure by the mid-2020s and four by 2030.
- Fuel switching to low carbon hydrogen, which has the potential to increase the abatement of industrial emissions from 9 $MtCO_2e$ to 11 $MtCO_2e$ by 2035.
- Establishing the world's first net zero industrial cluster and related systems by 2040.
- Almost no fossil fuel in use by 2050 unless combined with carbon capture.

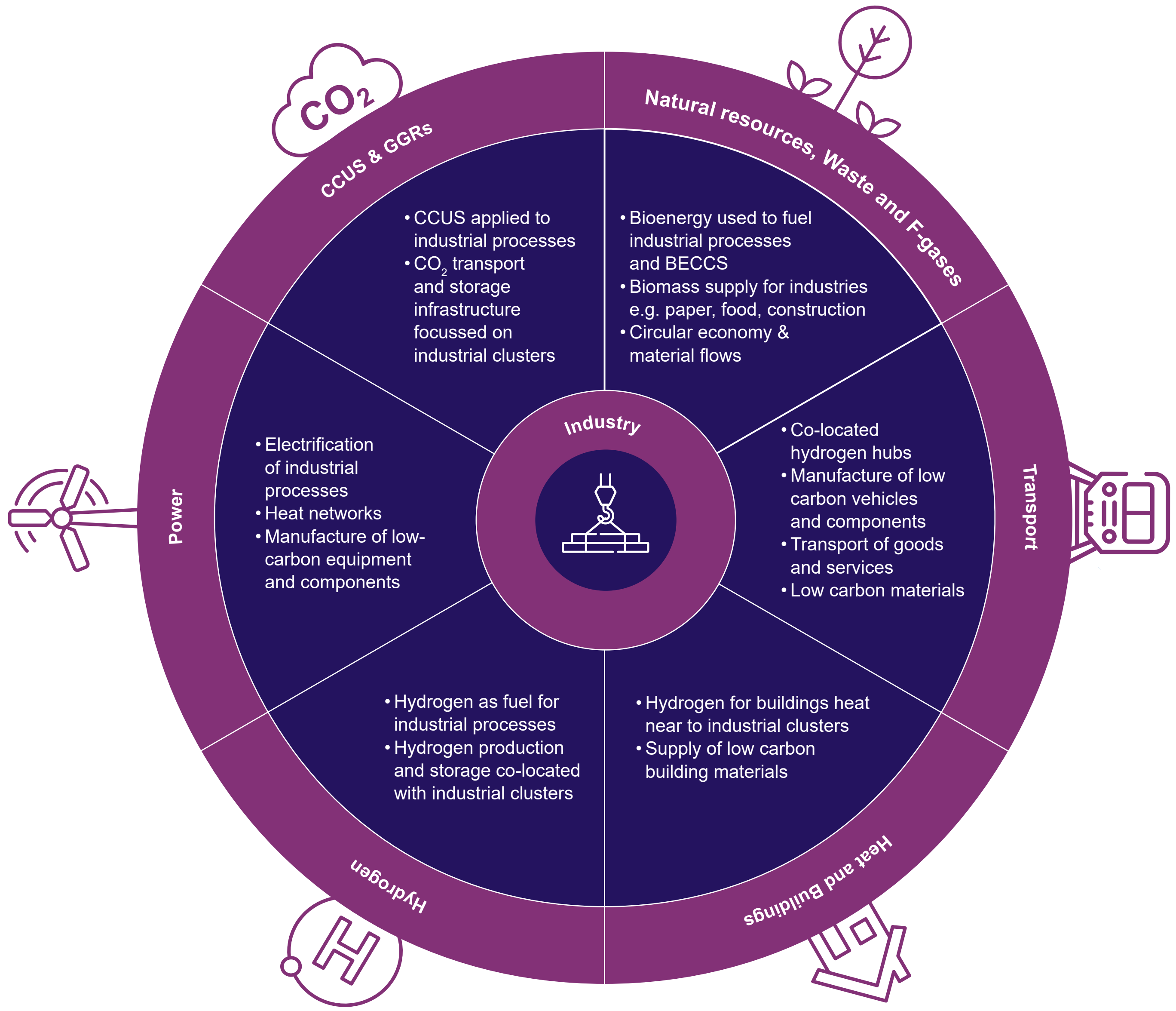
The next decade will be critical for laying the policy and infrastructure foundations for deep decarbonisation whilst ensuring a range of decarbonisation options are available to industry by 2030. The 2020s are also critical to reach maximum energy and resource efficiency levels before more expensive decarbonisation options are rolled out from the 2030s onwards. At that point, deep decarbonisation must become the norm across UK industry. A range of technologies are required to reduce emissions across different industry sectors and sites. Broadly, these fall into three categories:

- Resource and energy efficiency.
- Switching to low carbon fuels, such as electricity, hydrogen and bioenergy.
- Carbon Capture, Utilisation and Storage (CCUS) for industrial emissions.

There will be no universal solution and a multi-faceted approach to innovation and wider deployment is required with a need to evaluate and experiment. Environmental and pollution control regulation will also need to adapt for new technologies so that decarbonisation of industry delivers co-benefits for other objectives such as air quality. Alongside technology development, there is a need to strengthen the market for low carbon industrial goods as well as improving transparency on embodied emissions. Mechanisms such as carbon pricing and getting end-users to choose low carbon products and services will be important, including through data transparency, product labelling, public procurement and partnerships with the private sector.

The UK is well positioned to expand its low carbon exports related to industrial decarbonisation. This can build on the UK's existing strong competitive position in fields such as biochemicals (possibly in the future utilising CO_2 from CCS), data analytics and process optimisation, but there are also likely to be new opportunities to develop knowledge and technologies covering the full range of UK industry sectors: metals and minerals, chemicals, food and drink, paper and pulp, ceramics, glass, oil refineries and less energy intensive manufacturing. Significant opportunities are also likely in emerging industries, including low carbon hydrogen and CCUS.

Figure 12: System interlinkages between Industry and other sectors



Research and innovation: challenges and needs

Research and innovation is needed this decade to identify and trial solutions which are best suited to different industries and contexts and to reach maximum energy and resource efficiency levels before more expensive decarbonisation options are rolled out from the 2030s onwards. From then, deep decarbonisation must become the norm across UK industry.

Challenges	Key research and innovation needs
Improving resource and energy efficiency	In addition to policies that encourage accelerated uptake of existing technologies, innovation in resource and energy efficiency is needed in all parts of the manufacturing supply chain. Reduce the impact of extraction and use of raw materials. Development of alternative, renewable feedstocks, along with a step change in the use of recycled material into new products is needed. For example: • Research on potential for the chemical sector to use biological feedstocks to replace existing products and produce new (e.g. bio-degradable) products and materials. • Low carbon material inputs such as lower clinker cements and concretes, alternative binders and cement formulations. More resource efficient manufacturing processes. New technologies and methods for manufacture of existing and new materials are needed, these include: • Advanced technologies and new manufacturing processes that can provide a step-change in emissions reductions, such as new steelmaking technologies including electrolysis of iron ore to produce “green steel”. • Research and testing related to new heat recovery techniques. • Advanced manufacturing technologies, such as near net shaped and additive manufacturing (or 3D printing) to create lighter, cheaper and less resource intensive materials, reduce lead times and extend product life cycles. • Digital Twin technology to identify potential issues and inefficiencies and improve the cost effectiveness, efficiency and flexibility of production. Reduce the impact of a product in use. Redesigning a product to have a lower environmental impact including: • Light weighting to reduce the weight of material inputs into a product. • Using eco-design to design products for disassembly, remanufacture or recycling of end-of-life parts or products so that they can return to like-new or better performance, or new products that can be made with reused / recycled and alternative materials. • Increasing product lifetime or switching to / creating re-useable products where possible.

Challenges	Key research and innovation needs
	End of life. Minimise the loss of materials at the end of life and prevent the impact of any waste on the environment. For example: • Business model innovation (leasing, product service systems or pay as you go) that supports more efficient use of resources. • Advanced separation and sorting of waste that enables more and higher quality recycling. • Design and produce biodegradable and compostable materials with properties comparable to difficult to recycle materials, such as engineering plastics.
Switching to low and zero-carbon fuels (e.g. electricity, hydrogen and biomass)	Innovation is needed in a wide range of lower carbon fuels (including hydrogen, electricity and bioenergy), as well as ancillary technologies to enable fuel switching, such as metering of new fuels and site infrastructure. Support needs to take into account wider environmental goals, such as improving air and water quality, and necessary innovation in abatement technologies for pollutant emissions from new fuels. For hydrogen: • Demonstrate low carbon hydrogen as a feedstock for industrial sectors, new products and synfuels. • Technologies for equipment categories where there is a potential for significant demand for hydrogen, including industrial boilers and combined heat and power systems (CHPs). • Technologies for high temperature direct firing e.g. primary steel production, glass, ceramics, chemicals. • Innovation to connect dispersed sites to hydrogen networks in industrial clusters, e.g. repurposing parts of existing natural gas grid. • Innovation to make existing gas equipment 'hydrogen-ready'. • Innovation to reduce costs to support low carbon hydrogen being competitively priced. For electrification: • Innovation and trials to reduce costs to increase uptake of low temperature heat electrification technologies.

Challenges	Key research and innovation needs
	• Innovation to develop technologies for medium and high temperature (>650°C) heat applications by 2030. • Smart technologies, storage and demand side response to provide flexibility and allow industry to use energy when it is cheapest and cleanest. For bioenergy combined with CCUS (BECCS): further research to understand how to increase supplies of sustainable biomass and ensure it is used in the most impactful way. Innovation to unlock other low carbon fuels including waste, ammonia and process heat from sources such as advanced nuclear reactors and alternative technology options, such as large-scale hydrogen fuel cells. Research to understand the best fuel switching options for a range of sectors. Zero emission options for Industrial Non-Road Mobile Machinery.
Capturing and storing industrial emissions *Research and innovation needs relating to CCUS generally are covered in section 4.3. This table covers needs relating specifically to industry*	The maturity of CCUS technology varies across industrial applications. CCUS applied to sources such as steel and cement is still in the demonstration or prototype stage and requires innovation in the near term. • Heat recovery solutions and integration of the capture process with the wider site. • First-of-a-kind CCUS demonstration plants across industrial sources. • Understanding of how capture rates can be improved, particularly for flue gas streams with low CO_2 concentration. • Research into bespoke solutions, tailored to the specific conditions on site including treatment of flue gas impurities. • Dispersed sites may not easily connect to CO_2 transport and storage infrastructure. Innovation in alternative means of transport and possibly capture technology is required, e.g. modular carbon capture. • Understanding the potential for local synergies between carbon capture and carbon utilisation opportunities, e.g. producing synthetic fuels or other chemicals.

Figure 13: Industry research and innovation needs timeline

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Improving resource and energy efficiency	Reduce use of raw materials and development of alternative, renewable feedstocks, including in chemicals and cement production			
	Advanced technologies and new manufacturing processes, such as new steelmaking technologies to produce "green steel"			
	Research and testing related to new heat recovery techniques			
	Advanced manufacturing technologies to create lighter, cheaper and less resource intensive materials			
	Digital Twin technology to identify potential issues and inefficiencies and improve the cost effectiveness, efficiency and flexibility of production			
	Reduce the impact of a product in use, including light weighting, eco-design for disassembly, remanufacture or recycling of end-of-life parts or products, or products made with reused/recycled and alternative materials, increasing product lifetime or re-use			
	Business model innovation (leasing, product service systems or pay as you go) that supports more efficient use of resources			
	End of life: Advanced separation and sorting of waste that enables more and higher quality recycling; design and produce biodegradable and compostable materials with properties comparable to difficult to recycle materials such as engineering plastics			
Switching to low and zero-carbon fuels and feedstocks (e.g. electricity, hydrogen and biomass)	Hydrogen: Demonstrate low carbon hydrogen as a feedstock for industrial sectors, new products and synfuels			
	Hydrogen: Technologies for equipment categories with potential for significant demand for hydrogen, including industrial boilers and combined heat and power systems			
	Hydrogen: Technologies for high temperature direct firing e.g. primary steel production, glass, ceramics, chemicals			
	Hydrogen: Innovation to connect dispersed sites to hydrogen networks in industrial clusters			
	Hydrogen: Making existing gas equipment 'low carbon ready'			
	Hydrogen: Innovation to reduce costs to support hydrogen being competitively priced			
	Electrification: Innovation and trials to reduce costs to increase uptake of market-ready low temperature heat electrification technologies			
	Electrification: Develop technologies for medium and high temperature (>650°C) heat applications			
	Electrification: Smart technologies, storage and demand-side response to provide flexibility and allow industry to use energy when it is cheapest and cleanest			
	Bioenergy with CCUS (BECCS) - further research on how limited supply sustainable biomass should be used and how supply could be increased			
	Innovation to unlock other low carbon fuels including waste, ammonia and process heat from sources such as advanced nuclear reactors and large scale hydrogen fuel cells.			
	Research and understand the best fuel switching options for a range of sectors with different characteristics, where the optimal pathway to net zero is uncertain			
	Zero emission options for Industrial Non-Road Mobile Machinery			
Capturing and storing industrial emissions	Heat recovery solutions and integration of the capture process with the wider site			
	First of a kind CCUS demonstration plants across industrial sources			
	Improve capture rates, particularly for flue gas streams with low CO_2 concentration			
	Research into bespoke, site specific CCUS solutions including treatment of flue gas impurities			
	Innovation for alternative means of transport and capture for dispersed sites that may not easily connect to transport and storage infrastructure			
	Research the potential for local synergies between carbon capture and carbon utilisation opportunities			
Policy ambitions	Connecting two of the UK's major industrial clusters to decarbonisation infrastructure by 2025 and four by 2030			
	20 TWh of fossil fuels replaced with low carbon alternatives by 2030, and 6 Mt CO_2e captured by 2030 and 9 Mt CO_2e by 2035			
	Industrial emissions to fall by two-thirds by 2035 compared to todays' levels and by 72% for sixth carbon budget			
	World's first net zero industrial cluster by 2040			
	No fossil fuel in use by 2050 (unless carbon emissions are captured)			

4.2.2 Scaling up the supply and demand for low carbon hydrogen

Context

Hydrogen is one of a handful of new, low carbon solutions that will be critical for the UK's transition to net zero. As part of a deeply decarbonised, highly renewable energy system, low carbon hydrogen could be a versatile replacement for high-carbon fuels used today. The UK is therefore expected to need significant amounts of low carbon hydrogen in the energy system[25]. Due to its flexibility, hydrogen could be used in buildings for heating and cooking, power and transport sectors and as a fuel or feedstock for industrial processes and products. It is a leading option where electrification is difficult, such as for high temperature heat in industry (e.g. kilns) and for heavy transport including some shipping, aviation and buses as well as HGVs and trains. It could also provide energy system benefits, including for managing peak loads and grid balancing.

The Hydrogen Strategy[26] sets out a roadmap for how we will meet our ambition of working with industry to deliver 5GW of low carbon hydrogen production capacity by 2030, along with the development of associated infrastructure, supply chains and hydrogen end-uses across different sectors. Over the 2020s, Government will support the creation of hubs where low carbon electricity, CCUS and hydrogen congregate. The Hydrogen Advisory Council has been created to improve coordination with industry to overcome near-term challenges.

Beyond our 2030 ambition, hydrogen demand is expected to increase rapidly over the 2030s and 2040s, and analysis suggests we could need 7 – 20 GW of low carbon hydrogen production capacity in 2035[27]. This scale-up underlines the need for innovation support to bring forward a greater range of high efficiency, novel technologies across the hydrogen value chain.

Currently, there are two main focuses for low carbon hydrogen production:

- CCS enabled hydrogen: through reformation of natural gas using steam methane reformers or autothermal reformers, coupled with CCS. Due to CO_2 capture rates, there will be some residual emissions with these technologies. GGR technologies (including DACs) will be needed to make up this deficit.
- Electrolytic hydrogen: through electrolysis of water using low carbon electricity. The main electrolyser technologies are alkaline electrolysis, proton and anion exchange membrane electrolysis and solid oxide electrolysis cells. If produced using renewable electricity, this production method is zero carbon.

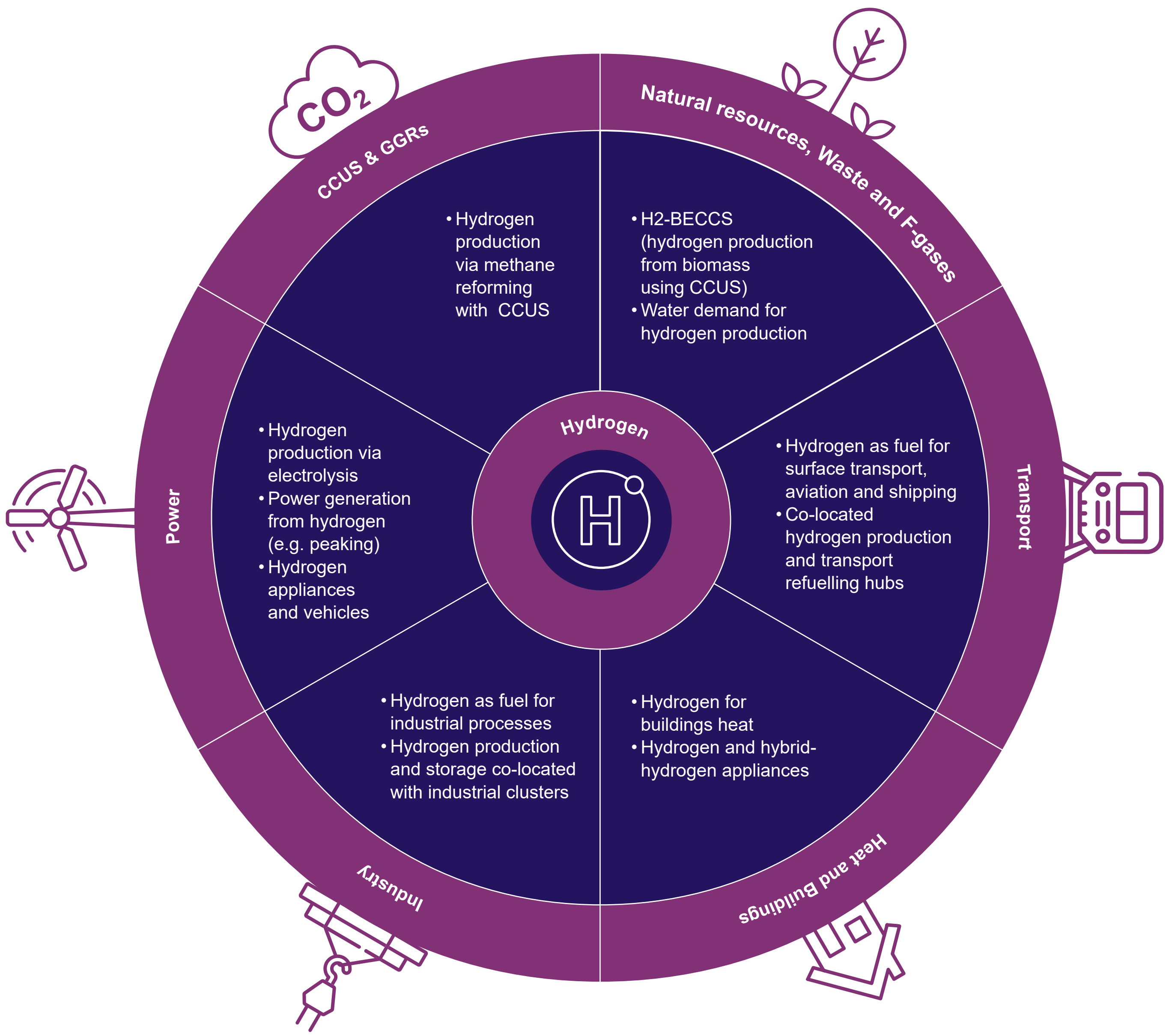
However, there are also other potential hydrogen production routes which are the subject of active research and development. These include using nuclear energy for high temperature processes, biomass gasification with CCUS ("biohydrogen"), photocatalysis and solar thermochemical production. Research and innovation on these production routes can help accelerate the evolution of the hydrogen economy in the UK and support critical decisions on hydrogen's role.

Production and storage of hydrogen may also play an important role in smoothing the intermittency of renewable energy. Hydrogen has the potential to be stored and used when demand requires it to support security of supply and to meet peaking loads. We will need to see significant development and scale-up of hydrogen network and storage infrastructure over the 2020s if low carbon hydrogen is to play its role in supporting UK decarbonisation[28]. Various options exist for storing hydrogen at scale, including as a compressed gas (e.g. in underground salt caverns), using another chemical carrier such as ammonia or through the development and use of solid hydrogen storage systems such as solid phase absorbent technology.

Hydrogen distribution will also need to be developed. Hydrogen can be transported by road, rail or boat as a compressed gas or liquid, or using a different storage medium, such as ammonia. For larger scale transmission and distribution, pipelines can be used. Newer natural gas pipeline networks could be used to distribute hydrogen through blending (i.e., hydrogen injection into gas grids) with the potential to convert them entirely to hydrogen over time.

International collaboration on hydrogen innovation is crucial to accelerate cost reductions. As a co-lead of the Mission Innovation (MI) Clean Hydrogen Mission[29], the UK is working with other MI members and the private sector to catalyse cost reductions in low carbon hydrogen across the value chain, with the goal to increase the cost-competitiveness of low carbon hydrogen by reducing end-to-end costs to $2 per kilogram by 2030. In addition, working with partner initiatives and organisations, the Mission members will deliver at least 100 large-scale integrated clean hydrogen valleys worldwide by 2030. These will be demonstration projects to test different production, storage and transport methods and end-use applications, aiming to reach critical levels of investment and experience.

Figure 14: System interlinkages between Hydrogen and other sectors



Research and innovation: challenges and needs

Demonstrating low carbon hydrogen production methods as efficient, reliable and low-cost at increasing scales is a key innovation priority for the next 5 - 10 years. A number of UK projects are already planned for both methane reformation with CCUS and electrolytic hydrogen routes, but ongoing innovation is required alongside a better understanding of the wider system and environmental impacts.

Hydrogen end-uses are covered in other sections of the report (e.g. industry, buildings, power and transport).

Challenge	Key research and innovation needs
Efficient, cost-effective production of low carbon hydrogen at scale	Demonstrate hydrogen production using next generation methane reforming technology, coupled with CCUS. Demonstrate hydrogen production via electrolysis, initially at the 10s MW scale at different sites. Also, continue to develop next generation electrolysers and demonstrate advanced manufacturing methods to drive costs and efficiency. Continue to improve efficiency and reduce costs of production as deployment increases, including a range of high efficiency / novel technologies across the value chain. Research and development to further drive down emissions from hydrogen production. Develop lower TRL and novel production technologies (e.g. hydrogen from next generation nuclear and biohydrogen with CCUS) to enable demonstration in the 2020s or 2030s. Alternative ammonia production processes, to improve or replace high energy intensive Haber-Bosch process.
Demonstrating effective, low-cost methods of bulk hydrogen transportation and storage	**Transportation** Build the evidence base for injecting hydrogen into the existing gas grid, both the safe blending of up to 20% hydrogen and full conversion to 100% hydrogen. Research and innovation to improve efficiency and costs of hydrogen distribution. Understand and model the needs of hydrogen grid transmission.

Challenge	Key research and innovation needs
	Progress technologies and infrastructure for international transport (e.g. port infrastructure, liquefaction technologies, hydrogen carriers and associate conversion technologies). Progress techniques, technologies, and materials required to compress hydrogen, including for storage and transport. Develop infrastructure and technologies for international transport and improve integration of different hydrogen networks. Demonstrate longer distance hydrogen transmission – scaling-up to international transport in 2030s. Develop components for safe hydrogen distribution and use. R&D to understand and address the safety challenges of storage and supply. Understand impact of hydrogen on distribution and storage materials. **Storage** Enable efficient use of short and long-term storage options, including: Assess the impact of hydrogen on materials for storage and supply and identify options / solutions. Identifying the optimal storage solutions across the hydrogen system, including developing novel short term, transportable and large-scale solutions. Enable efficient use of short- and longer-term storage options, including assessing the need for underground storage. Develop options for hydrogen storage including medium scale storage, increasing the efficiency of ammonia storage and cracking, and solid hydrogen storage systems such as solid phase absorbent technology.

Challenge	Key research and innovation needs
Power generation	Explore the role of fuel cells in applications such as decentralised power, industrial CHP and heat networks. Develop and demonstrate large, centralised hydrogen fuelled power generation options, such as hydrogen turbines, in the 2020s.
Effective use of hydrogen at the system level	Whole systems analysis to understand systems level questions, such as interfaces within and between hydrogen sub-sectors, interactions with broader energy system, trade-offs between technologies and uses, and optimal deployment scenarios. Research and innovation to align hydrogen production and demand, enable supply chain development and improve safe integration into the wider energy system.
Understanding how hydrogen will impact the environment and society	Assess the atmospheric and terrestrial environmental impacts of a hydrogen economy. As the hydrogen economy develops and is deployed, develop mitigation measures against any negative environmental impacts, including water usage. Understand and forecast impact of hydrogen on international markets. Ongoing research into consumer attitudes / acceptance towards hydrogen and identify measures to build consumer confidence.

Figure 15: Hydrogen research and innovation needs timeline

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Efficient, cost effective production of low carbon hydrogen at scale	Demonstrate hydrogen production using next generation methane reforming technology coupled with CCUS			
	Demonstrate hydrogen production via electrolysis, initially 10s MW scale at different sites & develop next generation electrolysers / advanced manufacturing methods to drive costs and efficiency			
	Increase efficiency and reduce costs of production technology and processes as deployment increases			
	Research and development to further drive down emissions from hydrogen production			
	Development of lower TRL and novel production technologies (e.g. hydrogen from next generation nuclear / biohydrogen with CCUS to enable demonstration)			
	Alternative ammonia production processes, to improve or replace highly energy intensive Haber-Bosch process.			
Demonstrating effective, low-cost methods of bulk hydrogen transportation and storage	Build evidence for injecting hydrogen into the existing gas grid			
	Research and innovation to improve the efficiency and costs of hydrogen distribution			
	Understand and model the needs of hydrogen grid transmission			
	Develop infrastructure and technologies for international transport and improve integration of different hydrogen networks			
	Demonstrate longer distance hydrogen transmission - scaling up to international transport in 2030s			
	Assess the impact of hydrogen on materials for storage and supply and identify options / solutions			
	Identify the optimal storage solutions across the hydrogen system, including developing novel short term, transportable and large-scale solutions			
	Enable efficient use of short and longer term storage options, including assessing the need for underground storage			
	Develop options for hydrogen storage including medium scale storage, increasing efficiency of ammonia storage and cracking			
	Develop solid hydrogen storage systems such as solid phase absorbent technology			
Power generation	Explore the role of stationary fuel cells in applications such as decentralised power, industrial combined heat and power and heat networks			
	Develop and demonstrate large centralised hydrogen fuelled power generation options, such as hydrogen turbines, in the 2020s			
Effective use of hydrogen at the system level	Analysis of hydrogen at the whole system level			
	Enable ecosystems for hydrogen research and innovation			
	Align production and demand			
	Address safety questions and incorporate safety by design into hydrogen technologies			
	Research and innovation to enable supply chain development across the value chain and address technology barriers			
	Research and innovation to optimise integration into the electricity / energy system			
Understanding how hydrogen will impact the environment and society	Assess environmental impact of a hydrogen economy (by 2025) and mitigate against impacts (on-going)			
	Address new questions as technologies are developed and deployed			
	Understand and forecast impact of hydrogen on international markets			
	Understand and address acceptance barriers			
Policy ambitions	Complete hydrogen neighbourhood trial and 20% blending testing (2023)			
	Ambition for 1GW hydrogen production capacity (2025)			
	Hydrogen village trial (2025); Potential hydrogen town by end of 2020s			
	5GW low carbon production capacity by 2030			
	1 Net zero carbon industrial cluster (2040)			

4.3 Carbon Capture Utilisation and Storage (CCUS) and Greenhouse Gas Removal (GGR)

Context

CCUS technologies are likely to have applications across many parts of the economy as the UK transitions to net zero. Tata Chemicals CCU plant is set to be the UK's first operational project. In the near term, the government's ambition is for CCUS to be deployed in two industrial clusters by the mid-2020s and four low-carbon hubs, spread across the UK, capturing 10 $MtCO_2e$ annually by 2030[30]. This will demonstrate CCUS technology across multiple industrial sectors, providing crucial "learning-by-doing" for industry, academia and the wider UK supply chain, and is key to confidently scaling CCUS in the 2030s.

In addition, CCUS infrastructure is needed to support GGR solutions. Even in ambitious decarbonisation scenarios there are likely to be some residual GHG emissions in 2050. The Net Zero Strategy estimates that 75-81 $MtCO_2e$ of engineered removals will be needed per year by 2050 to compensate for residual emissions in the most difficult to decarbonise sectors such as aviation and parts of agriculture and industry[31].

CCUS technology will be applied to larger point sources of CO_2 emissions, including stack emissions or process emissions. Potential applications include:

- **Industry**. CCUS has the potential to be applied to a variety of industry sectors and processes. This includes emissions captured from the combustion of fossil fuels in industrial processes as well as non-combustion emissions such as those from limestone calcination in cement production.
- **Bioenergy with CCUS**. Combining bioenergy production with CCUS technologies (BECCS) offers one of the main routes to removing CO_2 from the atmosphere, providing that sustainable biomass feedstocks are used. BECCS could potentially be applied in many sectors including power generation, hydrogen production, renewable fuel production (e.g. sustainable aviation fuel) and industry.
- **Gas power with CCUS.** This has the potential to enable continued fossil fuel combustion for electricity generation whilst substantially reducing emissions. This offers a potential route to low carbon baseload and / or dispatchable generation.
- **Hydrogen production with CCUS**. Applying CCUS technology to methane reformation provides a way of producing low carbon hydrogen from natural gas or biomass. This is likely to be a particularly important route providing the bulk supply of low carbon hydrogen necessary to establish the UK hydrogen economy in the 2020s, while electrolytic hydrogen technologies scale-up and costs come down.

Innovation is needed to improve current CCUS technology and to deploy next-generation technology. Next-generation CCUS technology aims to have better performance, lower environmental impact and be more widely applicable than current technology.

GGR solutions typically fall into two broad categories and it is likely a combination of several approaches will be necessary to achieve the level of removals required for net zero.

Engineering-based solutions include:

- **Bioenergy with Carbon Capture and Storage (BECCS)**
- **Biochar** - a charcoal-like product produced by the combustion of biomass in the absence of oxygen (known as pyrolysis). This may be added to soils to increase carbon storage in soil.
- **Direct air carbon capture and storage (DACCS or DAC)** – the use of chemical processes to capture CO_2 and other GHGs directly from the atmosphere and permanently store it in geological formations or use it to generate carbon containing fuels.
- **Enhanced weathering** - involves spreading crushed minerals over the land surface to increase chemical reactions which remove CO_2 from the air.
- **Sea water CO_2 (and other GHG) removal solutions.**

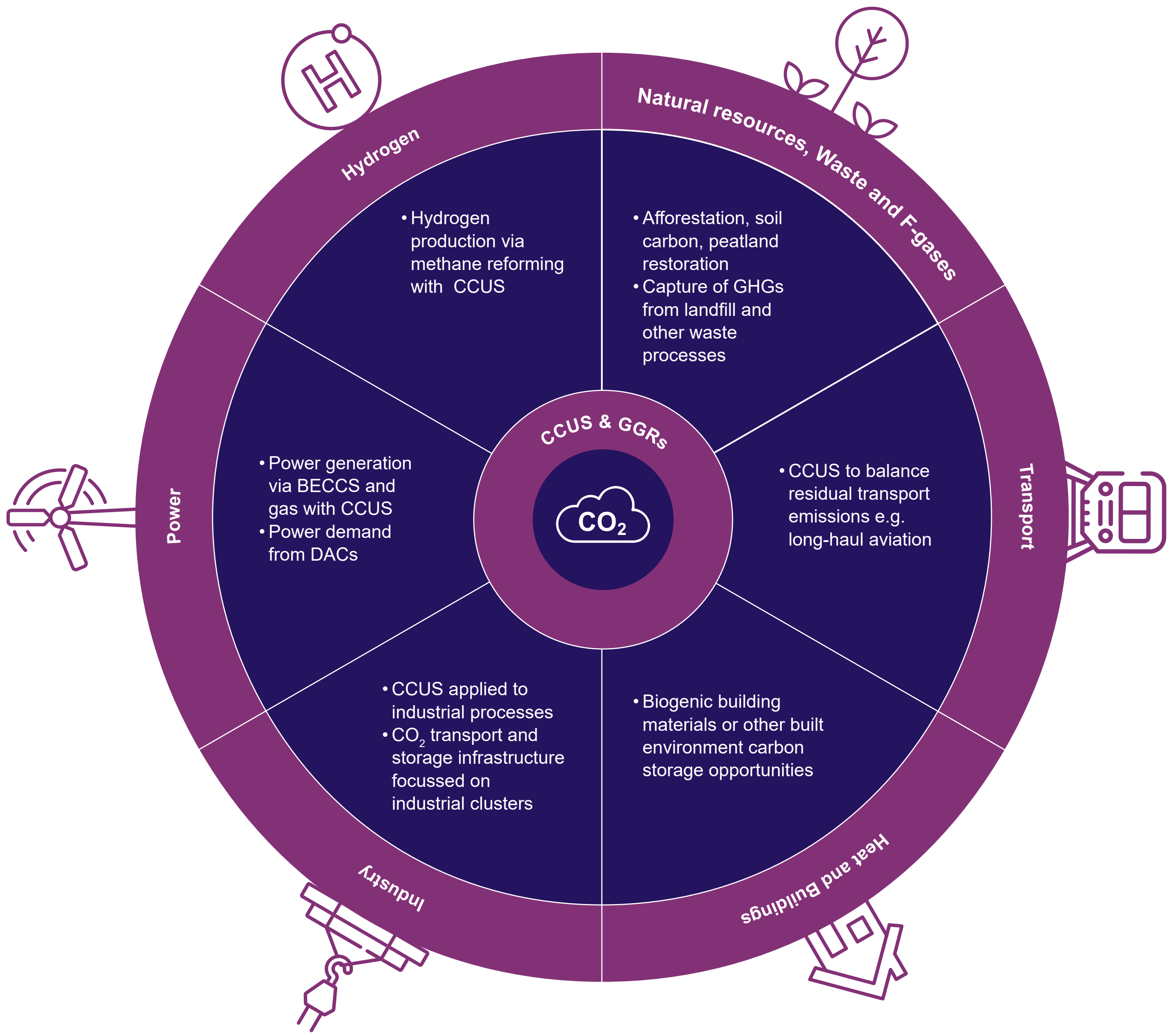
Nature-based solutions (covered in section 4.6) include:

- **Afforestation** - increasing forest area to raise CO_2 absorption.
- **Habitat restoration** - the rewetting and restoration of peatlands, wetlands and other coastal habitats, which in turn enhances natural carbon absorption from the atmosphere.

Monitoring, reporting, and verification (MRV) of emissions removals will be key for these technologies to reach commercial scales. For some GGR approaches, the amount of carbon captured and stored can be easily measured and may not require periodic monitoring. In others, establishing this with necessary certainty and verifying that carbon remains secure will be more challenging. Both biological storage (e.g. soil or trees) and geological storage (e.g. sub-surface geological formations) are recognised as potential pathways, but they vary significantly in terms of durability of storage and associated risk of reversal.

CCUS has potential to be a significant opportunity for the UK, combining expertise on offshore engineering and sub-surface geology and large reservoir space for CO_2 storage close to major European generators. The UK also has an excellent academic pedigree in early-stage scientific research and is well placed to develop a global leadership position in GGR technologies. The upcoming Biomass Strategy, due in 2022, will further consider the role of BECCS in delivering negative emissions and we will consult on business models for engineered GGRs in Spring 2022. The UK is well placed to develop these strengths and create significant export and growth opportunities as domestic and international supply chains develop, including options for CO_2 use in the manufacture of synthetic fuels and other chemicals and products, with the International Energy Agency suggesting that all synthetic fuels produced post-2040 will be either of biomass or DAC origin[32].

Figure 16: System interlinkages between CCUS &GGRs and other sectors



Research and innovation: challenges and needs

CCUS, BECCS and DACs technologies will ultimately rely on much of the same supporting infrastructure and will face similar challenges in terms of business models, financing and risk sharing arrangements, and policy and regulatory requirements. The table below covers research and innovation needs common to these technologies. Research and innovation needs related to nature-based removals and sustainable biomass feedstock production, specifically perennial energy crops and short rotation forestry, are covered in section 4.6.3 in the context of the management of natural resources.

Challenge	Key research and innovation needs
Capturing CO_2 from point sources, efficiently and at low-cost	Pre-combustion capture – gas: advanced reformer technologies to unlock the potential to combine hydrogen production with CCS for power. Cost reduction is possible using cheaper and more energy-efficient materials and processes. Post-combustion capture – gas & solid fuels: R&D into new solvent and adsorption processes to reduce costs and improve capture performance as well as reduce regeneration costs, corrosion effects, environmental impact, and product degradation. Oxy-combustion: new technologies for lower-cost air separation in oxy-combustion. Other advanced low-cost capture technologies such as calcium looping. Reduce the parasitic load of capture technologies to improve efficiency. Increase CO_2 capture rates and efficiency of carbon capture technologies. Research, development and demonstration related to CCUS and GGR supply chain development and plant operations.
Removing GHGs directly from the air or sea, efficiently and at low-cost	RD&D for a range of options for capturing CO_2 and other GHGs directly from the air or sea: • Higher TRL Direct Air Capture (DAC) technologies as well as approaches such as enhanced weathering of silicate rocks. • Novel (lower TRL) approaches for capturing CO_2 or other GHGs such as methane and NO_2. Innovations in monitoring and verification to help verify estimates of CO_2 captured where it cannot be measured by volume.

Challenge	Key research and innovation needs
Reducing energy demand from engineered removal technologies	Improve efficiency and reduce energy demand of engineered GGR technologies, e.g. DACs requires electricity to run fans to move air through or across a capture medium and heat to separate captured CO_2 from reactants.
Exploring routes to deploy BECCS *(See also section 4.1.4, 4.2.1 and 4.6.3)*	Develop and demonstrate efficient, cost-effective biomass gasification technologies that can produce high quality syngas and be co-developed with BECCS deployment (hydrogen and renewable fuel production). Explore routes to innovate and optimise BECCS supply chains to combine BECCS with other existing and emerging technologies (combustion, gasification, anaerobic digestion, etc.) to produce power, heat, sustainable transport fuels (e.g. sustainable aviation fuel), or hydrogen, while fully assessing the environmental consequences of these approaches.
CO_2 transport and storage infrastructure	**CO_2 Transport:** • Geographical cluster development to enable the identification of lowest-cost infrastructure opportunities. • Research into sharing of infrastructure and capacity for transport and CO_2 storage. **CO_2 Storage:** • De-risking and developing solutions for the scale-up of both short and long-term CO_2 stores, including technologies that characterise the connectivity of sands and structural features and innovation to tackle challenges that arise from the build out of planned full-scale stores. • Technologies and methods that model, simulate, appraise and monitor stores faster, and with a higher degree of confidence. To include modelling of stores at broad geographical scales and to support optimisation, planning and management of stores in real-time. • Measuring, Monitoring, and Verification of CO_2 storage to prevent, observe, and report leaks. Improve long-term monitoring techniques, move towards performance-based standards. • Development of depleted oil and gas reservoir storage technologies and methodologies to enable offshore CO_2 storage. • Unlocking the potential of CCUS on more dispersed sites that cannot easily connect to CO_2 transport and storage infrastructure, innovation in alternative means of transport and storage and possibly capture technology is required, such as ship transport (port-to-offshore) and land-based gas transport (rail) solutions.

Challenge	Key research and innovation needs
Developing economic ways to utilise captured CO_2 in products or processes	Development of carbon utilisation opportunities, e.g. sequestering carbon in long-life products or in the production of synthetic fuels and other chemicals - acknowledging the need to better understand lifecycle emissions and future innovation needs. Research to deepen understanding of the role of modern methods of construction on net zero.
Creating the conditions for future scale-up and deployment / commercialisation	Scaling-up CCUS technologies and GGR approaches from pilot to commercial first-of-a-kind demonstrations needs to happen over the next 10–15 years to allow widespread roll-out from the 2030s onwards. This implies: • Demonstrating CCUS at scale across a range of industrial applications. • Demonstrating hydrogen production using next generation methane reforming technology with CCUS. • Demonstrating BECCS and gas CCS at scale in the power sector. • Demonstrating DACs and other GGR approaches at scale. Policy, regulatory and risk-sharing frameworks and commercially acceptable business models will be as important as technology innovation in enabling the widespread deployment of CCUS and GGR. Further RD&D may be needed to develop and test these frameworks and business models, building on work currently being undertaken by BEIS, including solutions for the integration and interlinking of CCUS technologies to achieve combined capture, utilisation and storage. Research into public attitudes towards CCUS and GGR and how this could be mobilised to support the required deployment of these technologies.

Challenge	Key research and innovation needs
Monitoring, Reporting, and Verification	Monitoring, reporting and verification methodologies for different GGR approaches must be developed by 2030 to ensure commercial-scale roll-out can occur. Before GGRs can be fully deployed on a commercial basis, in either voluntary markets or as part of a compliance-based approach, it will be vital to understand: • How much CO_2 has been removed from the atmosphere. • When that removal has taken place. • At what rate that removal will persist, and for how long. • In what type of sink it has been stored. • The characterisation and durability of that store. • The point at which a given store reaches maximum stability / saturation. To ensure the credibility of a removal, and support market legitimacy and perception, it is also important to consider: • Additionality – proving the removal activity is additional to what was happening anyway, in the absence of the GGR intervention. • Avoid double counting – ensuring geographical accountability and accuracy, so that a removal is not credited or accounted for twice.
Managing environmental impacts and co-benefits	Further understand how GGR / CCUS technologies impact the environment.

Figure 17: CCUS and GGR research and innovation needs timeline

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Capturing CO_2 from point sources, efficiently and at low cost	Pre-combustion capture – gas: advanced reformer technologies & cheaper and more energy-efficient materials to reduce cost			
	Post-combustion capture – gas & solid fuels: Research and development into new solvent and adsorption processes to lower cost and improve capture performance			
	Oxy-combustion: New technologies for lower-cost air separation in oxy-combustion			
	Other advanced low-cost capture technologies such as calcium looping			
	Reduce the parasitic load of capture technologies to improve efficiency			
	Increase CO_2 capture rates and efficiency of carbon capture technologies.			
	Research, development and demonstration related to CCUS and GGR supply chain development and plant operations			
Removing GHGs directly from the air or sea, efficiently and at low cost	Research, development and demonstration for a range of options capturing CO_2 and other GHGs directly from the air or sea across a range of TRL levels			
	Monitor and verify improvements to help verify estimates of CO_2 captured			
Reducing energy demand from engineered removal technologies	Improve efficiency and reduce energy demand of engineered GGR technologies			
Exploring routes to deploy BECCS	Develop and demonstrate efficient, cost-effective biomass gasification technologies			
	Optimise biomass BECCS supply chains to combine BECCS with other technologies (combustion, gasification, anaerobic digestion, etc) to produce power, heat, sustainable transport fuels, or hydrogen, while fully assessing the environmental consequences			
CO_2 transport and storage infrastructure	Develop geographical cluster to enable the identification of lowest-cost infrastructure opportunities			
	Research into sharing of infrastructure and capacity for transport and CO_2 storage			
	De-risking and developing solutions for the scale-up of both short and long-term CO_2 stores			
	Methods that model, simulate, appraise and monitor stores faster, and with a higher degree of confidence			
	Measuring, Monitoring, and Verification of CO_2 storage to prevent, observe, and report leaks			
	Development of depleted oil and gas reservoir storage technologies to enable offshore CO_2 storage			
	Innovation in alternative means of transport, storage, and capture of CO_2 for dispersed sites including sharing of infrastructure / capacity			
Developing economic ways to utilise captured CO_2 in products or processes	Development of carbon utilisation opportunities, e.g. sequestering carbon in long-life products. Also in the production of synthetic fuels and other chemicals			
	Research to deepen understanding of the role of modern methods of construction on net zero			
Creating the conditions for future scale-up and deployment / commercialisation	Demonstrate CCUS at scale across a range of industrial applications			
	Demonstrate hydrogen production using next generation methane reforming technology with CCUS			
	Demonstrate BECCS and gas CCS at scale in the power sector			
	Demonstrate DACCS and other GGR approaches at scale			
	Develop and test policy, regulatory and risk-sharing frameworks and commercially acceptable business models			
	Research into public attitudes towards CCUS and GGR technologies			
Monitoring, Reporting and Verification (MRV)	Development of technology-specific MRV to enable robust carbon accounting and assignment of credits to support carbon markets			
Managing environmental impacts and co-benefits	Further understand how CCUS / GGR technologies impact on the environment			
Policy ambitions	Connect two of the UK's major industrial clusters to decarbonisation infrastructure by 2025 and four by 2030			
	3 $MtCO_2e$ captured by 2030			
	For GGRs, ambition for 5$MtCO_2$ of engineered removals annually by 2030			
	World's first net zero industrial cluster by 2040			
	No fossil fuel in use by 2050 (unless carbon emissions are captured)			

4.4 Heat and buildings

Context

The UK has around 30 million buildings[33] which are collectively responsible for around 30% of total UK GHG emissions (direct and indirect)[34]. Most buildings currently rely on natural gas for heating, hot water and cooking, whilst others use electricity, oil, liquified petroleum gas (LPG) or solid fuels. Much of the UK's existing building stock also has poor levels of energy efficiency; for example, approximately two-thirds of UK homes have an EPC rating of D or below[35], meaning that much of the heat generated is wasted. To reach net zero, virtually all heat in buildings must be decarbonised by 2050.

From 2025, the Future Homes Standard will ensure that all new-build homes will have low carbon heating and high levels of efficiency, meaning that no further energy efficiency retrofit work will be necessary to enable them to become zero-carbon over time as the electricity grid continues to decarbonise. For net zero, the construction industry will also need to adopt low carbon materials, low carbon construction techniques, repurpose existing buildings where practical and improve the efficiency of its supply chain operations (including maximising the potential of local or regional manufacturing).

Alongside this, a key challenge is to retrofit the significant proportion of homes and non-residential buildings[36] that require remedial work to achieve high standards of energy efficiency and to use low carbon heating sources. The diverse nature of the UK's building stock, which includes large commercial properties, public sector buildings (such as schools and hospitals), and a range of domestic properties (from flats to large, detached homes), also means that decarbonisation measures will be informed by local and site-specific requirements, as well as end-user preferences and needs. Developing appealing solutions and an understanding of end-user choices are both critical, as decarbonising buildings may cause disruption for homes and workplaces.

For decarbonising heat there are various potential options, including heat pumps, hydrogen, heat networks and biomethane. Some of these solutions may also have a role to play in delivering cooling, particularly as the UK adapts to the impacts of rising global temperatures. The government has committed to making a strategic decision by 2026 on the long-term role of hydrogen for heating, including through community hydrogen heating trials, and to increase the number of heat pumps installed to 600,000 per year by 2028. Innovation will be critical to ensure the right solutions are available and cost-effective. We will also need innovation in business models, finance and across supply chains.

Future heating systems are also likely to be increasingly integrated with other forms of energy production, storage and demand, at both building and community scales. End-user preferences may become more specific, for example wanting more control over heating systems, comfort cooling as well as heating, and more engagement with energy consumption and tariffs. These changes point to an increasing need for smart technologies, behavioural insights and new business models and market arrangements. Buildings will be increasingly linked to the power and transport sectors and associated infrastructure, with interlocking innovation needs for integrated, low carbon, flexible technologies installed in homes and businesses across the country. We need to understand and prepare for the energy requirements of a decarbonised building stock, whilst maximising the potential to enable system-wide flexibility.

Improved energy efficiency and flexible demand will also help to tackle fuel poverty for domestic end-users, improve wellbeing, and help to reduce energy costs for both domestic and non-domestic end-users.

Retrofitting millions of buildings will create hundreds of thousands of UK jobs[37] and the creation of a domestic market for low carbon materials and products will help drive the transformation of UK industry, in turn supporting exports and growth. Heat network engineering, procurement, construction management and automatic monitoring services are also projected to expand along with potential new markets in hydrogen heating for buildings. Energy efficiency measures could support up to £6 billion gross value added (GVA) and 175,000 jobs by 2030[38]. The development of and integration into domestic and international supply chains by UK companies will be essential to secure maximum economic benefit and market share.

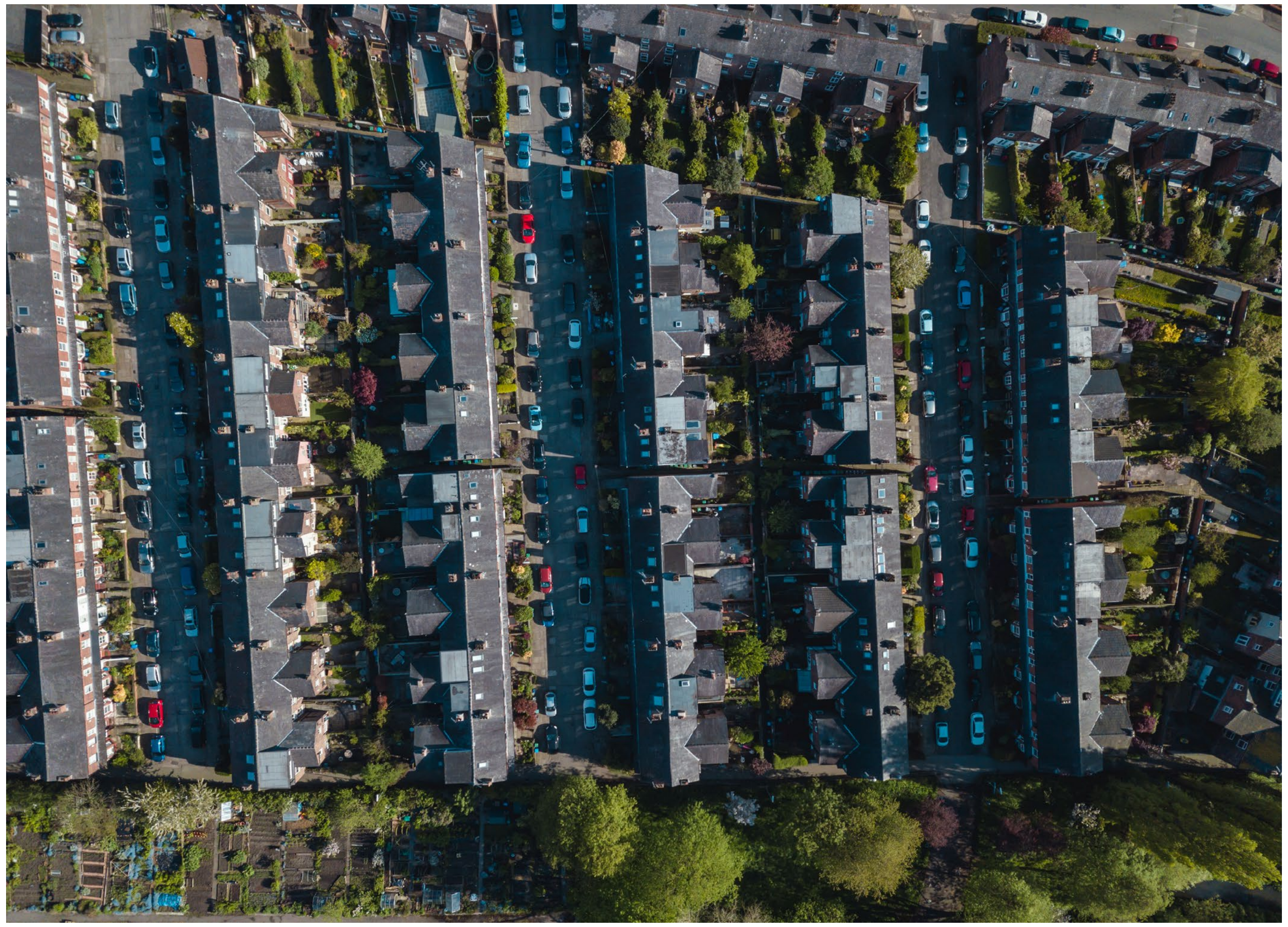
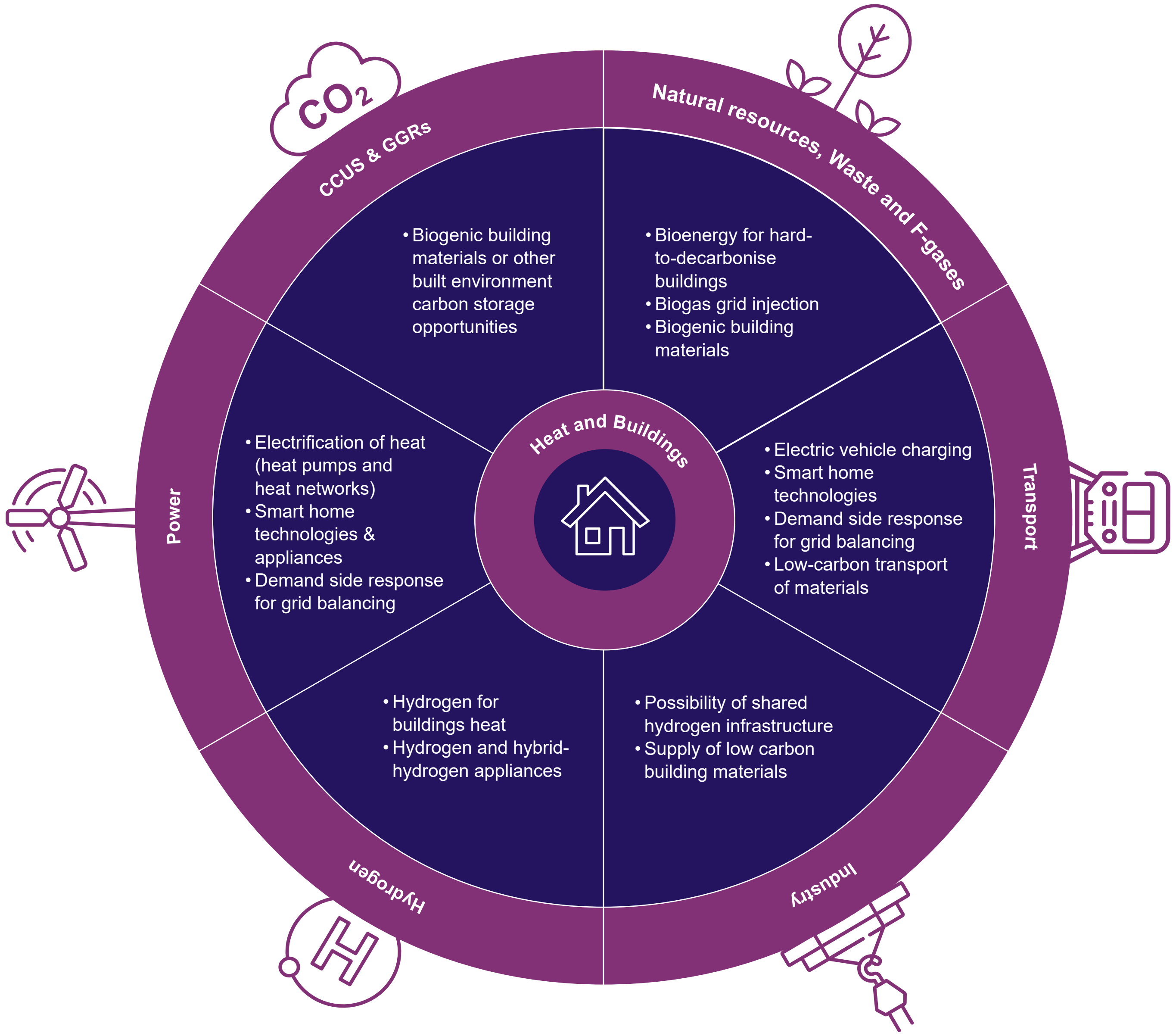


Figure 18: System interlinkages between Heat & Buildings and other sectors



Research and Innovation: challenges and needs

Given the diversity of potential heat decarbonisation options and the varied contexts in which these will be applied, research and innovation over the next decade will need to develop and test solutions at increasing scale in a range of different situations. For hydrogen, this involves supporting industry to deliver a hydrogen neighbourhood trial by 2023, a hydrogen village trial by 2025, with an aim for a hydrogen town by 2030. For heat pumps, optimising the installation process, in particular driving down installation costs and product innovation, are the immediate priorities.

Other priorities include accelerating delivery of decarbonisation solutions through innovative business models and offers, such as an integrated Whole House Retrofit approach, and research to understand how end-users may want to access solutions that best suit their needs. Developing lower-cost, lower-disruption solutions for hard-to-treat properties, such as solid wall insulation, is another key priority. In parallel, research and innovation in the construction industry is needed to transform the design, construction and materials used in buildings.

Challenge	Key research and innovation needs
Develop an enabling environment for system-wide decarbonisation of building stock	Leverage data to research and establish the real energy performance of buildings to inform decisions and drive improvements. Integrate retrofit solutions to identify and deliver the optimal mix of building fabric interventions and heating, cooling and storage technology, suited for different buildings and end-users. Develop innovative business models (e.g. energy as a service, builders / installers who can offer a Whole House/Building Retrofit package rather than an individual measure) and market arrangements (e.g. time-of-use tariffs). Further innovation to encourage standardisation of components, contracts, and installation practices to reduce costs and facilitate local supply chains. Support organisations to develop and trial green finance options, including: • Lender partnerships with energy efficiency and low carbon technology suppliers, stimulating development of a competitive green finance market. • Incentivise home and business owners to make improvements.

Challenge	Key research and innovation needs
Removing barriers to widespread energy efficiency retrofits in existing domestic and non-domestic buildings	Increase accessibility and availability of energy reduction and efficiency measures by encouraging innovation to: • Reduce upfront cost through systems engineering, including testing whole building approaches (such as Whole House Retrofit) for domestic and non-domestic end-users. • Reduce space requirements of retrofit and other energy efficiency solutions. • Develop energy reduction and efficiency solutions for hard-to-treat properties as well as alternative market innovations to support energy efficiency. • Develop the new supply chain models needed for deploying energy efficiency solutions, including whole house/building retrofit approaches, at scale. • Develop low-cost and transparent ways of measuring real-world performance of energy efficiency measures (for example, though Smart Metering Enabled Thermal Efficiency Ratings) to incentivise improved performance and support new end-user services and products.
Developing, demonstrating, reducing the costs of and de-risking low carbon heating and cooling technologies *Research and innovation needs relating to supply of clean hydrogen are covered in section 4.2.2*	For hydrogen: • Carry out necessary research and innovation to demonstrate safety, feasibility and impacts of converting parts or the whole of the existing natural-gas network to hydrogen. • Understand the wider implications of hydrogen as a fuel, e.g. hydrogen emissions (upstream and downstream), and energy system impacts. • Increase readiness and further innovation on hydrogen heating appliances and understand the impacts of safety measures on buildings e.g. hydrogen-ready boilers, particularly for commercial / industrial use, hybrid-hydrogen heat pumps, hobs / cookers etc. • End user trials testing user acceptance involving practical demonstrations. For heat pumps: • Reduce costs and improve efficiency e.g. industrialised manufacture and supply chain innovation. • Reduce disruption from installation and use of heat pumps, including time taken to install, space requirements, noise and ease of use. • Develop solutions to enable the phase out high global warming potential refrigerants, including F-gases, and move towards the use of natural or low impact refrigerants (see also section 4.6.4). • Trial innovative new business models to drive uptake, including flexibility services. • Improve collection of performance data, including at low temperatures. • Demonstrations of innovative heat pump solutions in a range of homes and at neighbourhood / district scale.

Challenge	Key research and innovation needs
	• Demonstrations of mass heat pump uptake in concentrated areas. • Develop solutions that optimise heat pump deployment to provide wider system benefits, including demand shifting to utilise low carbon energy sources and to help manage local electricity network capacity. For bioenergy in buildings: • Better understand potential role of biomass and liquid biofuels for providing heat to off-gas grid properties, potentially with hybrid heat pump systems. Support needs to take into account wider environmental goals, such as the government's statutory targets to improve air and water quality, and necessary innovation in abatement technologies for pollutant emissions from new fuels. For anaerobic digestion: • Routes to improve biomethane and / or hydrogen yield though the use of a variety of biomass feedstocks. • Address the challenge of storing, spreading and, in some cases transporting digestate, in order to support identifying and growing new markets for digestate as a beneficial and sustainable product. • Identify mitigation technologies and techniques best suited to address the potential negative impacts of digestate, including the impact of ammonia emissions on the government's statutory air quality and biodiversity targets. For gasification: • Research and innovation into feedstocks and the gasification process, as described in 4.1.4, with heating in buildings a possible end-use for fuels from gasification.
Maximising the potential of heat networks	Research and trials to incentivise connections to heat and cooling networks, to minimise the need to compel or enforce connections in heat network zones. Research and trials of disaggregated models of delivery or alternative business models to increase pace of delivery where zoning is an enabler and where it isn't. Research and trials of innovative solutions to access heat from existing and future heat sources; mine waste, geothermal, nuclear (AMR and SMR), industrial clusters, and Energy from Waste installations. Research and trials to identify optimal ways of transitioning high temperature combined heat and power (CHP) systems to future net zero options. Research and trials to understand the role of solar thermal in heat networks and the potential role of thermal stores for the wider system. See also section 4.1.1. Research to identify and develop innovative delivery models that enable effective expansion of networks in heat network zones over time.

Challenge	Key research and innovation needs
Integrating smart, low carbon technologies and solutions *Innovation needs for system flexibility are covered in section 4.1.1*	Develop and demonstrate standardised, cyber secure, interoperable smart systems to integrate low carbon technologies and energy efficiency at the building level e.g. heat-pumps (including hybrids), battery storage, hot water storage, electric vehicles, heating controls and smart appliances. Innovation to enable technologies in buildings to provide appropriate data in appropriate formats according to energy data best practice to key parties such as networks, system operators, suppliers and service providers. Improve understanding, modelling, and calculation methodologies for energy storage, for example how insulation, hot water tanks and batteries can and should be combined to provide an optimal solution.
Understanding end-user behaviour to drive uptake *Further research and innovation needs related to end user behaviour and willingness and ability to flex demand is captured in section 4.1.1*	Improve understanding of barriers to deployment of energy efficiency improvements, smart technologies and low carbon heating, how this differs for different domestic and non-domestic end-user groups, and how it differs for different segments of the population, for example, factors such as age / life status, income, ownership status of the home, geographical factors, etc. Develop understanding of the necessary advice and support needed to tackle low levels of awareness, empower end-users and support the necessary levels of uptake and acceptance for both near and longer-term deployment of low carbon heating and energy efficiency measures, including innovative financing trials. Develop understanding of any impacts, of installing low carbon heating and energy efficiency measures on end-user usage habits. Further research into end user green choices, acceptance and preferences to support near-term deployment ambitions.
Driving down emissions associated with construction	Development of new construction technologies, materials and techniques that can improve productivity, carbon performance and reduce waste, such as the use of digital design and offsite manufacturing technologies to create a larger range of building types. Research and innovation to optimise the design and specification of buildings to reduce the materials needed in construction or repurposing, and/or to look at innovative ways of reusing waste material into new configurations (by recycling cement, steel and other carbon-intensive materials into new building material). Research into embedding a focus on measuring and mitigating embodied and operational carbon emissions into the procurement and management of public sector infrastructure and construction projects.

Figure 19: Heat and buildings innovation needs timelines

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Develop an enabling environment for system-wide decarbonisation of building stock	Leverage data to research and establish the real energy performance of buildings including research on factors increasing the risk of gaps between models and actuals to inform decisions and drive improvements			
	Integrate retrofit solutions to deliver optimal mix of building fabric interventions and heating, cooling and storage tech for different buildings and end-users			
	Develop innovative business models (e.g. energy as a service) and market arrangements (e.g. time-of-use tariffs) and improve workforce upskilling processes			
	Further innovation to encourage standardisation of components, contracts and installation practices			
	Support organisations to develop and trial green finance options			
Removing barriers to widespread energy efficiency retrofits in existing domestic and non-domestic buildings	Reduce upfront cost through systems engineering, including testing Whole House Retrofit and capturing real world performance to support new services			
	Reduce space requirements of retrofit and other energy efficiency solutions			
	Develop energy reduction and efficiency solutions for hard-to-treat properties			
	Develop the supply chain models needed for deploying energy efficiency solutions at scale			
	Develop low-cost and transparent ways of measuring the real-world performance of energy efficiency measures (for example, though Smart Metering Enabled Thermal Efficiency Ratings) to incentivise improved performance and support new end-user services and products			
Developing, demonstrating, reducing costs of and de-risking low-carbon heating and cooling technologies	Hydrogen: Demonstrate safety, feasibility and impacts of using hydrogen as a fuel and converting existing gas network to hydrogen, e.g. emissions, wider energy system impacts			
	Hydrogen: Increase readiness of and further innovation for hydrogen heating appliances e.g. hydrogen-ready boilers, hybrid-hydrogen heat pumps, hobs / cookers, etc.			
	Hydrogen: End user trials testing user acceptance involving practical demonstrations			
	Heat pumps: Reduce costs & improve efficiency e.g. industrialised manufacture and supply chain innovation			
	Heat pumps: Reduce disruption from installation and use of heat pumps			
	Heat pumps: Develop solutions to enable the phase out high global warming potential refrigerants, including F-gases			
	Heat pumps: Trial innovative new business models to drive uptake, including flexibility services			
	Heat pumps: Improve collection of performance data, including at low temperatures			
	Heat pumps: Demonstrations of innovative heat pump solutions in a range of homes and at neighbourhood / district scale			
	Heat pumps: Demonstrations of mass heat pump uptake in concentrated areas			
	Heat pumps: Develop solutions that optimise heat pump deployment to provide wider system benefits, including demand shifting			
	Bioenergy: Understand potential role of biomass and liquid biofuels for providing heat to off-gas grid properties, potentially with hybrid heat pump systems			
	Anaerobic digestion: Routes to improve biomethane yield though the use of a variety of biomass feedstocks / possibility of heating through fuels from gasification			
	Anaerobic digestion: address the challenge of disposing of digestate and processes to remove contaminants and finding new markets for digestate			
	Anaerobic digestion: Identify mitigation technologies and techniques to address potential negative impacts of digestate, including emissions of ammonia			
	Gasification: Research and innovation into feedstocks and the gasification process, with heating in buildings a possible end-use for fuels from gasification			

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Maximising the potential of heat networks	Research and trials to incentivise connections to heat and cooling networks			
	Research and trials into disaggregated models of delivery or alternative business models to increase pace of delivery			
	Research and trials of innovative solutions to access of heat from, e.g. mine waste, geothermal, nuclear, industrial clusters and Energy from Waste installations			
	Research and trials to identify optimal ways of transitioning high temperature combined heat and power systems to future net-zero option			
	Research and trials to understand the role of solar thermal in heat networks			
	Research and trials to understand the value of thermal stores for the wider system			
	Research to identify and develop innovative delivery models that enable effective expansion of networks in heat network zones over time			
Integrating smart, low carbon technologies and solutions	Develop and demonstrate standardised, cyber secure, interoperable smart systems to integrate low carbon technologies and energy efficiency at the building level			
	Innovation to enable technologies in buildings to provide appropriate data to networks, system operators, suppliers and service providers			
	Improve understanding, modelling and calculation methodologies for energy storage, e.g. how insulation, hot water tanks and batteries can be combined to provide an optimal solution			
Understanding end-user behaviour to drive uptake	Improve understanding of deployment barriers for energy efficiency improvements, smart tech and low carbon heating for domestic and non-domestic end-users			
	Develop understanding of necessary support to tackle low levels of awareness, empower end-users and support uptake of low-carbon heating and energy efficiency measures			
	Develop understanding of any impacts of installing low carbon heating and energy efficiency measures on end-user usage habits			
	Further research into end user green choices, acceptance and preferences to support near-term deployment ambitions			
Driving down emissions associated with construction	Development of new construction technologies and techniques to improve design and specification, productivity, carbon performance and reduce waste			
	Research and innovation to optimise the design and specification of buildings to reduce the materials needed in construction or repurposing, and/or to look at innovative ways of reusing waste material into new configurations			
	Research into embedding a focus on measuring and mitigating embodied and operational carbon emissions into the procurement and management of public sector infrastructure and construction projects			
Policy ambitions	Decide on the long term future of heat by middle of this decade			
	Install 600k heat pumps per year by 2028			
	Potential end to high-carbon heat sources off the gas grid			
	Hydrogen neighbourhood trial by 2023, hydrogen village trial by 2025, hydrogen town by 2030			
	As many homes as possible to meet EPC band C by 2035			
	Future homes standard			

4.5 Transport

Context

Transport is the largest emitting sector in the UK. Surface transport, aviation and shipping combined accounted for 32% of the UK's GHG emissions in 2019[39] and over recent decades efficiency gains have been offset by growth in travel demand. To meet the UK's net zero target, the Net Zero Strategy estimates that transport emissions could need to drop by 76-86% compared to 2019, down to 23-40 $MtCO_2e$ by 2050. This will require substantial change across all transport modes supported by cross-cutting technology development to facilitate a shift in user green choices and attitudes.

The Transport Decarbonisation Plan sets out the greenprint for decarbonising the UK's transport system. It considers how people and goods move and sets out what will be needed to deliver the required emissions reduction on the way to net zero, including through place-based solutions, technology deployments and shifts to lower carbon and active modes of transport like walking and cycling, considering the needs of the whole journey. In addition, the Government is consulting on our Jet Zero Strategy, which will set out the approach and principles to deliver the ambition of decarbonising aviation. Close working with other sectors including energy infrastructure, buildings, and land use will be required as well as multiple routes to decarbonisation to mitigate risk in any one technology. The speed of the transition and complex interdependencies involved will require systems-level understanding and solutions.

Research and innovation is needed both to demonstrate and accelerate the deployment of technologies that are already close to market, and to develop and test emerging solutions that have potential to be the foundation for future advances. This is crucial in the harder to decarbonise maritime and aviation sectors, but also essential to ensure the UK retains its technological leadership in the automotive sector, one of the places where we are already seeing an acceleration in activity. It also means social research and behavioural science to accelerate the adoption of active travel and public transport and to enable the shift to zero emission vehicles as well as a better understanding of how we can provide people with better choices around travel.

Co-benefits of improved air quality and reducing adverse health impacts are likely to provide an additional incentive for change. Necessary new skills will need to be developed and widely available in time across manufacturing, supply chain and service industries. Innovation in the electricity market, infrastructure, and flexible services will be required to support decarbonisation in transport. Whilst the electrification of most surface transport will create new demand for electricity, it also provides opportunities for enhanced system flexibility through vehicle to grid technologies (see chapter 4.1.1).

Transport-related research and innovation should include the following.

1. Address the transport modes, nodes and use cases where there are currently no clear or agreed solutions (the harder to decarbonise areas) alongside efforts to increase efficient and sustainable supply of resources for technologies that are close to market (e.g. newer battery technologies).
2. Understand how we can make lives better by changing the journeys people need to make. This includes technologies that alter the need to travel, change travel modes or shift travel times, social trends which impact on commuting and work and changes to how we transport goods.
3. Understand when, where and how much decarbonised energy is required for each transport mode, and for the system as a whole, now and into the future.
4. Develop transport-specific energy supply technologies and other supporting infrastructure, including manufacture, as part of a place-based, decentralised wider energy system.
5. Support new product development leading to manufacturing scale-up and investment, anchoring the value chain in the UK to maximise UK content and economic benefit alongside meeting net zero targets and exploring co-benefits.
6. Deliver systems-level decarbonisation and modal shift, by bringing behavioural and technological solutions together at scale to meet user needs for particular geographical areas, sectors, and services.

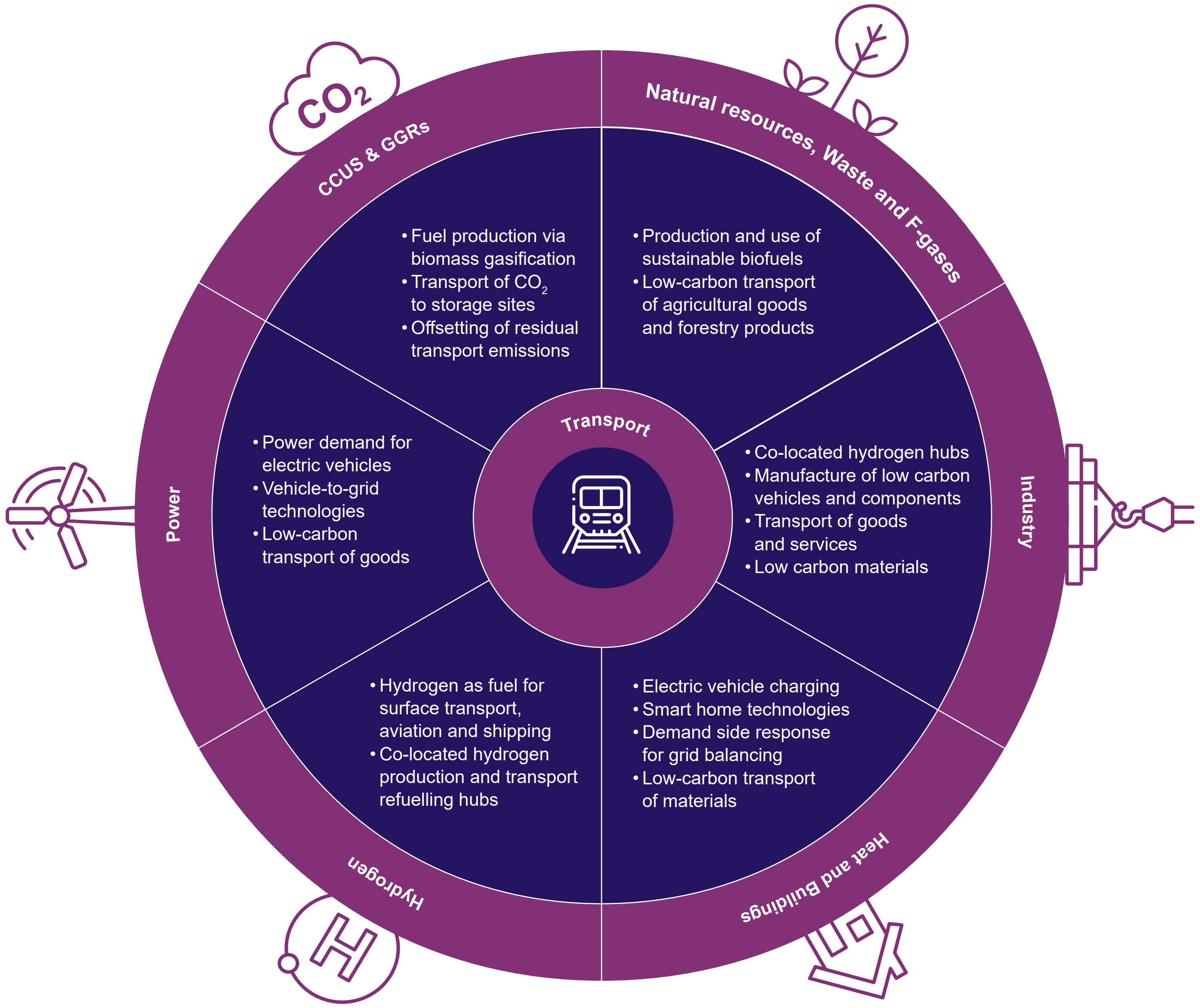
Innovation needs include options for road freight, maritime and aviation to identify and develop best fit technology pathways for the UK by the mid-2020s; preparation of demonstration programmes and trial infrastructure which will be ready to test and understand the implementation of these new solutions in the mid-2020s to enable roll-out through the 2030s – especially where vehicles have long operational lives like trains and ships; and identifying complementary options for decreasing road emissions to meet Carbon Budget 6. This includes behaviour change, modal shift and data-driven approaches.

The medium-term (2025-30) focus will be completing demonstration programmes in trucks, maritime and aviation; continuing to support the penetration of electrification throughout the light road vehicle fleet; supporting decisions on UK-wide infrastructure needs (charging infrastructure, hydrogen, ports and airports) and how they are best integrated into the wider energy system; as well as data and asset sharing in the freight and logistics system to enable better carbon efficiency in the short-term and efficient deployment of zero-emissions vehicles and other assets in the medium / longer term.

The challenges of transportation are heightened by the international context. Most modes have interfaces with other countries or at the very least similarities which have implications for standardisation of technologies, the harmonisation of regulations, and the sharing of learning and effort. For example, as a core member of the Zero-Emission Shipping Mission[40], the UK is working across the entire maritime value-chain— ships, fuel production, fuel infrastructure— through a focus on 'green shipping corridors'.

Investments in research and innovation will also provide market opportunities for UK companies, especially in the hardest-to-decarbonise transport sectors such as shipping, aviation and heavy goods vehicles, where all countries will be facing the same challenges, and in relation to the development and commercialisation of hydrogen and sustainable aviation fuels. In addition, by pursuing an integrated approach that combines active travel and micro-mobility with behavioural science and new low emissions infrastructure, the UK can showcase systems-levels solutions and export related technologies and services to other countries.

Figure 20: System interlinkages between Transport and other sectors



4.5.1 Transport and mobility as a system

Research and innovation: challenges and needs

Much of the innovation and deployment needed to decarbonise transport will have impacts at the system level, cutting across specific transport modes and energy vectors.

Key areas for attention include developing a better understanding of system level interdependencies and ensuring that people and place are both central to a net zero transition. Behaviour change and choice need to interact with technology innovations if we are to successfully deliver the required decarbonisation. Research into behaviour and the application of behavioural theory can build an understanding of current and future users' needs and likely green choices and how best to influence them, informing structural changes in policies, regulation, and infrastructure. Embedding these insights into transport decarbonisation decisions will allow for more effective and targeted investment in transport research and innovation.

Challenge	Key research and innovation needs
Enabling an integrated, multi-modal transport system	Understand how to integrate transport into local and national decarbonised energy system planning, including both the electricity system and a future hydrogen economy without impacting the government's statutory targets to improve the environment, such as for air quality. System analysis to identify interactions with wider systems and infrastructure, including optimal locational configurations for refuelling and charging infrastructure for different modes of transport. Investigate the potential for co-location of assets and infrastructure to improve efficiencies. Research into the role of different policy and regulatory frameworks, such as carbon pricing and emissions zones, to impact choices and acceptance of actors across the supply chain and end-users. Research into skills which support the transition in transport across the board, some of which are not visible yet. Research into new approaches for sharing and integrating data to enable a smoother transition (e.g. in freight) and enable holistic understanding of the role of different interventions on overall carbon impact. Understanding how to unlock efficiency benefits in freight and logistics by better leveraging of data and sharing.
Accelerating the adoption of active travel and public / shared transport	Innovations in the design of buildings, the wider built environment, including towns and cities, that support more sustainable green choices and enable low carbon forms of travel. Research to encourage the safe shift to more active forms of travel such as cycling, walking and newer forms of micro-mobility, considering how user needs and experiences are shaped and any barriers to making that shift. Also understanding co-benefits such as improved cardiovascular health and improved air quality and how these can provide additional incentives for people to embrace behavioural shifts. Understanding the potential impacts of innovations which impact on transport use e.g. digital technologies.
Addressing regional needs and place-based approaches	Ensure technological and market changes are built around an understanding of end-users and the communities in which they live and work. Understand local / regional needs and opportunities so that decarbonisation approaches build on existing skills to support local economic growth. Understand transport's role in improving equity across the UK, including equitable solutions for rural areas and maximising potential for new skill development. Understand how decarbonisation interventions can deliver wider co-benefits in terms of air quality, noise and health, including for vulnerable groups. Understand the benefits of the colocation of transport energy infrastructure, such as marine and aviation refuelling which could share raw materials or other aspects of operations.
Improving efficiency and reducing carbon intensity / eliminating emissions for production of vehicles, vessels and infrastructure	Fuel and energy efficiency improvements, new materials and light weighting improvements selected on the basis of whole life cycle analysis. Embedding circular economy approaches throughout product lifecycle, including innovations in design, retrofit, and reuse. Application of low carbon construction techniques, skills and materials for new transport infrastructure – concrete, steel, road surfaces, etc. Improve data usage and connected travel that actively reduces journey length and improves journey efficiency across modalities.

Challenge	Key research and innovation needs
Understanding and enabling hydrogen's role in transport *Hydrogen production is covered in section 4.2.2*	Understand the role of transport in the hydrogen economy and vice versa, including the role of a centralised versus decentralised hydrogen production system. Understand societal barriers to uptake and use of hydrogen vehicles. Identifying requirements for fuel handling, distribution and refuelling technologies for hydrogen across all modes and for ammonia within the maritime sector and (potentially) aviation. Accelerate hydrogen research, development and demonstration in core enabling technologies, such as fuel cells. Understanding and demonstrating the value of hydrogen storage onboard all vehicles, including secondary engine solutions. Hydrogen safety and security research, standards, and technologies. Potential hydrogen role in synthetic fuel production. Demonstration of end-use at scale, including hydrogen refuelling and use in multi-modal operational trials.
Supporting the urgent roll-out of electrification across all transport modes	Understanding and designing electricity storage, distribution, and recharging technologies across all modes and impact of large-scale electrification of transport on the power system. Developing battery technologies for heavier modes with higher power requirements. Developing more sustainable battery technologies which are less reliant on scarce mineral supply chains, and innovation to mitigate end-of-life impacts (including recycling and repurposing of batteries). Development of new electric power trains and drives and other key components and subsystems of electromobility. Large scale trials and demonstration of successful system level integration to de-risk adoption of technology for new users.
Understanding the medium and long-term behavioural changes of travellers as a result of COVID-19	Working to lock-in beneficial changes in travel behaviour, e.g. increases in cycling, and countering less beneficial changes like increased car usage. Undertaking long term behavioural studies to understand the impact of COVID-19 on people's travel patterns, including a move to more flexible working resulting in less demand for commuting, or any aversion of crowded spaces which could result in reduced use of public transport and how this will impact upon travel planning and future policy development.

4.5.2 Land transport

Research and innovation: challenges and needs

Surface transport accounted for 22% of total UK GHG emissions in 2019[41]. Electrification is expected to be the principal decarbonisation solution, but other low carbon fuels, particularly hydrogen, may have an important role to play particularly for HGVs, other larger vehicles, and for trains on hard-to-electrify lines. Research and innovation challenges focus on technologies for different transport modes, how to design and build new refuelling and recharging infrastructure and how to integrate electric vehicles with the wider electricity system. Complementary approaches to reducing emissions from roads will also be key for meeting Carbon Budget 6.

Challenge	Key research and innovation needs
Supporting the development and deployment of zero emission road vehicles	For light road vehicles: • Improving the efficiency and scaling of Electric Vehicle (EV) manufacture, including relevant technologies for the EV supply chain. • Advances in zero emission on-vehicle technologies to improve EV range, efficiency and capability. • Trialling of EV infrastructure improvements including charging and vehicle to grid (V2G) integration, also flexible / smart charging. • Accelerating advances in lithium-ion battery technology, such as lifespan, range, recyclability and weight. • Development of novel battery technologies which can improve on the environmental impacts or other aspects of performance of current technologies later in the transition to net zero. • Make smart charging attractive and accessible to diverse users, through trial products and incentives, as well as developing cyber secure and interoperable smart charging products. • Improve the user experience of zero emission vehicles through advances in range capability, accessibility, cost reduction and other aspects of usability. For buses and coaches: • Research to understand how to deploy hydrogen and electric buses to respond to local factors such as climate, topography, population density and travel needs. • Research in decarbonised coach solutions to meet coach-specific requirements. For HGVs, municipal vehicles and non-road machinery: • Testing and demonstration of candidate technologies including hydrogen, battery and electric road systems (such as overhead catenary lines) to support the deployment of infrastructure at scale and reduce other environmental impacts. • Decarbonised agricultural, construction, and mining vehicles and supporting refuelling / recharging solutions. • Fuel cell flexibility, efficiency, reliability and materials sustainability. • Mega-charging for HGVs.

Challenge	Key research and innovation needs
Complementary approaches to roads decarbonisation	• Research into approaches to drive modal shift. • Research into changes in travel behaviour. • Data-driven techniques to reduce road transport emissions.
Decarbonising railways	Develop and demonstrate solutions for lines which are uneconomical to electrify and where rolling stock needs to run across the whole network, as in freight and maintenance. Demonstration and evaluation of efficient hydrogen trains and cost-effective hydrogen rail infrastructure. Investigate hydrogen distribution by rail to support other modes and sources of demand, including hydrogen rail depots and their role as potential hydrogen economy nodes. Trial and demonstrate zero emissions rail freight infrastructure, including warehouses and depots.

4.5.3 Aviation and maritime

Research and innovation: challenges and needs

Aviation emissions (including the UK's share of international aviation) have more than doubled since 1990[42]. Maritime emissions are growing as a proportion of all transport emissions, with domestic shipping producing more GHGs in 2019 than buses and rail combined[43]. If UK international shipping emissions are also included, the maritime sector produces almost three times the GHG emitted in 2019 by buses and rail combined.

Both aviation and maritime are amongst the most difficult-to-decarbonise sectors of the economy with most low carbon and zero-carbon solutions at very early stages of development. As a result, research and innovation is particularly crucial in these sectors and a variety of potential solutions need to be developed and tested over the coming decade, to enable the best options to be scaled up. This includes Sustainable Aviation Fuels obtained from low carbon feedstocks which could be combined with existing conventional jet fuel to reduce emissions. The transnational nature of aviation and maritime underscores the importance of global collaboration to develop fully interoperable solutions for the refuel and recharge of aircraft and vessels.

Challenge	Key research and innovation needs
Developing net zero emission flight and associated operations	Integrated research and innovation activity across aerospace sector capabilities including, improving efficiencies, zero emissions flight, Sustainable Aviation Fuels markets and removals and influencing end-user choices. Zero emissions aircraft and airside vehicles across vehicle type, load and journey length, with care to avoid increases in non-CO_2 greenhouse gases. Preparing UK airports for adoption of net zero emission aircraft and zero CO_2 airside operations (ground vehicles and refuelling infrastructure). Facilitate continued UK research and innovation on aerospace manufacturing. Zero emissions flight airfields and operations: • Zero emission flight airport infrastructure research and innovation. • Continued development of more efficient and zero emission aircraft. • Certification and infrastructure requirements for large zero emission commercial passenger aircraft. • Continued modernisation of UK airspace. Develop and trial sustainable aviation fuel production in the UK. E-fuels, gasification and waste lipids present options, but each has wider system implications which need to be understood.
Decarbonising maritime	Deliver research and innovation to unlock industry investment in clean maritime technologies, tackling supply and demand side barriers as well as developing infrastructure and user confidence. This includes: • Trials and demonstrations to accelerate the market penetration of zero emission vessels and systems, including battery electric vessels, charge points and other port infrastructure for the bunkering and refuelling of alternative fuels. • Technology development and demonstrations of pre-commercial vessels and infrastructure using hydrogen, ammonia and other zero emission solutions without impacting on the government's timescales to meet other statutory targets (e.g. air quality), enabling solutions to reach market level and building market confidence. Demonstration of hydrogen and ammonia bunkering and dispensing at ports and at sea. Other priorities include: • Research and innovation for automation and other technologies which can boost energy efficiency of port related activities. • Work to understand the energy usage at ports, including impact on the grid.

Figure 21: Transport Innovation Needs Timelines

Transport and mobility as a system

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Enabling an integrated, multi-modal transport system	Understand how to integrate transport into local and national decarbonised energy system planning			
	System analysis to identify interactions with wider systems and infrastructure, including optimal locational configurations for refuelling/charging infrastructure			
	Investigate the potential for co-location of assets and infrastructure to improve efficiencies			
	Research into the role of different policy and regulatory frameworks, such as carbon pricing and emissions zones, to impact behaviour of actors across the supply chain and end-users			
	Research into skills which support the transition in transport across the board, some of which are not visible yet.			
	Research into new approaches for sharing and integrating more data to enable a smoother transition, e.g. in freight			
	Understand how to unlock efficiency benefits in freight and logistics by better leveraging of data and sharing			
Accelerating the adoption of active travel and public / shared transport	Innovations in the design of buildings and the wider built environment that support more sustainable green choices and enable low carbon forms of travel			
	Research to encourage the safe shift to more active forms of travel such as cycling, walking and newer forms of micro-mobility			
	Understand the potential impacts of innovations which impact on transport use e.g. digital technologies			
Addressing regional needs and place-based approaches	Ensure technological and market changes are built around an understanding of end-users and the communities in which they live and work			
	Understand local / regional needs and opportunities so that decarbonisation approaches build on existing skills to support local economic growth			
	Understand transport's role in improving equity across the UK, including for rural areas and maximising potential for new skill development			
	Understand how decarbonisation interventions can deliver wider co-benefits in terms of air quality, noise and health, including for vulnerable groups			
	Understand the benefits of the colocation of transport energy infrastructure, such as marine and aviation refuelling			
Improving efficiency and reducing carbon intensity / eliminating emissions for production of vehicles, vessels and infrastructure	Fuel and energy efficiency improvements, new materials and light weighting improvements selected on the basis of whole life cycle analysis			
	Embed circular economy approaches throughout product lifecycle, including innovations in design, retrofit, and reuse			
	Application of low carbon construction techniques, skills and materials for new transport infrastructure – concrete, steel, road surfaces, etc.			
	Improve data usage and connected travel that actively reduces journey length and improves journey efficiency across modalities			

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Understanding and enabling hydrogen's role in transport	Understand the role of transport in the hydrogen economy and vice versa, including centralised vs. decentralised hydrogen production system			
	Understand societal barriers to uptake and use of hydrogen vehicles			
	Identify requirements for fuel handling, distribution and refuelling techs across all modes and for ammonia in maritime and (potentially) aviation			
	Accelerate hydrogen research, development and demonstration in core enabling technologies, such as fuel cells			
	Understand and demonstrate the value of hydrogen storage onboard all vehicles, including secondary engine solutions			
	Hydrogen safety and security research, standards, and technologies			
	Potential hydrogen role in synthetic fuel production			
	Demonstration of end-use at scale, including hydrogen refuelling and use in multi-modal operational trials			
Supporting the urgent roll-out of electrification across all transport modes	Understand and design electricity storage, distribution, and recharging technologies across all modes and impact of electrification of transport on the power system			
	Develop battery technologies for heavier modes with higher power requirements			
	Develop more sustainable battery technologies which are less reliant on scarce mineral supply chains, and innovation to mitigate end-of-life impacts			
	Development of new electric power trains and drives and other key components and subsystems of electromobility			
	Large scale trials and demonstration of successful system level integration to de-risk adoption of technology for new users			
Behavioural changes of travellers as a result of COVID-19	Work to lock-in beneficial changes in travel behaviour during the pandemic, e.g. increases in cycling and countering less beneficial changes like increased car usage.			
	Undertake long term behavioural studies to understand the impact of COVID-19 on people's travel pattern			
Policy ambitions	End sale of new petrol and diesel cars and vans. All new cars and vans must be zero emission at the tailpipe (2035)			
	End sale of new non-zero emission HGVs (subject to consultation) (2040)			
	Net zero domestic aviation (subject to consultation) (2040)			
	Ambition to remove all diesel-only trains from the network (2040)			

Land transport

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Supporting the development and deployment of zero emission road vehicles	Light road vehicles: Research and innovation to improve the efficiency and scaling of EV manufacture including relevant technologies for the EV supply chain			
	Light road vehicles: Advances in zero emission on-vehicle technologies to improve EV range, efficiency or capability			
	Light road vehicles: Trial EV infrastructure improvements including charging and vehicle to grid (V2G) integration, also flexible / smart charging			
	Light road vehicles: Accelerate advances in lithium-ion battery technology, such as lifespan, range, recyclability and weight			
	Light road vehicles: Development of novel battery technologies which can improve on the environmental or other aspects of performance of current technologies later in the transition to zero			
	Light road vehicles: Make smart charging attractive and accessible to diverse users, through trial products and incentives, alongside developing cyber secure and interoperable smart charging products			
	Light road vehicles: Research and innovation to improve the user experience of zero emission vehicles through advances in range capability, accessibility, cost reduction and other aspects of usability			
	Buses & coaches: Research to understand how to deploy hydrogen and electric buses to respond to local factors such as climate, topography, population density			
	Buses & coaches: Research in decarbonised coach solutions to meet coach-specific requirements			
	HGVs, municipal and machinery: Test and demonstrate of candidate technologies including hydrogen, battery and electric road systems			
	HGVs, municipal and machinery: Decarbonised agricultural, construction, and mining vehicles and supporting refuelling / recharging solutions			
	HGVs, municipal and machinery: Fuel cell flexibility, efficiency, reliability and materials sustainability			
	HGVs, municipal and machinery: Mega-charging for HGVS			
Complementary approaches to roads decarbonisation	Research into approaches to drive modal shift			
	Research into changes in travel behaviour			
	Data-driven techniques to reduce road transport emissions			
Decarbonising railways	Develop and demonstrate solutions for lines which are uneconomical to electrify and where rolling stock needs to run across the whole network			
	Demonstration and evaluation of efficient hydrogen trains and cost-effective hydrogen rail infrastructure			
	Investigate hydrogen distribution by rail to support other modes and sources of demand, including hydrogen rail depots and their role in a hydrogen economy			
	Trial and demonstrate zero emissions rail freight infrastructure, including warehouses and depots			

Aviation and maritime

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Developing net zero emission flight and associated operations	Integrated research and innovation activity across aerospace sector capabilities, including improving efficiencies, zero emissions flight, sustainable aviation fuels, markets and removals, and influencing end-user choices			
	Zero emissions aircraft and airside vehicles across vehicle type, load and journey length, with care to avoid increases in non-CO_2 Greenhouse gases			
	Prepare UK airports for adoption of net zero emission aircraft and zero CO_2 airside operations (ground vehicles and refuelling infrastructure)			
	Facilitating continued UK research and innovation on aerospace manufacturing			
	Zero Emission Flight airport infrastructure research and innovation early in the transition, to support other elements of a net zero aviation system			
	Continue development of more efficient and zero emission aircraft			
	Certification and infrastructure requirements for large zero emission commercial passenger aircraft			
	Continue modernisation of UK airspace			
	Develop and trial sustainable aviation fuel production in the UK. E-fuels, gasification and waste lipids present options, but each has wider system implications which need to be understood			
Decarbonising Maritime sectors	Deliver research and innovation activity to tackle supply and demand side barriers as well as developing infrastructure and user confidence			
	Trials and demonstrations to accelerate the market penetration of zero emission vessels and infrastructure such as battery vessels, chargepoints and cold ironing			
	Technology development and demonstrations to enable pre-commercial solutions including hydrogen and ammonia fuel cell systems to reach market level			
	Demonstration of hydrogen and ammonia bunkering and dispensing at ports and at sea			
	Research and innovation for automation and other technologies which can boost energy efficiency of port related activities			
	Work to understand the energy usage at ports and provision of cold ironing (provision of shoreside power for ships at berth)			

4.6 Natural resources, Waste and F-gases

Context

Achieving net zero will require the strategic and sustainable management of land, waste and natural resources - including agriculture, biomass production, treescape and forestry, soil and peatland management, the marine and coastal environment, waste and recycling, urban developments and infrastructure, wastewater treatment and fluorinated gases (F-gases).

These sectors will need to contribute to net zero in four ways.

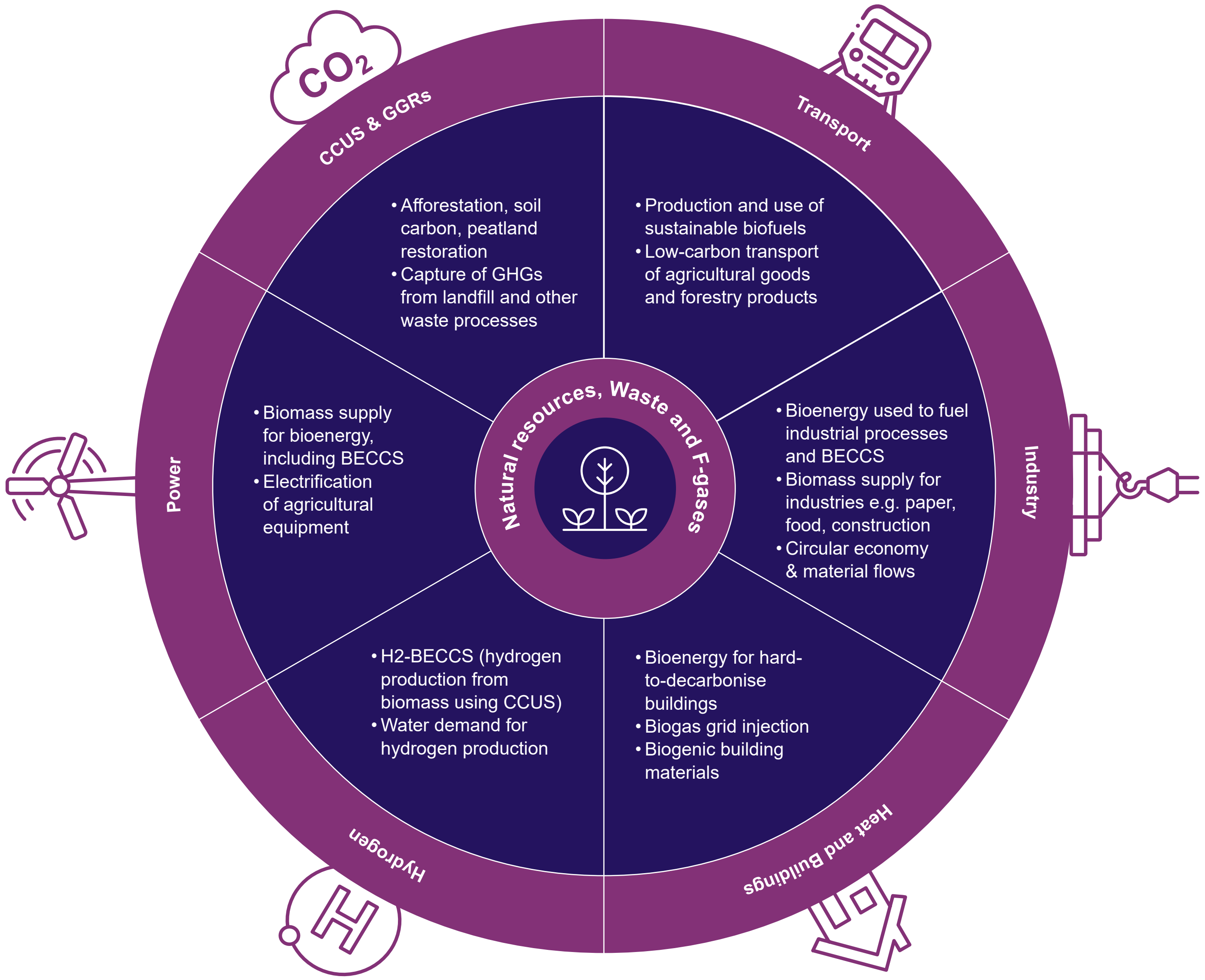
- By reducing direct emissions. Currently around 10% of the UK's total GHG emissions come from agriculture and around 4% from the waste sector[44]. These are mostly non-CO_2 emissions such as methane from livestock and decomposing waste, and nitrous oxide from the application of fertiliser and organic materials to land.
- By sequestering carbon dioxide from the atmosphere and helping to offset residual emissions from other hard-to-abate sectors. Afforestation and changes in land management offer routes to achieve this objective, but air quality currently has a significant impact on tree health, which may impact on their ability to sequester carbon at the rate expected.
- By providing sustainable biomass for energy generation directly and in the production of other fuels (e.g. sustainable aviation fuels) and the wider bioeconomy (e.g. wood in construction and for bio-based plastics). This can reduce emissions from materials with high GHG emissions, such as cement, and provide additional storage of carbon, although the risks of wider negative impacts from unsustainable biomass use must be carefully managed.
- By reducing the use of F-gases in equipment such as refrigeration and air-conditioning (driven by a switch to alternative gases and technologies).

Delivery of these aims must be achieved at the same time as improving biodiversity, air quality, water quality, natural capital, ecosystem services and resilience to climate change. The 25 Year Environment Plan sets out the UK's goals for improving the environment within a generation. It aims to deliver cleaner air and water, protect species and habitats, tackle waste and soil degradation and help to mitigate and adapt to climate change. The plan, which incorporates the government's statutory targets, aims to deliver once-in-a-lifetime changes to reform agriculture and manage land more sustainably.

Ongoing research and monitoring will be needed to provide the evidence base to guide policy and related decision making over time. This will require an integrated, systems-based approach that takes account of emissions reduction alongside the need to meet these other statutory environmental targets and social and economic goals. There will be co-benefits and trade-offs between different objectives, and these need to be managed responsibly with a broad understanding of wider impacts across different sectors and places. Social and behavioural considerations and a focus on environmental science will be as important as technology in driving innovation and the changes needed for net zero, such as changes in consumer demand for food, public acceptability of new products, and the willingness of farmers and land managers to adopt new approaches. As a result, research and innovation must focus on people as much as technology and environmental science.

Scientific breakthroughs in nutrition, genetics, informatics and big data, remote sensing, engineering, robotics, meteorology, and monitoring technologies are playing a key part in developing technologies to transform traditional practices. Business opportunities exist in the UK agri-tech sector, which serves a growing international market; in the biosciences and biotechnologies sector; in carbon professional services, such as selling expertise in low carbon farming practices; and in monitoring, reporting and verifying emissions. Carbon sequestration projects may also provide future opportunities when further developed.

Figure 22: System interlinkages between Natural Resources, Waste and F-gases and other sectors



4.6.1 An integrated and dynamic approach to land-use

Research and innovation: challenges and needs

There are multiple demands on land that influence how it is used and the urgency of net zero means that actions may need to be taken before all wider impacts are adequately understood. Compounding this challenge is the complexity of interactions between land management decisions, impacts on society and the natural environment and overall GHG emissions – including those outside the UK. Land-use planning is therefore a key consideration for research and innovation. A flexible and dynamic approach, that recognises the tensions and trade-offs in decision making will be essential, underpinned by the best possible understanding of the multi-objective systemic nature of land use and management.

Challenge	Key research and innovation needs
Land use allocation & planning considerations	Develop the tools and capabilities to inform land-use decisions and policy interventions at national and local scales, taking into account the interplay between land-use, end user preferences, land manager acceptability, policy and regulatory frameworks, incentives and technologies: • Research on green financing framework and practical applications of blended finance mechanisms. • Research on the economic values of protected landscapes. • Research on Monitoring and evaluation of landscapes policies.
Understanding system level greenhouse gas emissions and environmental impacts	Systems research to assess solutions within land, social, economic and environmental constraints, and considering a broad range of impacts including on natural capital and climate resilience: • Research into agroecological and integrated farm management practices. • Understanding the impact historical land use or pollution deposition may have on the ability to deliver carbon sequestration goals. Develop modelling and datasets for greenhouse gas impacts of agricultural processes, forestry, peat and soils, to understand impact of changes at system level in conjunction with other environmental pressures, such as air quality.

Challenge	Key research and innovation needs
Effecting sustainable and responsible land use change and effects on economic growth / levelling-up agenda	Research and innovation to identify the social, economic and cultural drivers of land use, barriers to sustainable land use change, and assess the options to effect these changes. Research and innovation into markets and financing to drive tree planting, perennial energy crops and short rotation forestry for bioenergy and the wider bioeconomy, peatland restoration and other forms of sustainable land use and tracking compliance / verifying delivery of intended reductions. Research to measure profitability of sustainable and responsible farming systems on peat and soils and how food production will be impacted. Research to review how existing land use models are informing economic growth decisions at both national and local level: • Understand how skills programmes and education strategy can support environmental goals and green growth. • Research on environmental taxation. • Research on environmental impacts of new trade agreements. • Research on corporate natural capital accounting. • Research on barriers to accessing nature for certain demographics.

4.6.2 Forests, peatland and the marine environment

Research and innovation: challenges and needs

The UK's natural assets, such as its treescape, forests, soils, peatlands and marine environments are important habitats for a range of species and provide multiple benefits to society, including carbon storage and sequestration, low carbon energy generation and feedstock production, biodiversity and improved natural capital assets. Net zero will require changes to the management of these environments and research is required to better understand these changes and their impacts, and new approaches and solutions will need to be developed and demonstrated.

Trees act as a natural carbon sink and are essential to meet long term targets. The government is committed to increasing tree-planting in the UK to 30,000 hectares (ha) per year by 2025 and alongside this there is a need to improve the management of existing woodlands. This must be underpinned by research into appropriate species selection and responsible land management practices.

Peat is the UK's largest terrestrial carbon store. Farmed lowland peat is currently responsible for 86% of England's peatlands carbon emissions, but is also some of the most productive agricultural land. Better management of lowland and upland peatlands will see a range of co-benefits alongside climate change mitigation. However, significant areas of peatland exceed safe thresholds for nitrogen deposition and ammonia exposure which damages the mosses responsible for peat production. The government is committed to restoring 35,000 ha of peat in England by 2025.

Healthy soils underpin a range of environmental, economic and societal benefits including carbon storage and biodiversity. The 25 Year Environment Plan sets the goal of sustainably managing all of England's soils by 2030. Developing a healthy soils indicator, soil structure and soil health measuring and monitoring schemes will enable the government to deliver on this target; research into methodologies and baseline data sets will support the development of suitable metrics and indicators.

Certain marine and coastal habitats, including saltmarsh, seagrass and marine sediments, are important long-term carbon stores. These habitats can be lost or damaged by human activities and their area is being squeezed by sea level rise, which can contribute to carbon emissions, whilst habitat creation and restoration could contribute to carbon removals whilst also providing a range of co-benefits for biodiversity and climate adaptation. Currently 38% of UK waters are in Marine Protected Areas, covering the majority of saltmarsh and seagrass habitats, with the Government now taking steps to ensure these are effectively protected. The marine environment also hosts infrastructure such as offshore wind, and this development must be pursued in ways that protect or enhance ecosystems.

Challenge	Key research and innovation needs
Sustainably expanding and managing forests and the wider treescape	Develop and trial improved ground based and remote sensing technologies and modelling for carbon storage calculations, including forest soils and trees outside woodlands. Expand long term plot monitoring to resolve uncertainties. Understand the variability and dependencies between different woodland types and silvicultural dependencies (rewilding, natural colonisation, etc.) including to changing climatic and environmental conditions. Understand silvicultural and arable agroforestry impacts on biomass and soil carbon, soil health and wider greenhouse gas balances. Manage and trial strategies to minimise damage to forestry from pests and pathogens. Field trials of short rotation forestry, including using exotic species for biomass. Develop and trial innovative finance models for land managers to transition to forestry. Develop and trial innovative supply chains for planting materials well adapted to the UK. Understand social and behavioural drivers and barriers e.g. land ownership, acceptability, skills, finance, incentives, co-benefits. Collaborative R&D with the commercial forestry and building sectors to increase supply and demand of timber in built infrastructure. Establish robust estimates of the abatement delivered by harvested wood products in use through carbon storage and product substitution.
Developing increased resilience of forest ecosystems to climate change impacts	Improved understanding of the resilience of woodlands and trees to climate change, including impacts of pests, diseases and other environmental pressures such as air quality. Genomic sequencing of tree populations and mapping of characteristics to improve enhancements beneficial to future circumstances. Research into the soil bacteria characteristics of different forest types, to understand how bacterial communities enhance (or disadvantage) resilience in different ways. Research into fungi characteristics of different forest types, to understand how fungi enhance (or disadvantage) resilience in different ways.

Challenge	Key research and innovation needs
Restoring sustainably and managing peatlands	Research into, and the development of, sustainable lowland peat management options that allow for productive and profitable agriculture to take place while water levels are raised, to sustain healthy and wildlife rich peatlands which provide ecosystem services such as carbon sequestration and flood mitigation and which do not lead to other negative impacts. Understanding the tensions and trade-offs between food production, greenhouse gas emission abatement and peat loss. Improved evidence on greenhouse gas balances of peatland restoration establishing the rate of deployment, scientific uncertainty, associated costs and trade-offs. Better understanding of optimal landscape scale water management for wetter peat (to reduce emissions) and mitigating flood risk. Innovative research to assess alternative approaches to peatland horticulture to enable an expanded sector while decreasing land-use emissions.
Managing soils for improved soil health and resilience	Researching and developing suitable data collection protocols and baseline data sets to develop a healthy soil indicator. Develop and pilot a soil structure measuring and monitoring method as a key physical element of the healthy soil indicator. Research into alternative farming methods, such as regenerative agriculture and agroforestry¸ to establish the soil health and potential carbon sequestration benefits of these systems. Research to understand the potential requirements of a Soil Carbon Code and the potential for a future carbon farming scheme in England.
Sustainably managing the marine environment	Research into greenhouse gas emissions and removals from coastal wetlands, including impacts of coastal erosion, wetland restoration, air quality, water quality, climate change, and sea-level rise. Including improved greenhouse gas accounting and reporting, with clear assessment of additionality and permanence of changes in carbon fluxes and stores. Assess the scale and direction of change in carbon storage and sequestration to human activities (e.g. trawling, dredging, coastal development) and how to accurately account for these. Understand the impact of different management interventions and ecosystem recovery on carbon fluxes and stores.

Challenge	Key research and innovation needs
	Research and long-term monitoring to understand impacts of decarbonisation infrastructure and habitat change on other users of marine spaces e.g. recreation, fishing, shipping, infrastructure development. Innovation in design and construction of offshore infrastructure (e.g. offshore wind, 5G phone sites) to minimise environmental impacts. Also research into social acceptance of offshore programmes and the financial implications of building offshore versus on land. Research into sustainable salt and fresh-water aquaculture systems. Identifying and measuring the benefit of ecosystem-based approaches to aquaculture on ecosystem functioning and services (e.g. carbon storage and sequestration, water filtration, nutrient cycling). Better understanding the solutions required to minimise and mitigate the environmental impacts (e.g. disease, escapees, discharge) of existing aquaculture systems.

4.6.3 Food and biomass

Research and innovation: challenges and needs

Over 60% of agricultural emissions are produced by livestock with the rest coming from crop production and fuel use in agriculture. Solutions are needed to reduce these emissions whilst also addressing other land-based challenges such as food security. Research and innovation needs to address both the supply and demand of agricultural products, and to develop solutions that support sustainable choices and acceptance of end-users and farmers. This may include non-traditional forms of production including vertical agriculture and lab-based production of alternative proteins.

The current biomass resource supply is diverse. A significant portion of biomass for use in energy generation and the wider bioeconomy is sourced from wastes and residues from the agriculture, forestry and waste sectors[45]. While the majority of biomass used in the production of renewable electricity and heat is from domestic sources, imported wood pellets are also important feedstocks. Most feedstocks used for renewable transport fuels derive from international sources.

Increasing the UK's domestic supply of sustainable biomass feedstocks (principally perennial energy crops and short rotation forestry) could support decarbonisation efforts through nature-based carbon sequestration. A number of research and innovation challenges need to be overcome to achieve a scale-up in domestic biomass. This also needs to be carefully managed so that using organic materials for energy does not direct resources away from agriculture and forestry or lead to unintended negative environmental impacts, including the ability to meet statutory environmental targets.

Challenge	Key research and innovation needs
Sustainable production of food, perennial energy crops and short rotation forestry	Research into novel technological approaches to decrease agricultural emissions and enhance sustainable production to meet food demand: • Transformational approaches to food production including (but not limited to) vertical agriculture, urban farming, synthetic alternatives to high carbon food products, agroecology, regenerative agriculture, no-till systems, etc. • Precision farming solutions to monitor all aspects of animal and crop production including health, nutrition and performance to optimise management and reduce inputs. To include artificial intelligence, sensors, autonomous systems and robotics. • Investments in both conventional and advanced breeding technologies in crop and plant production to build resilience, improve sustainability and enhance productivity. • Animal breeding, nutrition and biology to minimise enteric methane as well as nitrogen excretion, ammonia and carbon dioxide; minimising emissions per kg meat. • Technologies that decrease emissions from animal housing, such as methane capture, and from waste storage and application such as slurry storage and low emission spreading. • Technologies and techniques which reduce the impact of ammonia and other pollutants on sensitive habitats identified as areas for carbon sequestration. • Sustainable crop feeds, fertilisers, pesticides and herbicides (or alternatives). • Reduce energy consumption in agricultural production by low carbon machinery, minimum till cultivations, alternative energy sources, etc. • Improved ground based and remote sensing technologies and modelling for robust carbon storage calculations for agricultural land. Research to improve understanding of maintenance of soil systems to deliver multiple functions required from soil and developing an improved and efficient soil microbiome. Research into land management to achieve best use of different types of land. Advances in measuring and monitoring of emissions and environmental impacts from the whole agri-food supply chain, as well as social and economic impacts. Advances in plant breeding (including through biotechnology) to increase productivity, resilience to climate change, and to minimise the use of chemicals. Demonstration of novel systems and approaches: • Demonstrator farms or regions to understand changes at system level, e.g. agroforestry, paludiculture, novel ruminant housing systems. • Field and farm scale data collection and sensor development.

Challenges	Key research and innovation needs
	Understand economic and behavioural barriers to change and how these can be overcome to support farmers and land-managers transition to net zero. Research and pilot green finance and new farm business models to enable adoption and innovation of sustainable farming practices.
Sustainable consumption	Development of models to rapidly reflect changes in food demand. Develop metrics which can monitor and communicate embedded emissions in consumer goods. Continue research to better understand the health, environmental and resilience impacts of changing end-user preferences and markets. Research into social drivers of consumption and wastage and mechanisms to incentivise change.
Developing a sustainable bioeconomy *See also section 4.1.4*	Research to help develop and scale-up a sustainable and reliable supply of UK produced biomass: • Including forestry, second generation energy crops (i.e., non-food, lignocellulosic crops), agricultural residues, wastes and novel feedstocks. • Breeding to increase varieties and improve feedstock quality. • Better greenhouse gas lifecycle assessments of the production of different types of biomass feedstock and means to reduce these impacts, e.g. the use of bioenergy with carbon capture and storage (BECCS). • Understand locational / regional impacts on environmental services. • Understand and mitigate wider sustainability impacts. • Develop understanding of where bio-derived chemicals can displace fossil fuels in the medium-term; supporting these supply chains.

4.6.4 Waste and F-gases

Research and innovation: challenges and needs

Emissions from waste have reduced substantially since 1990 but further action is required to tackle methane from the decomposition of biodegradable waste in landfill sites, emissions produced from the treatment of wastewater, and emissions from the biological treatment, composting and incineration of waste. Innovation is required to support the reduction of waste to help meet government targets, turn unavoidable waste into useful products and to improve and deploy anaerobic digestion technologies.

F-gases account for around 3% of total UK GHG emissions[46] and hydrofluorocarbons (HFCs) – used for applications such as refrigeration and air-conditioning – are by far the biggest source. The UK has a target to cut HFCs by 79% by 2030 and has an international obligation for an 85% cut in HFC consumption by 2036, which requires the adoption of alternative gases and technologies that use them.

The UN Montreal Protocol Parties have committed to explore options to expand the global coverage of atmospheric monitoring of ozone-depleting substances and HFCs, to tackle illegal emissions of CFC-11 and safeguard the successes of the Montreal Protocol in ozone layer protection and climate change mitigation. The UK has world leading expertise on atmospheric monitoring which provides an opportunity to contribute to this work.

Challenge	Key research and innovation needs
Reducing waste and minimising emissions	**Anaerobic digestion (AD) technology** Research ammonia emissions mitigation technology; also understand the wider impacts of digestate, including on air, water and soil quality and the impact on the government's other statutory targets. Research into improved and more efficient AD, as described in section 4.4. **Landfill** In depth review of landfill waste codes and their sources to allow targeted policies for biodegradable waste streams, with particular focus on commercial waste streams and construction and demolition waste. Improved measurement of landfill emissions to allow a move away from estimates to empirical data, allowing capture of all landfill site-specific improvements and targeted interventions to reduce emissions at worst performing sites. Investigate relationship between woodlanding and soil oxidation of methane, to free up more land to meet tree-planting targets, while simultaneously reducing landfill emissions through bio-covers. **Biological Treatmen** Research policy options around reducing emissions from biological waste treatment, establishing technological, behavioural and economic barriers. This could also have impacts in the agriculture and wastewater sectors of the inventory and provide better evidence for future bioenergy strategies. **Waste reduction** Improve understanding of carbon impacts of waste prevention, resource efficiency, waste treatment and biodegradable waste policies. Research technological, behavioural and economic barriers to reducing plastic use, and increasing recycling ("reduce, reuse, repair, recycle"), including support for the development of bio-based and genuinely biodegradable plastics. Research into optimising food production, quality, shelf life, improving resource use efficiency and influencing end-user choices to reduce food waste and waste associated with production, processing and across the supply chain.

Challenge	Key research and innovation needs
Reducing process emissions and energy use in the wastewater treatment sector	Research and modelling to deliver emissions savings from the wastewater component (particularly industrial) of the UK Inventory through data improvements (both gathering of data and refining calculations). Widescale monitoring of emissions from wastewater treatment plants to be rolled out to better understand sources coupled with optimisation of current practices to minimise fugitive greenhouse gas emissions. Research and trials to better understand and then enable commercial deployment of novel and alternative treatment processes including anaerobic treatment, Membrane Aerated Biofilm Reactor and alternative processes for ammonia removal. Research into the barriers and implications of upgrading the UK water sector to advanced digestion processes. Research and options appraisal into the costs and benefits of different mitigation options available in the wastewater system, including new technologies, energy recovery possibilities (e.g. microbial fuel cells) and changes to data gathering (e.g. on private wastewater emissions).
Minimising UK F-gas emissions	Research into the technical feasibility and cost-effectiveness of low-Global Warming Potential F-gases and alternatives to F-gases, with consideration of their energy efficiency and domestic and international standards and building and safety rules relevant to their uptake.
Enhancing the global coverage of atmospheric monitoring of Montreal Protocol controlled substances	Research to improve the global coverage of atmospheric monitoring of ozone depleting substances and hydrochlorofluorocarbons by: • Identify the gaps in global coverage of atmospheric monitoring and suitable locations for monitoring sites • Pilot collaborative efforts to enhance atmospheric monitoring of controlled substances, including flask sampling or high frequency monitoring stations

Figure 23: Natural resources, waste and F-gases innovation needs timelines

An integrated and dynamic approach to land-use

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Land use allocation & planning considerations	Develop the tools and capabilities to inform land-use decisions and policy interventions at national and local scales, including research on green financing, economic values of protected landscapes and monitoring and evaluation of landscape policies			
Understanding system level GHG emissions and environmental impacts	Systems research to assess solutions within land, social, economic and environmental constraints			
	Research into agroecological and integrated farm management practices and impacts on carbon sequestration goals			
	Develop modelling and datasets for GHG impacts of agricultural processes, forestry, peat and soils, to understand impact of changes at system level			
Effecting sustainable and responsible land use change and effects on economic growth / levelling-up agenda	R&I to identify social, economic and cultural drivers of land use, barriers to sustainable land use change, and assess the options to effect these changes			
	R&I into markets and financing to drive tree planting, biomass cropping, peatland restoration and other forms of sustainable land use and track compliance			
	Research to measure profitability of sustainable farming systems on peat and soils and how production will be impacted			
	Research to review how existing land use models are informing economic growth decisions at both national and local levels			
Policy ambitions	Eliminate food waste from land-fill in England by 2030			
	Eliminate avoidable waste by 2050			
	30k hectares trees planted each year by 2025 (and potentially beyond)			
	Delivery of the Environmental Land Management Scheme			
	Delivery of the Biomass Strategy (BEIS)			
	Nature for Climate Fund set a target for 35k hectares of peat restoration in England by 2025			
	85% cut in hydrofluorocarbon consumption by 2036			

Forests, soil, peatland and the marine environment

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Sustainably expanding and managing forests and the wider treescape	Develop and trial improved ground based and remote sensing technologies and modelling for carbon storage calculations			
	Understand the variability and dependencies between different woodland types and silvicultural dependencies (rewilding, natural colonisation, etc.)			
	Understand silvicultural and arable agroforestry impacts on biomass and soil carbon, soil health and wider Greenhouse Gas balances.			
	Manage and trial strategies to minimise damage to forestry from pests and pathogens			
	Field trials of short rotation forestry, including using exotic species for biomass			
	Develop and trial innovative finance models for land managers to transition to forestry			
	Develop and trial innovative supply chains for planting materials well adapted to the UK			
	Understand social and behavioural drivers and barriers e.g. land ownership, acceptability, skills, finance, incentives, co-benefits			
	Collaborative R&D with the commercial forestry and building sectors to increase supply and demand of timber in built infrastructure			
	Establish robust estimates of the abatement delivered by harvested wood products in use through carbon storage and product substitution			
Developing increased resilience of forest ecosystems to climate change impacts	Improved understanding of the resilience of woodlands and trees to climate change, including impacts of pests, diseases and environmental conditions			
	Genomic sequencing of tree populations and mapping of characteristics to improve enhancements beneficial to future circumstances.			
	Research into the soil bacteria characteristics of different forest types and how bacterial communities enhance (or disadvantage) resilience.			
	Research into the fungi characteristics of different forest types and how fungi enhance (or disadvantage) resilience.			
Restoring sustainably and managing peatlands	Research and development of lowland peat management within a productive farming system to reduce emissions, enhance agricultural production and understand trade-offs between food production, wildlife, ecosystem services, Greenhouse Gas emission and peat loss			
	Improved evidence on Greenhouse Gas balances of peatland restoration establishing the rate of deployment, scientific uncertainty, associated costs and trade-offs			
	Better understanding of optimal landscape scale water management for wetter peat (to reduce emissions) and mitigating flood risk.			
	Innovative research to assess alternative approaches to peatland horticulture to enable an expanded sector while decreasing land-use emissions			
Managing soils for improved soil health and resiliance	Research and develop suitable data collection protocols and baseline data sets to develop a healthy soil indicator			
	Develop and pilot a soil structure measuring and monitoring method as a key physical element of the healthy soil indicator			
	Research alternative farming methods such as regenerative agriculture and agroforestry to establish soil health and potential carbon sequestration benefits			
	Research to understand the potential requirement of a Soil Carbon Code and the potential for a future carbon farming scheme in England			
Sustainably managing the marine environment	Research into Greenhouse Gas emissions and removals from coastal wetlands, including coastal erosion, wetland restoration; and improved Greenhouse Gas accounting and reporting			
	Assess scale and direction of change in carbon storage and sequestration to human activities; understand the impact of different management interventions and ecosystem recovery on carbon fluxes and stores			
	Research and long-term monitoring to understand impacts of decarbonisation infrastructure and habitat change on other users of marine spaces			
	Innovation in design and construction of offshore infrastructure (e.g. offshore wind, 5G phone sites) to minimise environmental impacts. Also research into social acceptance and financial implications of building offshore versus on land			
	Research into sustainable salt and fresh-water aquaculture systems, including solutions to mitigate the environmental impacts (e.g. disease; escapees; and discharge) of existing aquaculture systems			

Food and biomass

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Sustainable production of food, perennial energy crops and short rotation forestry	Transformational approaches to food production including (but not limited to) vertical agriculture, urban farming, synthetic alternatives, agroecology, no-till systems			
	Precision farming solutions to monitor all aspects of animal and crop production including health, nutrition and performance to optimise management and reduce inputs			
	Investments in both conventional and advanced breeding technologies in crop and plant production to build resilience, sustainability and productivity			
	Animal breeding, nutrition and biology to minimise enteric methane, nitrogen excretion, ammonia and carbon dioxide; optimising emissions per kg meat			
	Technologies that decrease emissions from animal housing, such as methane capture, and from waste storage and application			
	Technologies and techniques that reduce impact of ammonia and other pollutants on sensitive habitats identified as areas for carbon seqestration			
	Sustainable crop feeds, fertilisers, pesticides and herbicides (or alternatives)			
	Reduce energy consumption in agricultural production by low carbon machinery, minimum till cultivations, alternative energy sources, etc.			
	Improved ground based and remote sensing technologies and modelling for robust carbon storage calculations for agricultural land			
	Research to improve understanding of maintenance of soil systems to deliver multiple functions and developing an improved and efficient soil microbiome			
	Research into land management to achieve best use of different types of land			
	Advances in measuring and monitoring of emissions and environmental impacts from the whole agri-food supply chain including social and economic impacts			
	Advances in plant breeding (including through biotechnology) to increase productivity, resilience to climate change, and to minimise the use of chemicals			
	Demonstrator farms or regions to understand changes at system level, e.g. agroforestry, paludiculture, novel ruminant housing systems			
	Field and farm scale data collection and sensor development			
	Understand economic and behavioural barriers to change and how these can be overcome to support farmers and land-managers transition to net-zero			
	Research and pilot green finance and new farm business models to enable adoption and innovation of sustainable farming practices			
Sustainable consumption	Development of models to rapidly reflect changes in food demand			
	Develop metrics which can monitor and communicate embedded emissions in consumer goods			
	Continue research to better understand the health, environmental and resilience impacts of changing end-user preferences and markets			
	Research into social drivers of consumption and wastage and mechanisms to incentivise change			
Developing a sustainable bioeconomy	Forestry, second generation energy crops, agricultural residues, wastes and novel feedstocks			
	Breeding to increase varieties and improve feedstock quality			
	Better GHG lifecycle assessments of the production of different types of biomass feedstock and means to reduce these impacts, e.g. the use of bioenergy with carbon capture and storage (BECCS)			
	Understand locational / regional impacts on environmental services			
	Understand and mitigate wider sustainability impacts e.g. air quality			
	Develop understanding of where bio-derived chemicals can displace fossil in the medium term; supporting these supply chains			

Waste and F-gases

Challenges	Needs	Short term 2020-25	Medium term 2025-30	Longer term 2030s and beyond
Reducing waste and minimising emissions	Research anaerobic digestion (AD) technology: research ammonia emissions mitigation technology and wider impacts of digestate			
	Research into improved and more efficient AD			
	In depth review of landfill waste codes and their sources to allow targeted policies for biodegradable waste streams, with particular focus on commercial waste streams and construction and demolition waste			
	Improved measurement of landfill emissions to allow a move away from estimates to empirical data, allowing capture of all landfill site-specific improvements and targetted interventions to reduce emissions at worst performing sites			
	Investigate relationship between woodlanding and soil oxidation of methane, to free up more land to meet tree-planting targets, while simultaneously reducing landfill emissions through bio-covers			
	Research policy options around reducing emissions from biological waste treatment, establishing technological, behavioural and economic barriers. This could also have impacts in the agriculture and wastewater sectors of the inventory, and provide better evidence for future bioenergy strategies.			
	Improve understanding of carbon impacts of waste prevention, resource efficiency, waste treatment and biodegradable waste policies			
	Research technological, behavioural and economic barriers to reducing plastic use, and increasing recycling ("reduce, reuse, repair, recycle"), including support for the development of bio-based and genuinely biodegradable plastics.			
	Research into optimising food production, quality, shelf life, improving resource use efficiency and influencing end-user choices to reduce food waste and waste associated with production, processing and across the supply chain			
Reducing process emissions and energy use in the wastewater treatment sector	Research and modelling to deliver emissions savings from the wastewater component (particularly industrial) of the UK inventory through data improvements			
	Research and roll out of widespread monitoring of emissions from wastewater treatment plants, aimed at optimisation of processes to minimise fugitive GHG emissions			
	Research and trials to understand and enable commecial deployment of novel treatment processes, including anaerobic, Membrane Aerated Biofilm Reactor and alternative processes for ammonia removal			
	Research into the barriers and implications of upgrading the UK water sector to advanced digestion processes			
	Research and options appraisal into the costs and benefits of different mitigation options available in the wastewater system, including through new technologies and changes to data gathering			
Minimising UK F-gas emissions	Research into the technical feasibility and cost-effectiveness of low-Global Warming Potential F-gases and alternatives to F-gases, with consideration of their energy efficiency and domestic and international standards and building and safety rules relevant to their uptake			
Enhancing the global coverage of atmospheric monitoring of Montreal Protocol controlled substances	Research to improve global coverage of atmospheric monitoring of ozone depleting substances and hydrochloroflourocarbons as Montreal Protocol controlled substances, including identifying gaps in global coverage of atmospheric monitoring and suitable locations for new monitoring sites. Also, piloting collaborative efforts to enhance monitoring of controlled substances			

5. An integrated Net Zero Research & Innovation Framework

What research and innovation is needed?

This Framework highlights that urgent research and innovation is needed to accelerate the commercialisation of solutions at scale, which can provide the carbon emission reductions needed in the UK for Carbon Budget 6 and for net zero. Larger-scale demonstrations and trials will need an increased share of research and innovation spending through the 2020s and 2030s, recognising that almost half of the CO_2 reductions required to reach net zero by 2050 will need to come from technologies that are still in the prototype phase. Figure 24 illustrates key research and innovation challenges for the UK's transition to net zero by 2050.

Renewable energy generation will need to be rapidly deployed with research and innovation driving continual improvements and unlocking new opportunities, such as floating offshore wind, as well as enabling reliable low carbon electricity through nuclear. Innovation will be needed to transform the wider electricity system and networks and to realise the potential for biomass across a number of hard to decarbonise sectors and through BECCS to drive negative emissions.

Continuing innovation to improve resource and energy efficiency alongside proving the feasibility of low and zero-carbon fuels and feedstocks (e.g. electricity, hydrogen and biomass) will be needed to decarbonise industry with residual emissions captured at source or offset by greenhouse gas removals. Hydrogen is expected to become a key energy vector with research and innovation needed to support the scale-up of low carbon hydrogen supply, demand, transportation and storage.

Even in ambitious decarbonisation scenarios, there are likely to be residual UK GHG emissions in 2050. Research and innovation is needed both to support an urgent deployment of industrial-scale CCUS technologies and to develop other GGR solutions to address those residual emissions.

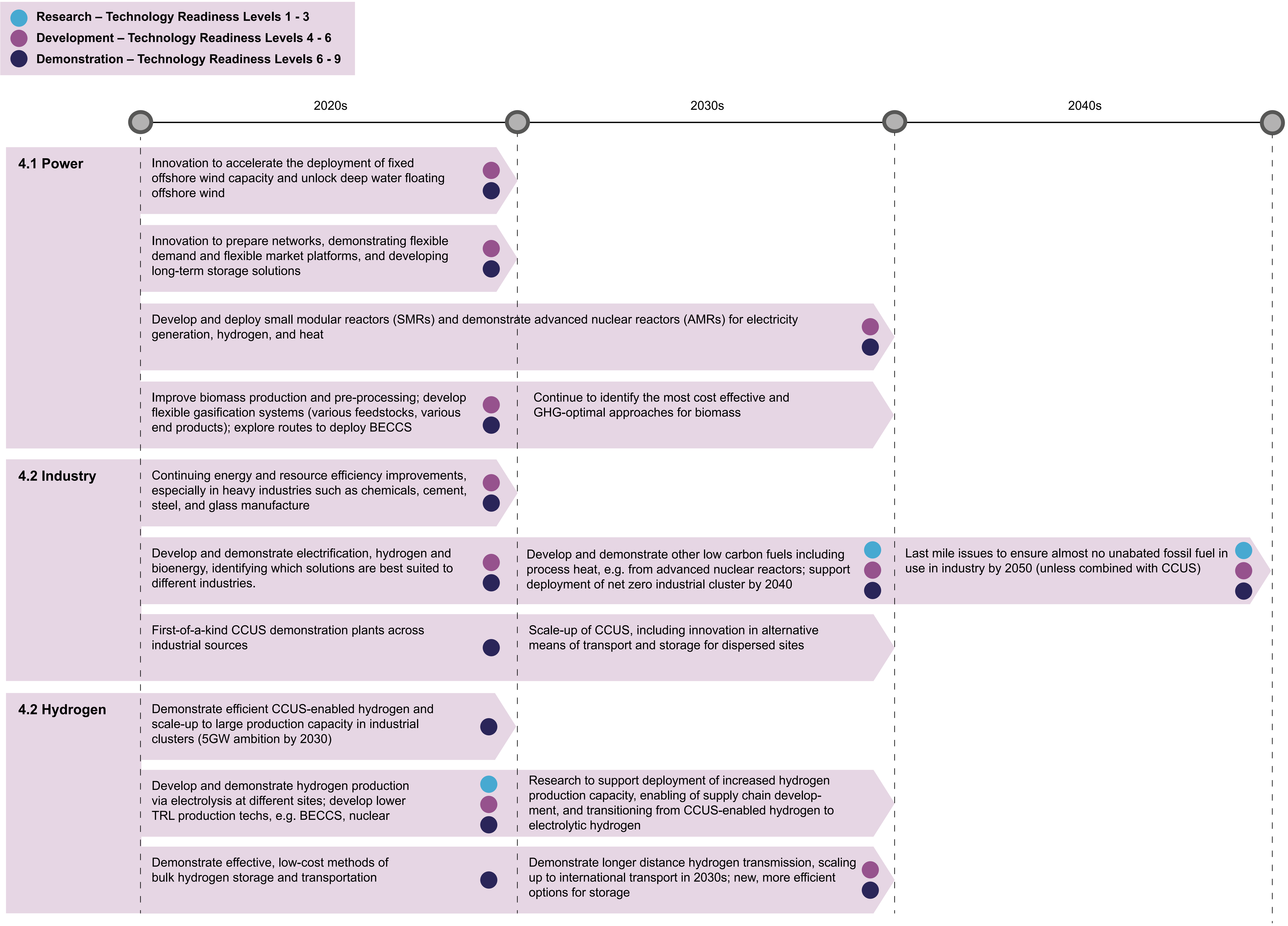
In our homes and buildings, innovation is needed in technologies, processes, business models and consumer behaviour to support large-scale retrofit of low carbon heating and energy efficiency measures, and to support key decisions amongst candidate options for heating our homes.

On roads, electrification is expected to be the principal option but other low carbon fuels, particularly hydrogen, may have an important role to play, for example in HGVs, with research and innovation on refuelling and recharging infrastructure also of importance. Zero carbon solutions for aviation and maritime are still at much earlier stages of development and will require significant investment out to 2050. Research is also needed to understand how peoples' journeys are changing and on solutions tailored for different local contexts.

How we best use the UK's natural resources and land remains a key research question. The answer will require deep understanding of tensions and trade-offs between food production, forestry and biomass production, habitat and peatland restoration, urban expansion, and promoting greater carbon sequestration alongside wider environmental benefits. Scaling-up a sustainable bioeconomy, decarbonising the agricultural sector, tackling methane from waste and developing sustainable alternatives to F-gases will also require research.

Underpinning all of this is the need for a whole systems approach. Research will help to build our understanding of the interrelated nature of different sectors and between new technologies, consumer behaviour and business models. This lens helps to highlight key cross-cutting themes such as the integration of digital solutions across all parts of our economy and society to drive greater resource and energy efficiency. Above all the need for broad public support and development of viable markets and supply chains needs to go hand in hand with the development of new technologies if research and innovation is to help deliver our net zero ambition. Choices will need to be made and the solutions will need to be deployed at scale and at a sustainable cost.

Figure 24: Net Zero Research & Innovation Roadmap for UK



- Research – Technology Readiness Levels 1 - 3
- Development – Technology Readiness Levels 4 - 6
- Demonstration – Technology Readiness Levels 6 - 9

	2020s	2030s	2040s
4.3 CCUS & GGRs	Demonstration of CCUS, including industry and hydrogen production; initial demonstration of BECCS and gas with CCUS; improvements to capture rates and efficiency	Research to support large-scale deployment of CCUS for industry and hydrogen production; scaling-up demonstration of BECCS and gas with CCUS	
	Innovation to develop supply chains, including on business models, financing, and risk sharing arrangements		
	Research to identify lowest-cost transport infrastructure opportunities; de-risking scale-up of CO_2 stores; improving measuring, monitoring and verification	Innovation for development of offshore storage and for alternative means of transport, storage and capture technology at dispersed sites	
	Develop greenhouse gas removal technologies and nature-based solutions	Demonstrate DACCS and other GGR approaches at scale	Improve efficiency and reduce energy demand of GGRs; research to support deployment of GGRs to meet targets
4.4 Heat and Buildings	Test whole house/building retrofit for domestic and non-domestic; develop new supply chain models; energy efficiency solutions for hard-to-treat properties		
	Demonstrate safety and feasibility of hydrogen heating, increase readiness of appliances and consumer trials Decision on hydrogen for heating (by 2026)		
	Reduce costs of heat pump manufacture; reduce disruption from installation and use; develop innovative business models to drive uptake; demonstrate in range of homes and at neighbourhood/district scale		
	Research ways to incentivise connections to heat & cooling networks; develop innovative solutions to access heat from existing and future heat sources (2020s–2030s)		
4.5 Transport	Improve the efficiency of EV manufacture; trialling infrastructure improvements including charging, vehicle to grid, flexible/smart charging; novel battery technology		
	Research deployment options for hydrogen and electric buses; demonstration of HGV technologies including hydrogen, battery, electric road systems; mega-charging for HGVs		

- **Research – Technology Readiness Levels 1 - 3**
- **Development – Technology Readiness Levels 4 - 6**
- **Demonstration – Technology Readiness Levels 6 - 9**

2020s | 2030s | 2040s

4.5 Transport

- Demonstrate hydrogen trains and infrastructure; research hydrogen distribution by rail to support other sources of demand
- Develop zero emissions aircraft and airside vehicles; prepare UK airports for zero emission aircraft; facilitate UK R&D on aerospace manufacturing
- Continued development of more efficient aircraft; certification and infrastructure requirements; develop and trial sustainable aviation fuel manufacture
- Demonstrate zero emission vessels, including with batteries, hydrogen, and ammonia; hydrogen and ammonia bunkering and dispensing at ports; zero emissions ports

4.6 Natural resources and land-use

- Research biomass supply including forestry, energy crops, agriculture residue, waste and novel feedstocks; improved GHG lifecycle assessments; crop breeding

  Research for anaerobic digestion and ammonia emission mitigation; food production and consumer behaviour to reduce food waste; trial bio covers on landfill
- Research to develop tools to inform land-use decisions; research to understand interplay between actors, policy/regulatory framework, incentives and technologies
- Research for sustainably expanding and managing forests, including improved tech and modelling for carbon storage; research on woodland types and silviculture; innovative finance models; social/behavioural drivers and barriers

  Research into lowland peat management with farming; improved GHG assessment of peatland restoration; optimal water management for emissions & flood risk
- Research coastal wetlands, including scale and direction of change in carbon storage; design of offshore infrastructure; sustainable salt and fresh-water aquaculture systems
- New practices and technologies to reduce agricultural emissions including precision farming; animal/crop breeding; sustainable fertilisers and pesticides; economic and behavioural barriers to change; demonstrator farms

- **Research – Technology Readiness Levels 1 - 3**
- **Development – Technology Readiness Levels 4 - 6**
- **Demonstration – Technology Readiness Levels 6 - 9**

2020s | 2030s | 2040s

3. Systems-wide / cross-cutting

Understand optimal net-zero pathways, interdependencies and trade-offs across physical, natural, social and technological systems

Integrate changes to energy supply, storage and use with increasing interlinkages between energy vectors and across different sectors of the economy

Enable an integrated, multi-modal transport system and accelerate the adoption of active travel and public transport; understand role of transport in the wider energy system, including the hydrogen economy

Digital solutions and technologies to support cross-sector integration, enable systems-level understanding and unlock resource and energy efficiency

Beyond technology, there is a need to understand how more sustainable behaviours can be incentivised, to develop new types of business and financial models and to deliver locally and regionally appropriate solutions

How to prioritise public investment?

The Net Zero Strategy sets out several viable pathways to net zero and we should avoid locking ourselves into any one technology pathway prematurely. This means investing widely and accepting some investments will not deliver the expected benefits or offer a viable commercial proposition. Ultimately it is the commercialisation of innovative low-carbon products and services, not the innovation itself, that leads to benefits by way of lower energy costs, reduced emissions of greenhouse gases, energy security and business growth.

However, within this we will need to prioritise. Working back from 2050, Figure 24 shows the sequence for technologies (and research for policy decisions) as they move through early-stage research, feasibility and technical development and onto demonstration at scale, to reach commercial deployment in time to deliver our Net Zero commitment.

For Government investment, we will prioritise spend based on:

- Expected contribution to delivering the UK's carbon budgets and major decarbonisation – accelerating delivery of carbon emissions reductions by increasing certainty of technologies / solutions, including by taking into account the current state of technologies and the potential for research and innovation to make rapid progress.
- Building and using UK comparative advantage globally – focussing on areas with the highest potential for UK business and jobs. Developing and commercialising technologies, processes and business models for the net zero transition can provide business opportunities and enhance economic competitiveness.
- Retaining optionality of different net zero pathways – investing in a portfolio of solutions (tolerating some failure) and ensuring technologies which we cannot reach net zero without are invested in, including greenhouse gas removals.

Government intervention will be needed where market failures prevent private sector investment, to de-risk and accelerate private sector action or where there is potential to develop areas of UK strategic advantage. This public research and innovation spending can be used to push technology development, which will complement market-pull mechanisms such as policy, regulatory and financial frameworks (e.g. Contracts for Difference; Internal Combustion Engine phase-out). Both approaches will be needed for success.

Based on our current understanding we expect to prioritise:

Major decarbonisation opportunities
Floating offshore wind
Energy storage at scale and system flexibility - enablers of high renewables system
Hydrogen - enabler of industrial fuel switching, heat and some negative emissions
Carbon capture, utilisation and storage for industry - critical for hard to abate areas
Buildings decarbonisation
Land transport, including zero emission road vehicles, rail, light rail and active travel
Aviation and maritime
Agriculture and food
Nature-based carbon removals, e.g. afforestation, domestic perennial energy crops, short rotation forestry, biochar, etc.

Major business opportunities
Transport - aviation, automotive, maritime
Energy storage at scale
Hydrogen
Nuclear - Small Modular Reactors, Advanced Modular Reactors and advanced fuel cycle, particularly in export
Offshore wind - with floating offshore wind potential new area for export and domestic deployment

Creates optionality in net zero pathways
Energy efficiency
Carbon capture, utilisation and storage - major enabler for industry, hydrogen and bioenegry with carbon capture and storage (BECCS)
Innovation within industrial energy sectors - hard to abate and cannot be substituted by other technologies
Sustainable land-use
Negative emissions technologies including Direct Air Capture

How should this Framework be used?

This Framework lays the foundation for net zero research and innovation planning within Government and aims to provide innovative businesses and academic and research communities with a tool to guide their own research and innovation agendas. We do not expect government programmes to cover all the needs identified by this Framework and we will prioritise those where government intervention is most needed based on the criteria outlined above. As research delivers more answers it should be possible to focus on scale-up and deployment spend in the key areas.

For publicly funded research and innovation, the Government intends to publish a Delivery Plan to show what current and planned programmes are being prioritised from this framework. The Net Zero Innovation Board[47], chaired by the Government Chief Scientific Adviser, provides the main government forum for discussing prioritisation and spending plans related to net zero research and innovation and will play a key role in assessing progress against the Delivery Plan and this wider Framework.

Given the scale of the transformation needed to reach Net Zero by 2050 any framework will necessarily need to adapt and change over time. We cannot, nor would we want to, plan for all the research and innovation needs over the next 30 years. Breakthrough technologies could revolutionise our understanding and approaches in some areas. Government, as well as business, will need to be agile and able to pivot our plans in the future. However, by publishing the UK's first Net Zero Research and Innovation Framework, we hope to provide fresh impetus to those goals, in the next 5-10 years, where it is known that research and innovation is urgently needed and drawing a line of sight from these out to 2050. A detailed plan for delivery against this Framework will follow.

Endnotes

[1] Chapters have been defined based on the underlying research and innovation challenges. In particular, hydrogen production has been highlighted within the industry chapter and end-uses of hydrogen within their related sector chapter. Similarly, given CCUS's potential impact across the net zero system, it has been highlighted as an area of focus alongside greenhouse gas removal (GGRs) technologies.

[2] In the International Energy Agency's 2050 net zero scenario, 46% of the annual CO_2 savings come from technologies still under development: IEA (2021) Net Zero by 2050, https://www.iea.org/reports/net-zero-by-2050

[3] Energy Innovation Needs Assessment. BEIS/ Vivid Economics (2019). Figures based on a 80% reduction in emissions by 2050.

[4] Internal BEIS analysis based on the Energy Innovation Needs Assessments

[5] UK Board of Trade Report (July 2021)

[6] Clean Growth Strategy (2018)

[7] IEA data (2019)

[8] IEA (2021) Net Zero by 2050

[9] TechNation (2020) UK Tech For A Changing World, https://technation.io/report2020/#forewords

[10] See Committee on Climate Change (2021) Independent Assessment of UK Climate Risk for additional information on risks to net zero from climate change

[11] Mission Innovation (2021) http://mission-innovation.net/missions/power/

[12] BEIS (2020)

[13] HM Government (2020) Energy White Paper

[14] ibid

[15] Mission Innovation (2021) http://mission-innovation.net/missions/power/

[16] BEIS and Ofgem (2021). Transitioning to a net zero energy system: smart systems and flexibility plan 2021. Available here.

[17] BEIS (2020). Modelling 2050 – electricity system analysis. Available here. Quoted in 2012 prices, undiscounted

[18] Digest of UK Energy Statistics (2021) Chapter 1: Energy

[19] See Climate Change Committee (2018) Biomass in a low carbon economy

[20] ONS, 2021 – Gross Domestic Product

[21] UK in a Changing Europe, 2020 – Manufacturing and Brexit

[22] This figure relates to industry sectors covered by the Industrial Decarbonisation Strategy (2021) and excludes related power sector emissions

[23] IEA (2021) Net Zero by 2050

[24] Industrial Decarbonisation Strategy (2021)

[25] Pathways modelled by BEIS for the 6th carbon budget impact assessment show that 250 – 460 TWh of hydrogen could be needed by 2050. Further analysis that draws on a number of sources indicates a range of 125 – 495 TWh. Throughout the 2030s and 2040s hydrogen demand is expected to rapidly increase, requiring hydrogen production capacity to increase from 5 GW in 2030 to 7 – 20 GW in 2035 and 15 – 60 GW in 2050.

[26] Hydrogen Strategy (2021)

[27] Hydrogen Strategy (2021)

[28] The Geological Society (2021)

[29] Mission Innovation (2021) http://mission-innovation.net/missions/hydrogen/

[30] The Ten Point Plan for a Green Industrial Revolution (2020)

[31] Net Zero Strategy (2021)

[32] IEA 2020 Energy Technology Perspectives

[33] National Statistics (2020) Households projections for England. BEIS (2020) Non-domestic National Energy Efficiency Data-Framework

[34] BEIS (2021) Final UK greenhouse gas emissions national statistics: 1990 to 2019' and BEIS (2021) Energy Consumption in the UK.

[35] MHCLG (2020), 'English Housing Survey 2019 to 2020: headline report' Annex Table 2.8.

[36] Approximately 28 million homes and 2 million non-residential buildings. National Statistics (2020), Households projections for England, Table 401 (https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/datasets/householdprojectionsforengland); BEIS (2020), 'Non-domestic National Energy Efficiency Data-Framework' (https://www.gov.uk/government/statistics/non-domestic-national-energy-efficiency-data-framework-nd-need-2020), based on 2018 data

[37] For example, the Energy White Paper estimates that bringing 2.8 million privately rented homes to EPC rating C could create 80,000 jobs per year, and installing 600,000 heat pumps a year could support 20,000 jobs by 2030

[38] BEIS analysis based on the Energy Innovation Needs Assessment (Vivid Economics 2019)

[39] Net Zero Strategy (2021)

[40] Mission Innovation (2021) http://mission-innovation.net/missions/hydrogen/

[41] Climate Change Committee (2020) Sixth Carbon Budget Report (includes adjustments from the UK's national inventory)

[42] Climate Change Committee (2019) Net Zero Technical Report

[43] ibid

[44] See: Climate Change Committee (2020) Sixth Carbon Budget. Globally, food systems - including agriculture, manufacturing, processing, packaging and consumption are estimated to be responsible for around one third of global GHG emissions

[45] Digest of UK Energy Statistics (2021)

[46] Climate Change Committee (2019) Net Zero Technical Report

[47] Net Zero Innovation Board (2021) https://www.gov.uk/government/groups/energy-innovation-board

HM Government