NET-ZERO SOLUTIONS AND RESEARCH PRIORITIES IN THE 2020S

KEY MESSAGES

- **Technological, societal and nature-based** solutions should work together to enable systemic change towards a regenerative society, and to deliver net-zero greenhouse gas (GHG) emissions.
- **Prioritise research into efficient,** low-carbon and carbon-negative solutions for sectors that are difficult to decarbonise; i.e. energy storage, road transport, shipping, aviation and grid infrastructure.
- **Each solution should be assessed** with respect to GHG emissions reductions, energy efficiency and societal implications to provide a basis for developing long-term policies, maximising positive impact of investment and research effort, and guiding industry investors in safe and responsible planning.

INTRODUCTION

To meet the UK's 2050 net-zero target, technological, societal, and nature-based solutions, innovative business models, regulatory arrangements, and new incentives to change behaviours will be required to reduce carbon emissions in all sectors of our economy and society. This briefing sets out a vision of plausible net-zero solutions and research priorities across different sectors to highlight, based on the available evidence, what we already know and what still requires further research. We then specify actions and co-benefits resulting from these solutions. The briefing focusses on innovations for this decade across eight sectors, as outlined in the Climate Change Committee's (CCC) net-zero report,[1] in no particular order.

SECTORAL SOLUTIONS

I. ELECTRICITY GENERATION, STORAGE, SYSTEM AND NETWORKS:

A. Generation

What we know: Technological forecasts indicate that renewable energy prices will soon be lower than fossil fuels.[2,3] The cost of new offshore wind energy has fallen by over 50% since 2015, and is now one of the lowest cost options for new power in the UK.[4] Extrapolation of current trends suggests the green energy transition can be accomplished in two decades for cheaper than business-as-usual, subject to the emergence of supporting technologies (e.g. storage) and infrastructures (e.g. network flexibility).[5]

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What to research: (i) Thin film solar cell materials which offer new form factors and installation paradigms, e.g. multi-junction photovoltaics (PV);[6–8] (ii) how to design wind turbines to provide flexible electrical output within the constraints of blades, turbines, towers, etc.; (iii) low-cost ways of providing flexibility from gas plants with carbon capture and storage; (iv) how to reduce cost of floating offshore wind; (v) improve robustness of tidal stream turbines and develop new technologies, e.g. floating offshore wind, wave and tidal; (vi) feasibility of small modular nuclear reactors; (vii) cumulative impacts of (marine) renewable energy on natural capital and ecosystem services, and options to monitor and mitigate them.

Actions to take now:

- Accelerate commercialisation, uptake and production of thin-film PV, e.g. perovskites.[9,10]
- Scaling promising renewable electricity generation technologies, ensuring diversity in energy sources.

B. Storage

What we know: Energy storage offers grid flexibility and can curb intermittency issues. Technologies that offer such storage include pumped hydroelectricity, cryogenic (liquid air), compressed air, grid-scale batteries, and thermal inertial of the heat network.

What to research: (i) Technologies with high round-trip efficiencies (>60%; e.g. cryogenic, compressed air, and batteries); (ii) methods to reduce the cost and water consumption of electrolysers; (iii) increase the efficiency of photocatalytic hydrogen production; (iv) hydrogen storage; (v) heat storage with high energy density; (vi) alternative materials for batteries; (vii) ways to determine storage capacity demand.

Actions to take now:

- Develop policy framework to ensure a level playing field and long-term competitive market and scale up for efficient grid-scale electricity storage.
- Replace the main mode of hydrogen production, methane steam reforming, with electrolysers driven by renewable energy.

C. System Planning and Operation

What we know: New investment mechanisms must be developed such that energy production and storage facilities are satisfying whole-system needs across sectors. Variability of wind and solar power presents system operation challenges: a large part of the generation mix is made of small-scale installations connected to the distribution network. This, and other distributed resources, (e.g. electric vehicle charging) influence the day-ahead/real-time markets and contribute to stable system operation.[11]

What to research: (i) Defining the controls of power electronic converters to provide stable power system operation;[12] (ii) new decision support tools based on advanced optimisation techniques; (iii) impact of climate change on renewable energy generation.

Actions to take now:

- Incentivise grid flexibility: meet (reduce) peak demand; flex production/consumption aligned with wind and solar variation; respond quickly to faults and contain electricity system frequency variations.
- Incentivise relevant sizing of storage/network capacity and place resources where they reduce the cost via market price signals.

D. Networks

What we know: The UK needs electricity network reinforcement or, in the case of offshore wind, an entirely new network. The electricity network needs to be capable of operating in a safe and stable manner with many of the generators and loads on it connected via power electronics.

What to research: (i) how to increase the capacity of High Voltage Direct Current (HVDC) converters and cables and facilitate operation on multi-terminal networks covering large areas, both nationally and internationally[13] (e.g. HVDC interconnections spanning latitudes for transfer of solar); (ii) stress on the grid due to climate change.

Actions to take now:

- Coordinate responsibilities of transmission system and distribution network operators and develop network protection methods for both AC and DC.
- Develop frameworks under which decisions can be taken on building hydrogen network capacity.

Co-benefits: (i) Beyond the electrical grid, lightweight, flexible solar modules,[14] realise new high power-to-weight-ratio applications e.g. electric vehicles or aerial delivery; (ii) widespread utilisation of hydrogen may reduce CO_2 emissions (boosting air quality) and add jobs.[15]

2. BUILDINGS:

A. New Builds

What we know: The built environment contributes to ~40% of UK emissions.[16] Of this, ~77% is operational, and 23% embodied in new assets from construction activity.[17] Heating contributes to 18% of UK emissions,[18] with 15% of total UK GHGs attributable to heating homes.[19] Reducing energy consumption for heating/cooling is critical, and now possible. High latitude regions provide opportunities for night cooling in summer.

Thermally massive buildings can meet cooling net-zero requirements if natural ventilation is incorporated into the design. Heating can be reduced if build quality (e.g. insulation) is improved and high-efficiency mechanical ventilation heat recovery units are used. Required heating can be zero carbon via heat pumps, district heating, or potentially hydrogen. A systems approach is required to deliver efficient buildings within budget constraints and suited to the local environment with clear regulations.[20]

What to research: (i) How to ensure that low-carbon buildings are affordable and accessible to all communities, whilst mitigating the risks of economic burdens; (ii) how to create a zero carbon building for the lowest cost based on life cycle analysis and factoring in embodied carbon; (iii) how to equip teams to collaborate and deliver buildings that meet design targets; (iv) Match energy demand in buildings with energy supply through decarbonised electricity via heat pumps and district heat networks.

Actions to take now:

- Implement consistent policy around operational and embodied carbon and ensure opportunity for construction teams to understand the new standards.
- Simplify building regulations for practitioners.
- Encourage a systems approach to building design such that they work with the local climate and transport emissions.
- Incentivise local supply chains to work together to deliver zero emissions at scale.
- Ensure all surveyors know if build quality is in accord with standards.

B. Retrofits

What we know: The majority of buildings existing in 2050 are already built. Therefore, retrofit measures are needed to decarbonise buildings (reducing overheating risk and ensuring flood protection, when appropriate). The rate of building retrofits needs to increase to reduce energy demand and ensure affordable, comfortable homes for all.[20] Housing, contributing ~1/3 of the building sector emissions, is a challenging sector to decarbonise due to the multiple owners and private nature. Reframing energy efficiency as infrastructure may stimulate policy and long-term plans, supporting new business models.[21]

What to research: (i) Retrofit is interdisciplinary but engineering has dominated the field.[22] A systems approach with consideration of social and natural impacts of infrastructure transitions is needed;[23] (ii) databases on impacts and co-benefits from retrofits.[24]

Actions to take now:

- Long-term framework which addresses statutory carbon targets and triggers investment confidence by business and owners.[16]
- Encourage re-use of buildings.
- Reduce VAT rates on products suitable for retrofit in existing buildings.[25]
- Engage practitioners, academics, policy makers and home owners to co-create.[26]
- Work with local organisations and share building energy efficiency databases.[26]

Co-benefits: (i) Physical and mental health improvement of householders reduces health-related costs, fuel poverty, inequality, and improves job creation/productivity;[27,28] (ii) Housing retrofits planned to protect householders against unintentional health risks[29] (e.g. indoor air pollution[30] or overheating[31]).

3. ROAD TRANSPORT:

A. Travel Demand Management

What we know: Meeting the energy needs of transportation from zero carbon sources will be made easier by reducing distance driven, vehicle weight per passenger, private ownership, and freight demand, and by providing reliable, rapid charging infrastructure for electric vehicles (EVs).

What to research: (i) Effectiveness of policies to reduce vehicle ownership/use; (ii) overcoming rebound effects (e.g. increased deliveries without vehicle ownership or longer trips with home working).

Actions to take now:

- Stop the road building programme, instead building strategic cycle networks and public transport.[32]
- Effective land use planning to produce dense, mixed use, and attractive low traffic neighbourhoods that prioritise walking and cycling.[33]
- Incentivise alternatives to private car ownership (e.g. car-pooling, car clubs, public transport).
- Encourage coordination of home delivery services to reduce duplication, traffic and carbon emissions.
- Remove barriers to electrification of urban delivery vehicles (including charging depots).

B. Electric Light Vehicles

What we know: Electrification of passenger vehicles is increasing rapidly, but not fast enough. The UK government has committed to phasing out the sale of new petrol and diesel cars and vans by 2030, and to end the sale of new hybrid cars and vans by 2035.[34]

What to research: (i) Charge-at-home for residents of apartment complexes or terraced homes. (ii) Alternative charging options and how chargers can couple different sectors, affecting network and traffic.

Actions to take now:

- Widespread public and private charging infrastructure to support the EV uptake.
- Plan motor taxes to replace fuel duty.

C. Heavy Good Vehicles (HGVs)

What we know: Three power options: (i) electrification with small battery packs and a national 'Electric Road System' (ERS), (ii) hydrogen fuel cells, (iii) biofuels.

What to research: (i) Hydrogen fuel cells in HGVs; (ii) a robust economic case for infrastructure providers, fleet operators, and HM Treasury; (iii) operational performance for freight transport and logistics; (iv) natural resource consumption, including conflict materials (platinum, cobalt), and land use change.

Actions to take now:

- Trials of ERS and hydrogen fuel cell vehicles, commissioned for the early 2020s.[35]
- Evaluate energy requirements e.g. cost, storage, safety, durability and resilience.
- Integrate transport and energy networks.

Co-benefits: (i) Public health benefits and reducing health inequalities through physical activity; (ii) reductions in air pollution;[36,37] (iii) reduction of road-related injuries/fatalities.[38]

4. INDUSTRY:

A. Carbon Capture, Utilisation and Storage (CCUS)

What we know: CCUS is required to achieve industrial decarbonisation by 2050. The CCUS Cost Challenge Taskforce[39] and the CCC[40] recommend CCUS development/deployment in energy-intensive industries to scale up and reduce costs. The UK Industrial Decarbonisation Challenge[41] aims to establish at least one low-carbon cluster by 2030 and the world's first net-zero industrial cluster by 2040.[42]

What to research: (i) CCUS industry deployment needs to accelerate but barriers exist: implementing a systems approach that integrates cluster level engineering and environmental/technical solutions with perspectives on economic, behavioural, policy.

Actions to take now:

- Deploy CCUS at scale by mid-2020s to fortify the first low-carbon and net-zero industrial clusters (i.e. hub of high-energy use industrial sites).
- Deliver a multidisciplinary research and innovation programme to support CCUS.
- Establish business models and frameworks to support CCUS commercialisation.
- Assess the skills required to develop a workforce to deliver industrial decarbonisation.

B. Energy and Resource Efficiency

What we know: Energy efficiency improvements in industrial processes can result in ~15-20% reduction in fuel usage and CO_2 emissions.[43] Increasing circularity of materials, including reuse, recycling and replacement, will reduce production of virgin materials and lower CO_2 emissions.[43] Decarbonisation will require many technologies reliant on critical materials and technology metals, which the UK does not have secure access to.[44]

What to research: (i) Integration between industrial sites to optimise energy/resource use; (ii) the potential for industrial synergy, i.e. circular economy at industrial cluster level; (iii) new primary supplies of critical materials and technology metals.

Actions to take now:

- Determine technical, environmental and economic benefits of industrial symbiosis clusters.
- Establish frameworks and business models to incentivise technology deployment and commercialisation to reduce energy demands.
- Develop new technologies for improving energy/resource efficiency, e.g. digital.
- Deliver a knowledge-sharing platform between sectors to share best practices.
- Develop new approaches to the reuse and recycling of technologies containing critical materials.[44]

C. Fluorinated-gases (F-gases)

What we know: F-gases are strong, artificial[45] GHGs regulated under the Montreal and Kyoto Protocols. Key sources include: refrigeration, cooling, and aluminium/magnesium and rare-earth smelting industries.[46] There are some existing alternatives to mitigate F-gases emissions (e.g. refrigerants).[47]

What to research: (i) Discrepancies between bottom-up and top-down inventories, better monitoring and quantifying of emissions; (ii) improvements in existing technologies (e.g. decarbonising anodes for aluminium production, replacement gases); (iii) explore mitigation options and alternatives, extensive Life Cycle Analysis for rising technologies; (iv) extend abatement technologies beyond semiconductors to aluminium and rare earth manufacture.

Actions to take now:

- Ensure the Kigali Amendment is ratified, implemented, and countries' commitments are monitored and reported.
- Promote and enhance legislation to control and reduce F-gases.[55]
- Increase awareness and visibility of the F-gases group, they are unknown to the public.
- Support industrial governance processes that display F-gases reduction practices.

Co-benefits: (i) Reducing emissions from shipping and transport of materials; (ii) new cooling approaches can improve air quality, energy efficiency and decarbonise energy supply.[56]

5. LAND/SEA USE AND AGRICULTURE:

What we know: Strategies for emission reductions include: nature-based solutions (NbS, see Box), low-carbon farming practices (including landscapes designed to store carbon at scale), shifting towards more plant-based diets, and reduced food wastage.

What to research: (i) How changing dietary advice and costs alter demand, and the just transition implications of such changes;[57] (ii) social and economic studies to complement technical feasibility assessments; (iii) robust assessments of the suitability of land- and sea-based approaches to carbon sequestration from the local to regional scale, ensuring balance with other land and sea use demands such as food production;[58] (iv) crop and animal breeding innovations; (v) feed additives (e.g. efficacy for different production systems); (vi) soil amendments (e.g. biochar, enhanced weathering); (vii) how to enhance monitoring and reporting skills; (viii) how changes in food production and land use affect resources required in other sectors (e.g. water) and downstream coastal and marine systems; (ix) circularity and resilience of food production systems (integrated crops/livestock); (x) impact of land and sea use decisions, including bioenergy crop production, and trade-offs with other ecosystem services.[59]

NATURE-BASED SOLUTIONS

Nature-based solutions (NbS)[48–50] are actions that involve working with nature to address societal goals, including addressing climate change and biodiversity loss, whilst supporting economic recovery and tackling tangibly a specific environmental problem.[48] NbS broadly involve the protection, restoration and connection of native habitats, sustainable management of working lands and seas, and creating new habitats in urban areas and across the broader landscape and seascape. There is substantive evidence[48,51] for NbS to cost-effectively support climate change adaptation via flood protection, erosion control, air/water quality regulation and urban cooling, while reducing sources and increasing sinks of GHGs.[52] Properly implemented, NbS can also enhance and sustain biodiversity while supporting a wide range of sustainable development goals.

We urge policymakers, practitioners and researchers to consider four guiding principles to enable NbS:[53,54]

1) NbS are not a substitute for the rapid phase-out of fossil fuels and should not delay decarbonising the economy;
2) NbS involve protection, restoration and/or management of a wide range of land and marine ecosystems (not just forests);
3) NbS are designed, implemented, managed and monitored by or in partnership with Indigenous peoples and local communities through a process that fully respects and champions local rights and knowledge, generating local benefits;
4) NbS support or enhance biodiversity, that is, the diversity of life from the level of the gene to the level of the ecosystem.

By considering its full range of synergies and trade-offs, with local people and biodiversity at the core, we can design robust and resilient NbS that sustain both nature and people with tangible socio-economic benefits (e.g. health benefits).

Actions to take now:

- Invest in research to support land and sea use change decision making at the field, farm and landscape scales (e.g. carbon modelling).
- Increase investment in R&D focussed on bringing low-carbon farming practices to market rapidly.
- Assess dietary advice and its alignment with the net-zero transition, to inform updated advice.
- Enhance capacity for land and sea-based research (e.g. interdisciplinary responses to sustainable land management and transition challenges).
- Address land-based workforce capacity gap.

Co-benefits: (i) Increased biodiversity; (ii) higher social and ecological resilience; (iii) more productive land use; (iv) healthier downstream ecosystems; (v) better diets and improved health.[60]

6. AVIATION AND SHIPPING:

A. Aviation

What we know: The decarbonisation of flight is possible, yet the scale of the problem is immense. The challenge requires a holistic optimisation of technology, infrastructure, operations, behaviour, demand management, economics and policy.

What to research: Three main technology pathways: (i) Battery-powered aircraft, however, current technologies limit their use to regional and sub-regional markets; (ii) hydrogen fuel offers zero carbon emissions, but the space required to accommodate the fuel tanks reduces payload and range. Other concerns include contrail production, storage and safety; (iii) sustainable aviation fuels can be dropped into existing aircrafts, however their production cost is at least twice as much as the other two pathways,[61,62] and are also limited by the energy required to produce them and the sustainable sourcing of feedstock.

Actions to take now:

- Investment in all three technology pathways is urgently required; a roadmap for fuel delivery, scale up, and infrastructure requirements is needed.
- Identify and implement suitable carbon pricing schemes, carbon caps and regulation to incentivise low carbon travel.

B. Shipping

What we know: The UK is a maritime leader in the green ammonia supply chain, with an internationally competitive advantage from being an early adopter, but efficiency improvements are insufficient. Ports could be a hot spot for new electrification and hydrogen use and are a key node for freight vehicles.

What to research: (i) Battery and hybrid-powered vessels for short-sea shipping; (ii) green/blue ammonia from hydrogen is the front-runner future fuel for over 90% of shipping globally. Trials of its use in marine machinery show green ammonia supply chains are rapidly gaining investment internationally;

Actions to take now:

- Displace current fossil fuel consumption with a mixture of electrification for short distances (e.g. ferries) and biofuels.

7. WASTE:

What we know: Two billion tonnes of waste is generated each year, likely to double by 2050.[63] Currently, waste management accounts for 5% of GHG emissions,[63] yet the environmental impact of producing waste is higher. Moving towards a circular economy, i.e. reducing waste before it is generated, would lower the 45% of global CO_2 emissions linked to goods and food production,[64] and pollution.[65]

What to research: (i) Improve on existing landfill (CH_4 capture/use), composting, anaerobic digestion, incineration (capture CO_2 and toxins), recycling (sorting/labelling) and water treatment processes; (ii) investigate novel technologies such as chemical and biological recycling and waste-to-energy; (iii) safe disassembly and recycling of electronic waste (e.g. PVs and lithium-ion batteries); (iv) strategies for eliminating waste (e.g. new business models, design products to be more circular economy compatible); (v) trade-offs and efficacy of different behavioural interventions, including education, policy, product design; (vi) use of organic waste for manufacturing.

Actions to take now:

- Update waste management facilities (CH_4 capture and sensors for plastic sorting) and embed in product design practices.
- Provide economic incentives for recycling, standardise the "biodegradable" label for plastics and promote further education/awareness on reducing waste and increasing recycling.
- Mandate producer responsibility schemes, banning unnecessary materials (e.g. single-use plastics).

Co-benefits: (i) Lessen the health and social impacts of waste management and pollution;[66] (ii) promote sustainable systems for using/reusing materials.[65,67]

8. GREENHOUSE GAS REMOVAL (GGR):

What we know: GGR encompasses capture and sequestration of GHGs from the air. To achieve net zero, GGR likely plays a role in balancing emissions which are difficult to stop completely.[1,68] Removal is vital for countries choosing to go "net negative". GGR techniques include both biological GGR, such as bioenergy with carbon capture and storage (BECCS) and afforestation, as well as NbS (see Box). BECCS could deliver GGR at a significant level and provide energy, chemicals, materials or fuel.[69] However, the GGR potential of different BECCS applications varies considerably, and BECCS is land intensive so could have negative impacts on biodiversity and food production if taken to scale. Other more technological approaches to GGR include direct-air CCS and mineralisation, but these are currently expensive and rely on infrastructure to transport and store CO_2.[48,70]

What to research: (i) How to balance CO_2 removal with achieving other sustainable development goals; (ii) sustainable biomass resource use; (iii) improved technological methods for CO_2 capture and storage; (iv) non-CO_2 capture; (v) innovative GGR methods that link carbon sequestration to CO_2 utilisation.

Actions to take now:

- Innovation support for new GGR technologies and incentives for deployment.
- Focus on reducing emissions across all economic sectors, emphasising the near-term, and innovating/piloting new technologies for removal and hard-to-treat emissions.
- Secure sustainable finance flows to scale up biodiversity-based community-led NbS.

Co-benefits: NbS can include: (i) increased biodiversity; (ii) higher social and ecological resilience; (iii) more productive land use.

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HOW TO CITE THIS PAPER

Ainalis, D., Bardhan, R., Bell, K., Cebon, D., Czerniak, M., Farmer, J. D., Fitzgerland, S., Galkowski, K., Grimshaw, S., Harper, G., Hunt, H., Jennings, N., Kehsav, S., Mackie, E., Maroto-Valer, M., Michalopoulou, E., Reay, D., Seddon, N., Smith, S. M., Smith, T., Simpson, K., Stranks, S. D., Tennyson, E. M., Uekert, T., Vera-Morales, M. and Woodcock, J. (2021). Net-zero Solutions and Research Priorities in the 2020s: *COP26 Universities Network Briefing.*

Sponsored by UK Research and Innovation (UKRI)

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