**UKRI Energy Deep Dive Origin and Initial Summary:**

The conception of UKRI and the evolution of the policy landscape, including the introduction of the UK Government's ambitious target to reduce all greenhouse gas emissions to Net Zero by 2050, provides an excellent driver to allow us to work seamlessly across the UK's energy research and innovation landscape.

In January 2020, UKRI produced the Energy Deep Dive paper following a request from the UKRI Board to understand the UKRI energy landscape. The paper provided a summary of UKRI's current (>£1bn) portfolio of energy research, innovation and skills activities and evidenced how since its inception in 2002, the Research Councils UK (RCUK) Energy Programme, has worked proactively to position the UK to meet its energy targets and policy goals through investment in multidisciplinary research, training and innovation in partnership with Innovate UK since its creation in 2007. The Energy Deep Dive paper identified a series of recommendations to enable UKRI to build on its successes and enhance our energy capabilities as we work towards Net Zero.

As a follow up to the Deep Dive paper, the UKRI Board requested that the UKRI Energy Programme return to the Board with a forward look and define UKRI's forward priorities for energy in the context of Net Zero. This paper was discussed by the UKRI Board in July 2020 and the UKRI Board was asked to:

- Note the breadth, quality and collaborative nature of the UKRI Energy Programme and importance of its role in decarbonising our energy systems.
- Endorse the position that the UKRI Energy Programme has a role to play in both addressing the UK's Net Zero 2050 legislative target and in facilitating the research and innovation that is needed to surpass this in the long term.
- Endorse the priorities outlined including our primary choices and consider how we can position our ambitious plan as part of UKRI's response to the Government's R&D roadmap and Spending Review.

The content of the paper built upon the advice we received from across the spectrum of the Energy community and could not have been done without our partners including colleagues in academia and business. As key members of that community the SAC, in March 2020, provided input and steer which shaped the content of the paper. This included the need to look at a whole systems level approach and the need to enhance leadership across the energy landscape. The advice provided by the SAC in March was key in the development of this paper.

Lucy Martin, Deputy Director Cross-Council Programmes, EPSRC will be attending the SAC meeting to provide a summary of the outputs of the July UKRI Board discussion of this paper and how we plan to take this forward.

UKRI ENERGY PROGRAMME
SCIENTIFIC ADVISORY COMMITTEE MEETING

**UKRI's Energy Priorities**

The UK's Net Zero 2050 target is an excellent driver to enable the UK to take an international lead in the technologies and solutions to achieve Net Zero. The UK can deliver large-scale, multifaceted, mission-based programmes spanning research, skills, innovation, demonstration and deployment. Nothing less can truly meet our Net Zero aspirations and environmental sustainability goals. Completely removing greenhouse gas emissions will require solutions that go beyond carbon neutrality to offset emissions that cannot be removed entirely. Responding to these challenges, UKRI has built ambitious plans, for the next Spending Review and beyond, around three cross-cutting topics: to build the UK a carbon neutral future, to circularise the UK economy and to sustain a rich, clean environment. Significant investment now will help to secure the UK's science and innovation leadership to open up exciting new opportunities for research, innovation and industry.

Achieving Net Zero requires an understanding of how all sectors across the UK can contribute. Optimising these contributions requires a whole systems approach. It is crucial that we fully understand the trade-offs and interactions between energy supply, land use, and waste and water management, alongside the associated implications for transportation and business, industrial, retail and domestic consumption and emissions. UKRI has a significant history of whole system approaches, for example through the RCUK/UKRI Energy Programme, which brings together a range of investments and institutions to explore all parts of the future energy landscape of the UK, the role of legislative and economic incentives and consumer behaviour. We can build on these foundations to develop a whole systems approach to the societal transformations needed to achieve Net Zero.

This paper presents UKRI's priorities for energy within this context, which have been developed in close consultation with business partners to ensure that UKRI is a leader in engaging with industry. The content presented has been steered by the UKRI Energy Strategic Advisory Committee and draws on input from BEIS, the Energy Innovation Board EIB (now the Net Zero Innovation Board, NZIB), EPSRC Council, the Committee on Climate Change (CCC) and learned societies.

In summary,

- There is a strong case for a three-fold uplift in investment in energy (from current levels of £0.4bn to £1.2bn of spend per year) as a component of enhanced investment to support UKRI's full response to Net Zero across the development cycle from research to deployment and implementation. Achieving the UK's 2050 Net Zero target will be heavily reliant on practical measures to decarbonise current hydrocarbon-based systems alongside the development and deployment of known zero carbon technologies, firmly anchored in a clear understanding of energy use and how best to achieve behaviour change. Further research and innovation across all sectors will be essential to secure global carbon neutrality beyond 2050.

- Business partners have confirmed that they will co-invest at scale in the UKRI Energy Programme if they are actively involved in defining a clear end goal for the UK's energy mix in 2050 along with interim milestones that look beyond technologies and consider whole systems requirements. This will enable them to manage their long-term risks, will identify areas where the market will need to be supported by policy and regulatory measures and will focus researchers on the most critical challenges. Further details on the role of business in our forward plans is provided in Annex 3.

- We will work in close partnership with government departments through NZIB and regulatory partners including Ofgem to ensure that our actions are mutually supportive in achieving the UK's Net Zero 2050 target, whilst ensuring that wider energy research findings inform future policy decisions. Alignment of policy and regulation to drive change and enable delivery in a cost-effective way through use of incentives and disincentives alongside research and innovation will be essential to achieve the desired practical progress to Net Zero and we must work in partnership with government to achieve this. Meaningful regulatory targets used as a tool for incentivising business-led innovation will be essential and further learning and insight will be generated through demonstration and deployment. We will work to ensure we maximise the interdisciplinary strengths of UKRI to capitalise on the central role that energy demand plays in UKRI's broader Net Zero ambitions.

- Our investment, which will be rooted in an understanding of the economic, regulatory, social and behavioural aspects of the UK's energy challenges, will focus on areas of significant UK potential that will be critical to the UK's Net Zero target. In any future scenario three things will be critical, the UK's future energy system must include: extensive electrification to enable a wide-spread transition to clean energy sources; solutions that decarbonise energy needs that cannot be readily met through electrification (e.g. industrial processes and domestic heating) and; the ability to capture, store and utilise $CO_2$ from essential processes that cannot be decarbonised[1]. Therefore, our primary choice is to work in partnership to secure:
  - **A reduction in UK energy demand** of the order of 40% by 2050[2], which will be critical as we increase our dependency on clean electricity given realistic future capacity levels. Whole systems approaches and improvements in modifying and matching demand to changing patterns of supply drawing on a range of generation technologies will be critical to this, as will an understanding of the needs and behaviour of energy consumers and the factors that shape these. Solutions will need to include a combination of engineering (applied data science, AI), behaviour change and regulation.
  - **Growth of a new hydrogen economy** as a solution for our energy needs that are not readily compatible with electrification. Hydrogen presents many opportunities for this purpose; it can be used as fuel for heat, fuel for transport, a vector for energy storage, a feedstock into industrial processes and could be distributed with only minor modifications to current gas infrastructures. As an alternative fuel it will also increase the resilience of the UK's energy system. Convergence of UK academic strength, policy need, technology maturity and business readiness in the UK means the time is ripe to secure significant global market share in this emerging area.
  - **Wide-scale deployment of carbon capture utilisation and storage** (CCUS) to enable capture of 176 $MtCO_2$ by 2050. As well as being critical to manage any emissions that cannot be completely removed, CCUS is essential alongside the introduction of large volumes of hydrogen into the energy mix. While it is possible to produce green hydrogen from electrolysers

1Net Zero – The UK's contribution to stopping global warming, Committee on Climate Change, May 2019. https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

2 Absolute Zero – Delivering the UK's climate change commitment with incremental changes to today's technologies, UK FIRES, November 2019. https://www.repository.cam.ac.uk/bitstream/handle/1810/299414/Absolute-Zero-digital-280120-v2.pdf?sequence=6&isAllowed=y

powered by renewable energy, most hydrogen today is made via a process using fossil fuels, releasing $CO_2$ into the atmosphere. This will need to be captured by CCUS until clean hydrogen can be produced at the levels to meet demand.

- In delivering a whole systems energy approach, a range of technology options will be required to support Net Zero electrification needs and the UK energy mix. Investing in these technologies will also position the UK well regarding offering significant export potential through the products, systems and services developed and contribute to a global Net Zero agenda beyond 2050:
    - The extensive potential of bioenergy and power through synthetic biology to engineer new biological functions that support renewable energy at scale from sustainably produced biomass such as purpose grown energy crops as part of a refreshed UK bioenergy strategy. Challenges exist around biomass production and energy generation including cost, efficiency, health and resource management, the development of the biorefinery concept and the development of biomass supply (enhancing the utilisation of waste and residues, development of multipurpose crops).
    - Advanced nuclear technologies with improved safety, efficiency and reduced cost to complement renewable sources to meet the UK's electricity capacity needs including the development and deployment of small modular reactor (SMR) technologies in the UK. SMRs will be capable of producing cost effective low-carbon electricity as well as creating significant export opportunities for UK businesses. Research into the economics and social acceptability will be essential to assess feasibility and enable take-up.
    - Energy storage capabilities to manage supply needs to meet inter-seasonal, inter- and intra-day demands as we transition to greater utilisation of renewable energy and increased electrification.
    - Production capabilities to exploit the potential of UK discoveries in advanced perovskite solar technology to secure extensive export potential.
    - Further inward investment into UK offshore capabilities to solidify the UK's position as a leader in offshore energy.

- Research will contribute to the decarbonisation of energy in the following ways:
    - Co-working with business to address the research questions that arise during deployment of existing technologies.
    - Understanding organisational and individual energy behaviour, the change required, and the levers that could help achieve this.
    - Delivering the disruptive energy science that contributes to achieving global carbon neutrality in the long-term including research that supports changes in behaviour, business models, regulation and markets.
    - Creating new scientific insights, innovative technologies, and more effective deployment by drawing on UK strengths in underpinning technologies to provide energy solutions (e.g. AI, bioscience, quantum technologies, design, advanced materials, behavioural science, modelling).

Annex 1 (Strategic Context) and Annex 2 (Research, Innovation and Technology Choices) provide further details on the evidence we have drawn upon to arrive at these conclusions.

Annex 3 (Essential Features of Our Future Energy Research and Innovation System) describes how UKRI, drawing on the successes of the RCUK Energy Programme, will create a productive and inspirational research and innovation environment through our delivery choices that will support the UK's ambition to be a leader in decarbonisation and environmental sustainability.

## Annex 1 – Strategic Context

### 1. Introduction

The introduction of the UK Government's ambitious target, in June 2019, to reduce all UK greenhouse gas emissions (GHGs) to Net Zero by 2050[3], provides UKRI with the opportunity to position the UK as a leader in the knowledge, products, processes and solutions required to deliver a global Net Zero ambition and to surpass this target in the long term through decarbonising the existing hydrocarbon-based energy industry, alongside developing new energy systems to transition from a fossil-fuel based economy. Working in partnership with business, policy makers and regulatory bodies will be critical to this goal. This paper summarises how we intend to do this.

UKRI's current energy portfolio, which equates to £1.2bn of investment (~£400m spend per year), supports research, training and innovation to solve global energy challenges of both the developed and developing world alongside UK-specific challenges driven by the uniqueness of the UK energy system. The current portfolio is driven by the challenge of wide-spread decarbonisation and has a focus on the whole energy system and the interrelationships of each element, which recognises that decisions on energy demand and generation, social policy and full life cycle management will be essential to reach Net Zero.

More recently, the current global pandemic and social-distancing measures are impacting the global and UK economy, with a significant downturn already realised. Whilst the eventual outcome remains unclear, UK Government has indicated a commitment to a green recovery for the UK, which although not yet fully defined, further reinforces their commitment to advance the decarbonisation agenda. The forward priorities for the UKRI Energy Programme recognise the evolving economic landscape and consider where the biggest opportunities exist to secure UK competitive advantage based on current UK readiness and capability to exploit opportunities.

For UKRI to fully rise to the scale of the Net Zero ambition, significant additional investment is required from UK Government. The UK's Net Zero legislation represents a significant scale-up in ambition and therefore, a scale-up in support is required to realise this ambition. Our business partners have advised that the current level of investment needs increasing by a factor of three to stay ahead of the curve and to meet the increased ambition of Net Zero.

### 2. Joining up the landscape to catalyse wide-scale deployment

We recognise that clear alignment across research, innovation, commercialisation, policy and regulation is required to make the UK's Net Zero 2050 target a reality. This will be critical to ensuring Net Zero solutions are deployed in the necessary timescales and that the research, innovation, demonstration and deployment activities all contribute to a national, shared goal facilitated by policy and regulatory measures to drive the economic potential.

We have received clear steers from colleagues across UKRI and their constituent disciplines, government and our business partners, who recognise that technology alone cannot provide the solution, that the readiness and associated acceptance criteria for Net Zero solutions needs to include an understanding of energy demand and the factors that shape it, public acceptability, economic viability, environmental and health considerations and requirements, policy levers, legislation, regulation and social readiness. The best technology in the world may never be adopted if these other features are not addressed. To help overcome these requirements a clear end goal of having a shared understanding of the

[3] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law

future UK energy mix for 2050 needs to be defined along with interim milestones that look beyond technologies and considers whole systems requirements. This will be essential to enable businesses to manage the long-term risks and to commit to this agenda. It will also help identify the areas where the market will need to be supported by policy and regulatory measures to drive change and will help focus the attention of our researchers on the most critical challenges associated with Net Zero.

An example of this type of joined up approach is how the UK has responded to the regulation of average $CO_2$ emissions in passenger cars in the EU with defined and measurable targets across time (95 g/km by 2021, 81 g/km by 2025 and 67 g/km by 2030). This regulation has resulted in automotive manufacturers working to decarbonise their fleet, in the short term by pushing the boundaries of ICE technology and longer term through investment at scale in the research and innovation required to transition to battery electric vehicles. The policy, research and innovation landscape in the UK has adapted to support this endeavour through investment in applied research in battery technology (Faraday Institution), business-led R&D, establishment of the UK Battery Industrialisation Centre to de-risk battery manufacturing investments for business and through the recent introduction of the Automotive Transformation Fund to support supply chain development and to secure Gigafactory investment in the UK. Recognising the importance of this intervention, the UK is currently consulting on implementing more ambitious targets and ending the sale of new petrol, diesel and hybrid cars and vans by 2035[4]. Our business partners have advised that this type of approach is one that results in meaningful change and is something that should be considered to support the decarbonisation of the UK's energy system. Meaningful regulatory targets can be used as a tool for incentivising business-led innovation.

An essential part of our forward plans is that we work closely with government departments through NZIB) and regulatory partners including Ofgem to ensure that our actions are mutually supportive in achieving the UK's Net Zero 2050 target and to advocate for a national long-term plan for the decarbonisation of our energy system to be developed that allows for and enables the commercialisation and deployment of Net Zero solutions. To support this the UKRI Energy Programme, via Innovate UK and EPSRC, have been in discussion with Ofgem and BEIS regarding how we can achieve greater alignment of our collective energy innovation funding and how we can co-invest in programmes that can benefit from the varying nature and eligibility of our individual funds. We have also been working in partnership with BEIS colleagues to provide the NZIB with a coherent picture of the current Net Zero innovation landscape and future needs.

UKRI must ensure a balance of research that both contributes to known targets such as Net Zero GHGs by 2050 and invest in disruptive, creative research to provide solutions to problems not yet known. Whilst we need to align with NZIB for the plans to 2050, it is the role of UKRI to think beyond 2050 and how fundamental research can open up opportunities for the UK to be at the forefront in delivering solutions that will achieve both global carbon neutrality and UK economic growth. Energy research and innovation must be connected into the broader UKRI investment focused on Net Zero to maximise the synergies with other areas that require decarbonisation including transport, housing and consumer behaviour.

[4] https://www.gov.uk/government/consultations/consulting-on-ending-the-sale-of-new-petrol-diesel-and-hybrid-cars-and-vans

## Annex 2 – Research, Innovation and Technology Choices

### 1. Our energy research and innovation priorities including our technology choices

The UK's shift from an 80% GHG reduction target to a Net Zero target is a profound one. As the CCC report notes, 'Net Zero is a more fundamental aim than previous targets' and we have saved the most difficult challenges (remaining 20%) still to decarbonise. In addition, the CCC report is clear that the Net Zero target focusses solely on emissions produced in the UK and does not include emissions that take place outside of the UK but that are produced as a consequence of UK commodity imports. UKRI therefore, has a significant role to play in facilitating research, innovation and effective deployment that will support future reductions and market opportunities beyond the focussed UK 2050 target and to support achieving decarbonisation of the global energy system in the long term.

Given the scale of the UK's Net Zero ambition we wish to grow the UK's energy research and innovation portfolio in areas essential to achieving a zero-carbon economy: generation, supply, demand and carbon capture utilisation and storage. Increased investment into UKRI Energy Programme will be critical to enable our ambitions to be realised.

Within our forward plans we recognise the need to support a systems level approach, focussing on two themes: (i) decarbonisation of current hydrocarbon-based systems, and (ii) transformative solutions to support a future Net Zero system. Meeting the UK's legislative Net Zero 2050 target will predominantly be achieved through the development and deployment of known technologies allied with significant behaviour change at both an individual and organisational level.

We recognise that there is a need for increased investment in whole systems innovation and deployment with a focus on bringing users, utilities, providers, regulators, researchers and innovators to work together to overcome system level challenges alongside business-led innovation projects. As mentioned, previously, we also recognise from our business partners, that innovation and deployment itself generates further research questions.

### 1.1 Whole Energy Systems

As recognised by the Prime Minister's Council for Science and Technology in their letter to the Prime Minister entitled 'Achieving Net zero through a whole systems approach', dated 30 January 2020, whole systems research and innovation is required to understand and act upon the complexities, interactions and interdependencies within the Net Zero landscape and its connections with other systems. Many of the currently available technologies for the decarbonisation of the energy system are inter-related and could be combined as part of solutions. There are also many dependencies across the energy system and wider GHG emitting systems (e.g. transport, agriculture, land use), which need to be fully recognised and understood as a whole system.

The UK has depth of expertise in the area of whole energy systems research that can be exploited as part of the Net Zero pathway. A core feature of UKRI's forward plans is to not only invest in the individual components that are necessary to support Net Zero, but also in programmes and partnerships that join up and undertake a whole system view across the UK Net Zero landscape. It will bring users, utilities, providers, regulators, researchers and innovators to work together to overcome system level challenges alongside business-led innovation projects.  This would include focussed whole systems research programmes, policy analysis and engagement, enabling the sharing of best practice and creating an international focal point for the UK's efforts.

Future research and innovation challenges in whole energy systems include:

- How will global, national and local developments influence the shape and pace of the UK's transition towards a low carbon energy system?
- What are the potential economic, political, social and environmental costs and benefits of energy system change, and how can they be distributed equitably?
- Which actors could take the lead in implementing the next stage of the UK's energy transition, and what are the implications for policy and governance?
- How do we take an engineering systems integration approach to reduce the risks associated with securing and delivering a fully integrated future UK energy system?
- How do we develop the very challenging modelling required for integrated energy systems that need to draw upon all components of the energy systems (e.g. human behaviours, energy conversion technologies, economic factors, multiple energy sources and storage components) and utilise machine learning?
- How do we ensure changes in energy demand reduction go further and faster, whilst needing to become more flexible?

One way in which some of these research and innovation questions could be taken forward is through investment to support the establishment and delivery of a Net Zero Futures Centre to provide coherence across the landscape by coordinating multiple activities focussing on Net Zero and providing real challenge to research related to Net Zero. This would include policy analysis and engagement, enable the sharing and promulgation of best practice across research and innovation and create an international focal point.

**1.2 Energy Demand**

As noted, in the UKRI Board discussion of the Energy Deep Dive earlier this year, there is a need for extensive research and innovation into solutions to reduce demand and consumption of GHG emitting commodities, alongside developing solutions to decarbonise the production and distribution systems themselves. Research and innovation into energy demand and its reduction through technical measures (e.g. energy efficiency) as well as behaviour change will be essential in supporting the transition to Net Zero. The EPSRC funded UK FIRES project estimates that to meet the Net Zero target, the UK must reduce energy demand by 40% from today's figures. As evidenced through the observed reduction in emissions resulting from recent social distancing measures, even with extreme changes, behaviour change alone can only go part of the way needed to achieve the desired reduction in demand. A recent article in Nature Climate Change stated that UK emissions dropped by 31% in April 2020 due to social distancing, leaving 69% of emissions still intact.

This research and innovation area has a focus on technical and socio-economic understanding of demand for energy services, rather than solely on one or the other. UKRI currently has £82.3m of investment into this area. When we talk about energy demand, we refer to all uses of energy: electricity, transport fuels and fuels for heating and industrial processes. Greater flexibility in electricity demand, often called demand side response, can also help. This involves a much greater understanding of the timing of energy demand and how it can be altered, either by changing our energy practices (e.g. doing the washing at different times) or storing energy locally (e.g. in hot water tanks or electric vehicle batteries). There are some technologies that promise to manage demand through smart devices connected via the internet and smart meters to a smart grid. Significant social changes will need to accompany these technological changes.
We can divide this into three main 'sectoral' areas: transport (where, how and why we travel), buildings (how to achieve comfortable, healthy, energy efficient buildings) and materials (how industry could adapt their processes and materials), as well as being supplemented by three cross-cutting themes, namely: flexibility (the timing of energy demand), digital (the influence of IT on energy demand) and policy (understanding how

public policy affects energy demand). We also have a specific focus on the decarbonisation of heating, fuel and transport poverty and the decarbonisation of steel.

Heating and cooling produce more than one third of the UK's $CO_2$ emissions and represents around 50% of overall energy demand. However, substituting fossil fuels with low-carbon technologies will be exceptionally complex given fossil fuels currently provide resilience to inter-seasonal differences, inter-day differences and peak weather events.

The UKRI Energy Programme recently convened a Decarbonising Heating and Cooling Forum, to help inform our forward plans in this space. External delegates included representatives from BEIS, Met Office, Ministry for Housing, Communities and Local Government, Arup and UKRI investments including the Energy Systems Catapult, UK Energy Research Centre (UKERC), Centre for Energy Systems Integration (CESI), Centres for Research into Energy Demand Solutions (CREDS). This identified that further research and innovation is needed to respond to the seasonal nature of demand for heating and cooling, the 'spikiness' of demand (e.g. 'beast from the east'), the significant complexity and cost of changing infrastructure, consumer behaviour and expectations and the potential significant rise in the demand for cooling as the planet warms. Given the global demand for cooling technologies, it was recognised that this also offers a significant export opportunity for the UK if we can develop solutions for decarbonising heating and cooling.

### 1.3 Energy Networks

UKRI currently support a portfolio of £112m of investment into research, innovation and training for energy networks. These look at a range of subjects such as the effects of decarbonisation on the existing energy supply and transmission networks and how future network technologies will deal with these challenges. This area includes research into generation and transmission networks of all scales; management of demand and integration of different energy vectors; and power electronics research into the design, fabrication and engineering of circuits for reliable high-power, high-voltage applications in the context of Energy Networks

Future research and innovation challenges for energy networks cut across many of the other areas described elsewhere in this document and include the need to:

- Work with whole energy systems and energy storage research communities to develop strategies to deal with an energy system that is adapted for decarbonisation through the greater use of renewables and to enable dealing with intermittency whilst still providing flexibility.
- Understand the networks demand of massively increased electrification across time, through the day, the seasons and the year;
- Understand the impact of different behaviours on this process;
- Understand how to deal with the impacts of different weather scenarios that are currently delivered by current energy networks.
- Integrate heat, electricity and gas networks.

### 1.4 Bioenergy

UKRI currently has a portfolio of **£76m** of investment in bioenergy research, innovation and training, which is focussed on delivering GHG savings through the production and thermochemical conversion of sustainable, advanced biofuels and other low carbon fuels to energy vectors (e.g. heat, electricity and liquid fuels). Feedstocks include algae, crop and forestry residues, food and municipal waste, animal wastes, perennial biomass, and carbon gases. Therefore, strong dependencies and linkages exist between bioenergy and research and innovation into the decarbonisation of agriculture, precision agriculture and waste and resource management and efficiencies. Using biomass as a resource for energy has the potential to reduce power intermittency and improve waste management methods and may play a part in flood defence.

The quality of skills, the transfer of knowledge and the level of UK investment in bioenergy are reflected in strong links with industrial organisations (e.g. Drax power stations, the first power station to use biomass as an alternative to coal), which have contracts in place to allow for feedstock pilot testing and which feedback research challenges that require addressing at higher Technology Readiness Levels (TRLs). In view of the limited resources in the UK for bioenergy (in terms of soil type, land surface area and climate), the research and innovation community has increased collaboration with relevant bioenergy stakeholders outside the UK (including Africa and the Philippines). The amount of funding leveraged from non-UK sources demonstrates the strength and quality of UK research and demonstrates the significant opportunity for the sales and exports of UK solutions to the rest of the world.

In September 2019, the Royal Society outlined the need for activity in biofuels to grow to support the move to a low-carbon economy and contribute to the UK's Net Zero target. Developments in bioenergy have potential for significant impact on the transport industry via drop-in fuels, particularly in aviation and in combination with CCUS. However, research and innovation challenges exist around cost, efficiency and health and resource management, the development of the biorefinery concept and the development of biomass supply (enhancing the utilisation of waste and residues, development of multipurpose biomass crops). To meet climate change targets the UK will need to rely on a variety of renewable energy sources, including energy from sustainably produced biomass such as purpose grown energy crops.

### 1.5 Energy storage

Continued commitment to fundamental research in energy storage, notably through EPSRC's SuperStore (SuperGen), has ensured the UK's pioneering role in the field. UKRI is now leading a major ISCF programme, the £246m Faraday Battery Challenge, recognising opportunities in the growing electric vehicle market and climate-related decarbonisation imperatives and the opportunity for the UK to secure competitive advantage in the manufacture of advanced battery technologies. The Energy Storage SuperGen Network+ is now helping develop the community and advance the development of energy storage technologies that span beyond electrochemical energy storage including thermal, mechanical and kinetic and will be vital in achieving the UK's Net Zero target.

Whilst it is critical that the ISCF Faraday Battery Challenge continues to blaze a path towards realisation of batteries (particularly for electric vehicles and increasingly for wider applications such as aviation), the greater utilisation of renewable energy and general increased electrification provides challenges in supplying energy to meet inter-seasonal demands, inter- and intra-day demands which will need energy storage solutions. EPSRC-UKRI is currently developing a programme for research into technologies for Grid-Scale Inter-seasonal storage. Wider research and innovation needs include thermal, mechanical, kinetic and hybrid energy storage, as well as research into integrating energy storage into and with renewable energy sources and power networks.

### 1.6 Fuel Cell Technology

UKRI currently has £18m of investment in fuel cell technologies research and innovation. In recent times this has not been a priority area for the UK and the low levels of funding reflects this. EPSRC currently funds 13 grants with a grant cost of less than £10m, which is dominated by the H2FC SuperGen. Most of the work in this area has been focussed on hydrogen fuel cells, with a recent focus on more speculative approaches, such as fuel cells powered by biological sources. The recent focus on the use of hydrogen (and other alternatives to fossil fuels such as ammonia) as a route to Net Zero (described in section 1.7 below) has created a surge in interest in fuel cells. A major focus has been on transport, particularly for freight and buses. For example, Mercedes has announced it will stop making Internal Combustion Engine trucks by 2039; it speculated that whilst battery buses maybe most appropriate for the urban environment, fuel cell buses will be a more successful solution to inter-city transport.

The UK is seen to have a strong fuel cell research community with good links to industry. Leading UK fuel cell companies include Adelan and Ceres Power. If fuel cells are to be a viable and widely used technology, sustainability of production, recycling and disposal must be considered. Alternatives to precious metal catalysts are to be sought at the materials level. Until fuel cells become more viable, the emphasis should be on developing new materials, improving manufacturing and identifying valid routes of commercialisation and scale-up, in an attempt to drive the technology as it stands towards commercial uptake while preparing the fundamental materials for the next generation of fuel cells.

### 1.7 Hydrogen

Currently, UKRI funds research, innovation and training into hydrogen and alternative energy vectors for the generation, storage and utilisation of synthetic chemical energy and synthetic fuels, of which hydrogen is one. This includes research and innovation into materials and devices used for their generation and storage and any socio-economic and environmental issues associated with this. UKRI currently invests **£13m** in sustainable energy vectors (including hydrogen) and **£14m** in fuel cell technologies. There is also potential for hydrogen to be part of the solutions developed within two of the Industrial Strategy Challenge Fund programmes, Industrial Decarbonisation (£170m) and Transforming Foundation Industries (£66m), with funding competitions for both currently underway. Hydrogen is likely to feature throughout the portfolio of demonstrators within the Industrial Decarbonisation Challenge.

Hydrogen presents many opportunities and benefits; it can be used as fuel for heat, fuel for transport, a vector for energy storage, and feedstock into industrial processes. As part of a revised energy mix, hydrogen builds greater UK resilience in a post-COVID-19 environment and could also support traditional sectors e.g. oil and gas, looking to pivot their business model. The addition of a second green technology alongside with batteries and energy storage adds resilience to the UK energy mix, as well as providing heating and green chemistry opportunities. It has the potential to contribute to the Government's levelling up agenda with regional hydrogen economies already developing strengths and primed to capitalise on these. Longer-term there is an opportunity over the longer term for hydrogen to be used as a potential aviation fuel and to build wider access to green energy in developing countries

Readiness and expertise to participate in the hydrogen agenda also exists within the UK business landscape through Johnson Matthey (catalysts and electrolysis) and ITM Power plc (electrolyser technologies). We have excellent engagement with both companies, who, for example, are project partners on 71 active research grants to the sum of £205m and 14 active research grants to the sum of £53m through EPSRC respectively. Siemens (electrolyser technologies) is also another business with activity in this space.

Further research and innovation is required to understand and address: public acceptance and perceptions, affordability, planning and consent, supporting infrastructure, hydrogen appliances (e.g. boilers, cooking hobs), safety requirements and policy incentives; subsurface storage of hydrogen; infrastructure and geological research and innovation for large natural feature storage options; coupling of offshore wind and hydrogen production; use of methane to produce hydrogen; climatic responses to a switch to hydrogen use; scale up and lowering cost of decarbonised hydrogen production methods e.g. electrolysis; biohydrogen production; hydrogen embrittlement of metals impacting on structural integrity of infrastructure; cost reduction; hydrogen storage and the use of advanced materials for safe housing as recognised in the Royal Society's Options for Producing Low-Carbon Hydrogen at Scale briefing, The manufacture and future use of zero-carbon ammonia (green ammonia) is a related vector that offers some advantages (e.g. a higher energy density, established storage and transport methods) and offers potential solutions in transport (especially shipping). As discussed in the Royal Society's Green Ammonia report, it offers;

- Energy storage – ammonia is easily stored in bulk as a liquid at modest pressures (10-15 bar) or refrigerated to -33°C. This makes it an ideal chemical store for renewable energy. There is an existing distribution network, in which ammonia is stored in large refrigerated tanks and transported around the world by pipes, road tankers and ships.
- Zero-carbon fuel – ammonia can be burnt in an engine or used in a fuel cell to produce electricity. When used, ammonia's only by-products are water and nitrogen. The maritime industry is likely to be an early adopter, replacing the use of fuel oil in marine engines.
- Hydrogen carrier – there are applications where hydrogen gas is used (e.g. in PEM fuel cells), however hydrogen is difficult and expensive to store in bulk (needing cryogenic tanks or high-pressure cylinders). Ammonia is easier and cheaper to store, and transport and it can be readily "cracked" and purified to give hydrogen gas when required.

The UKRI Energy Programme has identified hydrogen as a priority and sees huge opportunity in investment at scale to support the growth of a new hydrogen economy in the UK through a coordinated national effort. The convergence of UK academic strength, policy need (Net Zero), technology maturity and available business capabilities and readiness in the UK means the time is ripe to secure significant global market share in this emerging area whilst also utilising the technology to contribute to our decarbonisation commitments.

### 1.8 Marine Energy (Wave and Tidal)

UKRI currently has a **£42m** portfolio in marine energy research, innovation and training. Recently there has been a convergence of technology with offshore wind as floating offshore wind is an area that requires further research and development to unlock deeper water sites and broader global markets where shallow development is not an option. There are also several research challenges around integrating social and environmental aspects in the use and deployment of wave energy converters.

Modern research and development of wave energy in the UK was pioneered from the mid-1970s in response to the oil crisis. World-first, large-scale deployments were made in the UK, though mismatches between financial and technical drivers have hampered progress in the sector, and costs remain high, meaning an industrial base has failed to flourish. However, two recently concluded projects achieved respectively 50% and 30% reduction in energy cost of their wave devices, demonstrating progress towards the European SET-Plan LCoE target for wave energy of £90/MWh by 2035. Whilst the technology is not currently financially practical, the global potential for wave energy is vast and, with strategic investment, wave energy could not only be a significant contributor to our future renewable energy mix but also a lucrative export market for the UK.

The UKRI Energy Programme recently commissioned the ORE SuperGen to develop a wave energy roadmap to articulate how targeted research and innovation could play an important role in the wave energy journey to commercialisation which has very recently been published and to enable the capability to be matured in time to contribute to Net Zero 2050 targets. In response, EPSRC has just launched a call for proposals focussing on the key areas highlighted by the roadmap:

- Novel designs for niche applications
- Survivability and reliability of devices in the marine environment
- Power take off and control systems
- Modelling, forecasting and evaluation of wave energy resource
- New materials for wave energy converters

### 1.9 Nuclear Fission

UKRI currently has a portfolio of **£94m** of investment in nuclear fission research and innovation including waste management and nuclear decommissioning, fuel recycling and reprocessing, efficient and safer fuels, reactor plant life extension, advanced nuclear technologies, new nuclear builds, existing operations, regulation, public acceptability, and geological waste disposal.

Potential exists in the development and deployment of small and advanced modular reactor (SMR) technologies in the UK. The ISCF challenge in low cost nuclear will be the leading activity in the UKRI portfolio in this space and is intended to deliver on ideas for advanced nuclear technologies that were laid out in the Nuclear Sector Deal. SMRs already exist in the military sector (submarines) but this technology cannot be directly transferred to the civil sector. The ISCF low-cost nuclear challenge, proposed by a Rolls-Royce led consortium, aims to design and manufacture SMRs in the UK. SMRs will be capable of producing cost effective low-carbon electricity as well as creating significant export opportunities for UK businesses. An initial £36m joint public and private investment will enable a consortium to further develop this design. This is the first stage in a bid worth £500m, subject to future approvals, targeted at providing decarbonised energy generation to reach Net Zero targets. The full business case will be ready for approval later this year.

Further research and innovation is required to improve cost, safety and efficiency of advanced nuclear technologies as well as research into thermal hydraulics to better understand the reactor core, materials research for reactor build and research into the social acceptability of this technology which will be key to up take in the UK.

### 1.10 Solar Energy

UKRI currently has a portfolio of **£68m** of investment in solar energy research and innovation, focussing on new materials and systems for increased efficiency of solar energy conversion. UK researchers have a strong track record in technology deployment and new photovoltaic systems. Ossila Limited, a company founded by EPSRC-funded physicists at the University of Sheffield, was awarded a Queen’s Award for Enterprise in 2018. The SuperSolar Hub is a consortium of universities set up to focus solar research and development capabilities. The UK is home to both NSG, a world leader in the production of glass used in thin-film photovoltaics and Oxford PV, a spin-out from the University of Oxford, leading the development of perovskite technology. Solar cell efficiencies of devices using these materials have increased from 3.8% in 2009 to 25.2% in 2020 in single-junction architectures,[5] and, in silicon-based tandem cells, to 29.1%, exceeding the maximum efficiency achieved in single-junction silicon solar cells. Perovskite solar cells are therefore currently the fastest-advancing solar technology

As noted by Sir David Attenborough “If we could harness one 5000th part of the energy that the sun sprays on the Earth every 24 hours we could provide all the energy requirements of the entire human race.” UKRI research and innovation will continue increasing the stability and efficiency of perovskites and into development of perovskite cell systems and other new solar materials. Limitations exist around the UK's ability to manufacture the technology at scale and the depth of business capability and readiness to capitalise on our world class research findings. Opportunity exists to secure competitive advantage in this technology in the UK if coordinated action is taken to develop a UK supply chain and expand UK manufacturing capabilities for these advanced solar technologies.

### 1.11 Wind Energy

UKRI currently has a portfolio of **£47m** of investment in wind energy research and innovation. The opening of the Siemens £310m offshore wind turbine blade factory in 2016 was a milestone for the industry in the UK. EPSRC's £7.6m Prosperity Partnership programme in discovery research is helping to leverage significant long-term impact from this, by bringing Ørsted (formerly Dong Energy), the world's largest offshore wind developer, into the collaboration with leading academics. The foundations have been built over a decade, with Siemens investing in the Sheffield-Siemens Wind Power Research Centre ($S^2$WP) since 2009 to develop reliable and efficient wind turbine generators. The EPSRC-UKRI funded Offshore Renewable Energy SuperGen (£9m) is leading on the convergence of offshore wind, marine and tidal energy technologies notably in floating offshore wind and the Offshore Renewable Energy Catapult also has a prominent role in the sector, which has supported almost 600 SMEs supported and completed over 250 completed research projects, with another 100 currently in delivery.

The UK ranks 2$^{nd}$ in the world in offshore wind research and has many leading groups such as Strathclyde, Sheffield Bristol, Exeter, and Manchester which have contributed to anchoring some of the world's leading offshore wind businesses R&D capabilities in the UK and to the opportunities presented through the Offshore Wind Sector Deal. The UK is also home to some of the world's first floating wind farms around the coast of Scotland, even though the technology developers are not UK based. This demonstrates the attractiveness of the UK for development and demonstration and offers an opportunity to work in partnership globally and to attract foreign direct investment into the UK.

Further research and innovation is needed in materials research for larger blades; power conversion and transmission technology as offshore wind moves to deeper water; integration with other renewables such as the integration of green hydrogen in deep water ORE systems), turbines, sub-structures (including floating), electrical infrastructure; and, operations and maintenance and wind farm lifecycle. Innovation is also required to meet the offshore wind strike prices that have already been announced as these wind farms have not been constructed yet. To further contribute to the ambitions of the sector deal including securing 60% UK content by 2030 further support needs to be provided for supply chain development. Wider opportunities that are currently emerging in the operations and maintenance of offshore wind include the development and usage of robotics, AI and autonomous systems for this purpose which have the potential for improved safety and significant cost reduction.

### 1.12 Carbon capture, utilisation and storage

UKRI has maintained consistent support for this area (current portfolio valued at **£17m**), which has now been identified as a pre-requisite for achieving net zero GHGs in the UK according to the Committee for Climate Change (CCC) Net Zero report.

UKRI's major activity in this area is the UK CCS Research Centre (UKCCSRC), funding projects across capture, storage, systems and policy. Pilot-scale Advanced $CO_2$ Capture Technology (PACT) has supported 70+ industrial companies, 40+ academic partners, 670 test days and a total project value of nearly £70m, as well as creating the conditions for access to a global customer base. This research is also informing the £170m ISCF Industrial Decarbonisation challenge alongside the Strategic Priorities Fund (SPF) Greenhouse Gas Removal Programme through research on bioenergy with CCUS (BECCS) and direct air capture and carbon storage demonstrators (DACCS). UKRI-NERC's British Geological Survey (BGS) was the first organisation to identify CCUS as a possible option to reduce greenhouse gas emissions, giving the UK competitive advantage and the opportunity to meet emissions targets at lower cost.

As evidenced by the ISCF Industrial Decarbonisation Challenge (£170m), this technology now needs to be scaled up with demonstration, supporting the CCC recommendations. A prominent feature of the demonstrators and R&D funded through this ISCF challenge will be a focus on the design, development and demonstration of CCUS. Further research challenges remain around how do we achieve large-scale storage (the CCC estimates the UK will need to capture 176 $MtCO_2$ by 2050 and currently this figure is zero). $CO_2$ utilisation remains at a very early stage of research but offers solutions to the storage problem as well as a potential feedstock for industrial and energy processes.

Given the prominence of CCUS as a pre-requisite for achieving Net Zero and the need to significantly ramp up the UK's CCUS infrastructure to support this endeavour, this area is another priority of the UKRI Energy Programme, with the main drivers for this being UK leadership in the area and the national need for this as part of the solution for Net Zero.

## 2. Enhancing UK national infrastructure capabilities to facilitate the rapid decarbonisation of our energy system

The UKRI Energy Programme has responsibility for ensuring that the UK energy community has access to the facilities, equipment, data and e-infrastructure that is required to meet its objectives. This provides opportunity to have a coordinated approach and ensure that we utilise and connect the breadth of capabilities that exist throughout the UK and enable these to be exploited to augment local, regional and national strengths.

Given the practical focus on the Net Zero 2050 target, a priority for the future is ensure that the UK has the infrastructure capabilities to deliver the higher TRL activity needed to demonstrate and deploy the breadth of solutions, that have the potential to contribute to a future Net Zero energy system and where the UK has significant strength or competitive advantage. To achieve this, we plan to invest in living labs to converge users, product providers, utilities, researchers and innovators to work together to overcome system-level challenges. The intention is for living labs to build on pre-existing assets in the UK including connecting assets within the Catapult network, across universities, businesses and PSREs and to draw on local and regional strengths.

As described in the UKRI Infrastructure Roadmap[5] investment requirements to support our research and innovation priorities (section 10) include:

- Whole Energy Systems
    - Investing in better integration of nationally important energy models to foster interdisciplinary research across the cyber and physical elements of a multi-vector energy system. This could be through creation of a new centre for excellence or through enhanced connectivity of existing centres.
    - Establishment of a research facility for the decarbonisation of heat, to reduce the carbon footprint of domestic heating. This could be a single- or multi-site

[5] https://www.ukri.org/files/infrastructure/the-uks-research-and-innovation-infrastructure-opportunities-to-grow-our-capacity-final-low-res/

facility that would offer flexible demonstrators to develop the three main heat options (electrification, repurposing for hydrogen and district heating).

- Energy Storage
  - A ‘living laboratory’ for energy storage integration and local generation systems. To develop new energy systems and understand how people interact with them requires real-world studies. Creation of a ‘living lab’ at scale and in different environments (urban, sub-urban, mixed and industrial) would enable such studies. This could also support the study of social aspects of energy storage, such as large-scale consumer studies, to better understand how people interact with energy systems.
  - Large-scale offshore renewable energy storage demonstration facility. Facilities to complement the existing offshore renewable energy test facilities at the Offshore Renewable Energy Catapult. This could comprise of a wind turbine test facility where integrated energy storage technologies can be tested to demonstrate their ability to store surplus electricity thermally, kinetically, chemically or in batteries.
  - An energy materials research centre could be part of a larger, cross-sector capability. The energy component would focus on synthesis, characterisation and testing of new advanced materials and could research new bulk manufacturing methods.
- Fuel Cells
  - A research institute for fuel cells for the improvement of performance and reduction of cost. An R&D facility to address the remaining challenges that prevent the wider uptake of fuel cells and research and develop fuel cells technology.
- Hydrogen
  - One or more low-carbon hydrogen production demonstrators, probably with electrolysis, would be needed to demonstrate that hydrogen can be produced and supplied to the commercial market at a competitive cost.
  - Centre for the study of hydrogen use and safety of devices enabling certification of new devices, to more substantial activity focused on developing new devices with a role in independent certification to support UK manufacturers
  - A centre for R&D into re-purposing the current gas infrastructure (TRL 5–8), combustion (TRL 6–8), fuel cell research (TRL 6–8) and gas storage (TRL 3–6) would facilitate research to support the transition from methane to hydrogen.
  - A centre to research and develop underground storage of hydrogen. To store large quantities of hydrogen inter-seasonally, a facility or laboratory could be commissioned to study hydrogen storage and distribution systems equipped with measurement instrumentation coupled with an array of boreholes. This could be part of a broader subsurface research capability that also looks at CCS and geothermal energy.
  - Decision-makers need a better understanding of what a hydrogen economy could look like. A new research hub would assess the various hydrogen technology options and possible pathways that could be implemented to replace natural gas with hydrogen in the UK.
  - Geo-fluids research centre to investigate the development of UK geothermal potential. Building on the current UKGEOS facility to include geothermal heat, for example through a medium- to large-scale demonstrator capable of fundamental research on geothermal energy co-production, possibly coupled with oil and gas production. This could link to work on the underground

  - storage of hydrogen and the subsurface laboratory for $CO_2$ injection and storage
  - Alternative fuels R&D centre, a central coordinated hub focused on identifying the options for alternative fuels would lead to a more substantial effort, like the Faraday Institution, and could take a broad approach to studying alternative fuel technologies and assessing their viability. This could be focused on a single alternative or could be expanded to cover all options.
- Marine Energy
  - A facility for understanding largescale tidal stream/ wind/wave energy extraction and its interaction with the environment. A large laboratory-scale wind/wave/current combined basins and measurement system would bridge the current capability gap between small-scale wave tanks and full-scale at-sea sites. Alongside this fully, instrumenting current at-sea sites would enable state-of-the-art testing and development to take place.
- Nuclear Fission
  - Centre of excellence in nuclear engineering that would complement and possibly include an expansion of the Nuclear Advanced Manufacturing Research Centre (NAMRC). Such a centre would enable multidisciplinary nuclear energy engineering to support the UK newbuild programme. Additionally, demonstration sites could be commissioned in conjunction with the proposed nuclear development programmes, also supported by the work of the NAMRC and Catapults. This centre could also include wider cost reduction R&D in reactor and site construction.
  - Facilities for handling and analysing active materials would enable development and scale-up of newly developed techniques. This could include facilities to design and develop waste minimisation, treatment and management technologies in both active and non-active environments. This is a critical issue for the planning of new-build programmes in both SMRs and AMRs.
  - Developing dedicated facilities to research and test the fuels of future reactors (especially accident tolerant fuels) would help maintain and grow the UK's advanced fuel capability. This is important for both existing and future reactors, in both civil and defence applications.
  - Spherical tokamak for energy production (STEP): taking spherical tokamak studies through to the next development phase would require a large fusion demonstration reactor to develop the technology needed to generate electricity. The first phase of the STEP programme will develop the spherical tokamak approach to produce a concept design for the production of affordable fusion energy. The first year of this work is currently under way
  - A dedicated facility for thermal hydraulics research and testing would support the design and development of new reactors. Such a facility would need to cover one or more of the following areas: pressurised water, molten salts, liquid metal and advanced gas. These are areas of interest for code validation of SMRs, AMRs and any future advanced Pressurised Water Reactors (PWRs). This facility is in the initial scoping stages.
  - Centre or research institute for advanced reactor development, which would include new facilities that underpin design capability to support UK ambitions for new nuclear build would enable the informed assessment and development of future reactor designs, their regulation and operation.
- Solar Energy
  - Solar energy scale-up facility to support the development of new photovoltaic (PV) technologies. A demonstration facility would aid development of new PV technologies where the UK is in a leading position. This could take the form of

a national centre for low-cost printed PV that supports the distributed research community in the UK by taking newly discovered structures or production techniques and developing them for full manufacturing scale and installation.

- Carbon Capture Utilisation and Storage
    - Consider options for a network of coordinated facilities for demonstrating next-generation capture and utilisation technologies, as well as optimising amine scrubbing, at a scale of 1–10MWe equivalent. This would act as a bridge from small pilot plants to full-scale demonstrators and could also cover emerging next-generation capture technologies at a smaller scale. These can be developed through pilot plants operating at a scale of around 50–500kWe
    - A demonstration facility with CCUS as part of an integrated energy system would enable exploration of key implementation challenges. This could take the form of a 'borehole lab', with an array of boreholes, instrumentation and research capability.

## Annex 3 – Essential Features of Our Future Energy Research and Innovation System

### 1. The role of business in making a UK Net Zero energy system a reality

Our aim is to ensure that the UKRI Energy Programme is a leader in engaging with industry and to encourage collaboration between businesses in order to meet the challenge of decarbonisation of our energy system. We have therefore, liaised closely with business partners to identify how we can facilitate this and how we can secure a significant increase in the level of industry involvement and co-investment in the UKRI Energy Programme to accelerate the commercialisation and enable rapid deployment of Net Zero energy solutions.

Consultation with our business partners has exposed the need for a consistent and sustained funding environment that spans the entire development cycle from basic research through to innovation, scale-up, demonstration and deployment to facilitate the acceleration of commercialisation of Net Zero energy solutions. Given that achieving the UK's 2050 Net Zero target will be heavily reliant on the development and deployment of known technologies and solutions, there is a need for funding vehicles at the mid to high TRL to be put in place that are agile and responsive to business needs and opportunities over time and that are not single, tightly defined funding competitions. While ISCF has focussed on topic areas of strategic national importance and built critical mass of expertise, the future need is for a system that is more agile, flexible, spans the breadth of the energy system needs and is sustained over the longer term.

Our business partners have also advised that deployment and demonstration will generate further research questions, and this applied (or translational) research is an essential part of UKRI co-working with business to deliver new technologies. For example, scale-up and delivery of hydrogen production and distribution infrastructures generates research questions such as how to safely store hydrogen at scale and the need for the development and use of advanced materials for this purpose. Another example is the need for research into the public acceptability of nuclear energy as a viable proposition as we pursue scale-up and deployment of SMRs. There will remain a need for strong connectivity with the academic skills base and investment in research programmes to support this national effort.

It was also observed that at demonstration stage, the commercial viability of products, services and systems is not yet clear and therefore, co-investment between multiple business partners coupled with public investment is a model that would enable businesses to proceed into demonstration when it is not an affordable proposition for them as a single company to take forward alone. This is another measure that would significantly enhance the landscape if managed as a pre-competitive collaboration.

Businesses also recognise the longer term need to think beyond the UK's 2050 Net Zero target and agree that UKRI has a role in supporting research and innovation that will solve challenges to achieve wider decarbonisation including consideration of how to achieve Net Zero when factoring in the UK's imported emissions and how do we achieve global Net Zero. How can improve the sustainability of our energy system beyond Net Zero and how can we deliver it safer, faster or cheaper. Therefore, there was strong agreement that continued investment at scale in energy research is essential.

To address these needs, we propose to introduce long term funding streams that facilitate and support:

- A **long-term commitment to responsive business-led innovation** with clear signalling of future certainty and consistency of this funding opportunity. This would be used to support business-led programmes that address energy generation, supply and demand challenges to enable the UK to meet its short-term policy objectives for energy whilst contributing to longer term Net Zero targets resulting in business growth, new businesses, energy security, and increased energy efficiency. This route should also enable the rapid funding of proof of concepts when new opportunities arise to enable companies to seize opportunities and to develop the confidence for deeper collaborations.

- Industry-led, **co-designed applied research programmes** working with university partners on the research challenges that are critical to their goals. Expansion of the EPSRC Prosperity Partnership approach to do this at scale was recommended.
- **Collaborative demonstrators** that are designed, funded and delivered in partnership and that are identified and assessed based on national need, alignment to the UK Net Zero target, in areas where the UK can demonstrate a leading position and that provide complementarity to the current UK landscape. (Priorities for demonstrators are described in Annex 2)
- **Expansion of current successes within the UKRI Energy Programme** to contribute to the challenge of Net Zero at scale including:
    - Expansion of the mission of the **Energy Catalyst** to include support for commercialisation and deployment. Currently the Energy Catalyst is being modelled as a brand for ODA funding and would not tackle the UK Net Zero challenges directly.
    - Drawing on the **Energy Systems Catapult** to have a role in connecting businesses to capabilities across the wider Catapult network that can enable the commercialisation of their energy solutions. This will be achieved by placing energy system requirements into specific domains e.g. Connected, High Value Manufacturing and Future Cities and using additional funding streams to draw on this expertise to accelerate the move from proof of concept, to prototype, to commercialisation towards for full deployment.
    - Enhancement of the **UKRI Energy Programme research programme** to ensure we can support the disruptive energy science that contributes to achieving global carbon neutrality in the long term
    - Expansion of the membership of the UKRI Energy **Programme Strategic Advisory Committee** to have greater industry representation that reflects the broad interests of business within the energy area.

## 2. Long-term transformational discoveries to achieve and exceed Net Zero

There are significant opportunities in the convergence of UK strengths in underpinning technologies with the Net Zero challenge and on the specific challenge of the decarbonisation of our global energy systems. Examples include, but are not limited to, the discovery and application of artificial intelligence capabilities, digital infrastructure, modelling, design, advanced materials (including advanced functional materials, sustainable materials manufacture and resource efficiency), manufacturing technologies, biosciences and behavioural sciences, which have the potential to create new scientific insights, innovative technologies, and more effective deployment to provide energy solutions.

Emerging technologies such as quantum technologies, an area of UK strength, have the potential to play a role in reducing the UK's greenhouse gas emissions through for example, quantum key distribution as part of the solution for electricity grid security as we transition to increased digitalisation of our energy system, exploitation of quantum simulators and computers for novel materials design for energy applications such as nuclear fission or advanced battery chemistries and the use of advanced quantum sensors and imaging techniques to provide insight and analysis of materials and the performance of structures that far exceeds current state-of-the art, which could be used to monitor national energy assets whilst in service as part of non-destructive testing systems.

Opportunities exist to enhance our national productivity by challenging the manufacturing, AI and energy communities to integrate their research around a long-term vision of higher production rates and modularisation of high specification components for alternative energy systems (e.g. nuclear, wind, marine etc.). This requires significant learning across sectors to solve intractable manufacturing problems within a Net Zero framework and has the potential to attract inward investment to the UK.

The UKRI Energy Programme, building on the 18 years of success of the Research Council UK (RCUK) Energy Programme, will work to facilitate research and innovation programmes that will incentivise the application our world leading capabilities on the challenge of decarbonising the energy system through delivery of large-scale, multi-faceted, mission-inspired programmes that will:

- **Expose the need:** Through developing a shared understanding of the challenges and exposing these to the research community we can engage them in applying their expertise to the Net Zero challenge. UKRI has a leadership role as a trusted research and innovation convenor, able to actively manage and facilitate relationships across academia and industry drawing on the strengths of our Councils. We will introduce a **New Energy Horizons** fund**,** a UKRI-wide bottom-up fund to support transformative multi-disciplinary discovery energy science inspired by the challenge of achieving true Net Zero. This will be delivered using the best principles of responsive funding approaches within UKRI and not be constrained by Council or disciplinary interfaces.
- **Enable partnership working:** Our councils have a long track record of encouraging university-business partnership working, enabling our best researchers and innovators to work together in applying their knowledge and skills to user-defined problems, leveraging long-term, meaningful, academic-business partnerships that can contribute to regional strengths. Opportunity also exists to explore new ways of working and to improve efficiencies through partnership working. For example, EPSRC **Prosperity Partnerships** are facilitating strategic partnerships between business and universities by co-investment in large-scale, long term, user-inspired basic research programmes. Demand for these investments far out ways supply as evidenced by how over-subscribed each investment round is with high-quality research proposals.
- **Leverage our National Institutes:** We can draw upon on our broad portfolio of institutes spanning the research and innovation landscape such as the Catapults, The Alan Turing Institute, UKCRIC, the Henry Royce Institute, the UKGEOS and the Faraday Institution to identify ways to apply their expertise and assets to deliver a Net Zero energy system. We already have work underway to map out and identify the ways in which the broad portfolio of Catapults can contribute to the Net Zero agenda.
- **Invest at scale to mobilise talent:** use-inspired discovery science programmes provide the opportunity to convene and support the development of the best minds from across our universities and across career stages to work together at scale to address long term challenges. Investment in research and skills programmes will enable the UK community to tackle the most pressing problems of the day whilst also accelerating the development of our future research and innovation leaders from postgraduate to professor level. This is the model on which the Faraday Institution operates and has led to over 400 UK-based researchers collaborating to accelerate the development of battery technology.

## 3. Exploiting and contributing to global energy opportunities

Building on the 'Changes and Choices' advice paper by Professor Sir Adrian Smith and Professor Graeme Reid and the UKRI International Strategy, we will facilitate global partnerships to enable the UK research and innovation community to work with the best collaborators around the world to enhance the UK's energy capabilities and to capitalise on the export potential for UK products, systems and services within UK businesses.

**Best with best:** Opportunities include establishing a UKRI 'best-with-best' international partnership scheme enabling UKRI researchers to work with the best partners outside the UK. This will enable UK researcher and innovators to draw on the best capabilities globally, wherever they reside to support out national energy endeavour. This intervention specifically, will enable the UK community to work in an agile way and access pockets of talent globally. We will also focus on establishing bilateral or multi-lateral strategic partnerships with the leading energy research and innovation countries, initially focussing on those in which UKRI already has a presence (North America, China and India) but broadening to Japan, Germany, France and Korea given the breadth and quality of their national capabilities as evidenced in the UKRI Energy Deep Dive paper.

**Export and inward investment opportunities:** We will also design a series of global expert missions to both securing market and to enable UK businesses large and small to build links to further enhance their export opportunities. We will do this in partnership with the Knowledge Transfer Network, Enterprise Europe Network (EEN), the Department for International Trade and the Foreign and Commonwealth Office's UK Science and Innovation Network to ensure that these activities are coordinated and enable inward investment and export opportunities for energy solutions across the UK and globally.

**Achieving the UN's Sustainable Development Goals:** UK energy research and innovation has the potential to contribute to the decarbonisation of both the developed and developing world. A current weakness in the UKRI Energy Programme, as identified in the Energy Deep Dive is the application of UK energy research and innovation to the UN Sustainable Development Goals (SDG) and the challenges of the developing world. To date, this has mainly been supported through the Energy Catalyst but there is opportunity to build a much more effective and coordinated programme of activities. The UKRI Energy Programme will draw on pre-existing approaches and tools including GCRF, Newton and Ayrton and work with the UKRI International Development team, Department for International Development (DfID) and other partners to secure investment for, design and deliver appropriate interventions to support achieving affordable and clean energy. Research needs include:

- Global electrification and broadening access to clean electricity in the developing world (840 million people globally as of 2017 were still without electricity).
- Clean cooking fuels and technologies to reduce dependencies on inefficient and polluting cooking systems (over 2.5 billion people worldwide are still without access).
- The development and adoption of renewable energy technologies, including within transportation, heating and cooling technologies in the developing world.

## 4. Ensuring the UK has the researchers, innovators and entrepreneurs that are needed to realise a Net Zero energy system

Supporting the development of the next generation of leaders is central to the UKRI Energy Programme and one of the four original programme objectives. UKRI currently supports energy researchers at all career stages but with a particular focus on postdoctoral and early career fellowships given the need to increase UK capacity, diversity and leadership within this area to meet the growing research, policy and business needs. Our forward skills strategy is structured around three components that will support the development of individuals who will contribute to the immediate challenge of realising Net Zero GHGs in the UK by 2050 but also those who can provide the critical thinking and discoveries that will be needed to realise wide-scale decarbonisation in the UK and globally in the longer term. This will include:

1. **Expansion of our cohort-based doctoral training to meet demand:** The twin drivers of the 2.4% GDP target and Net Zero both require a significant increase in capacity and coverage of skilled people. Gaps in the current Energy CDT portfolio include energy networks, energy storage, solar power and bioenergy. There is also a need to uplift volume of existing CDTs to meet future industrial need (e.g. renewable energy, energy resilience, enabling the carbon transition) and an opportunity for sector-specific CDTs where appropriate.
2. **Connecting the landscape through people:** Enable the UK to fully realise the benefits of our energy capabilities and expertise through entrepreneurial training, public engagement, a 'UKRI-Government Department' secondment scheme to create much better exchange between research and policy and through focussed energy Knowledge Transfer Partnerships to strengthen the relationships between universities and business whilst supporting the career development of individuals. The UKRI Energy Programme will work closely with the UKRI Commercialisation team and the UKRI Public Engagement team to ensure that activities align to wider UKRI plans.
3. **Attracting and developing leaders in the UK:** A long-term commitment to early career fellowships to support the development, attraction and retention of skilled energy researchers and innovators in the UK. Business partners advised that this would also protect against major skills losses from the UK during the anticipated period of reduced industry activity due to the current economic impacts of the pandemic.

### 5. Increasing visibility and participation in UK energy research and innovation

The wide-spread shift to the pro-sustainability narrative that is now visible throughout the UK media and within the public in support of the decarbonisation agenda and the need for the UK to implement changes to reduce emissions presents the perfect opportunity for UKRI to build public engagement and involvement into our energy research and innovation programmes. This is particularly important given that we have received clear steer from our business partners, who recognise that technology alone cannot provide the solution, that the readiness and associated acceptance criteria for Net Zero solutions needs to include public acceptability, economic viability, environmental and health considerations and requirements, policy levers, legislation, regulation and social readiness. The best technology in the world may never be adopted if these other features are not addressed. Public engagement and involvement in our portfolio will be critical to support this.

The UKRI Energy Programme will work closely with the UKRI Public Engagement team to develop and implement a public engagement strategy that raises the profile of the UKRI Energy Programme and engages the public in research and innovation in achieving Net Zero, whilst also acting to inspire the next generation of energy researchers and innovators. Opportunities exist through delivery of citizen science programmes focussed on the challenge of reducing energy demand and engagement fellows who can provide the expert voice on the topic of decarbonisation of our energy system to the media.

We also plan to use opportunities presented by COP26 in November 2021 as a platform to celebrate the achievements of the UKRI Energy Programme to date and to communicate the ambition of the future UKRI Energy Programme. We will take this forward with the UKRI

COP26 team and the UKRI Communication Team. Aligned to this the UKRI Energy Programme, a UKRI-wide funding opportunity to support one-year COP26 Fellowships has just been announced which is run out of ESRC and EPSRC. The Fellowships will be an opportunity for early career and experienced researchers to engage with the international climate negotiations in the run up to the 26th Conference of the Parties of the UN Framework Convention on Climate Change (COP26). The overarching purpose of the fellowships is to support the international climate negotiations through the provision, synthesis, translation or interpretation of scientific evidence.