Perspective Economics

Engineering and Physical Sciences Research Council

AGGREGATE REPORT

Engineering & Physical Sciences Research Council

Impact of the Energy Research Programme

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Executive Summary

I.1 Introduction

The Energy Programme was set up in 2004 to provide funding to UK academic researchers with a focus on energy research across the remit of multiple Research Councils. The Energy Programme's overarching mission is to position the UK to meet its energy and environmental targets and policy goals through high-quality research and post-graduate training. It seeks to tackle all aspects of the energy trilemma, including energy security, affordability and environmental sustainability. Perspective Economics was commissioned in May 2020 to conduct a retrospective study into grants funded predominantly by EPSRC under the Energy Programme since 2004. This report presents analysis and findings from a two-part study that comprised an independent review of 17 Energy Programme grants and an aggregate analysis of data and documentation regarding the Programme in its entirety.

I.2 Strategic Context

UK government legislative and policy developments since the 2007 Energy White Paper, spanning environmental sustainability (net-zero), green growth and the industrial strategy are placing an ever-increasing onus on the UK's energy research infrastructure and networks to deliver the scientific and technological advances required to achieve the UK's strategic ambitions. Several fundamental market failures continue to provide robust justification for government intervention in energy research, both in terms of funding and an overarching coordinating function.

The study demonstrates a clear alignment between the challenges and opportunities associated with energy research and the stated objectives of the Energy Programme. There is strong evidence to suggest that EPSRC funding is critical for:

a) ensuring that the UK achieves its net-zero target by 2050;

b) positioning the UK as a global leader in various aspects of energy research and c) stimulating economic growth via national and international industrial expansion.

I.3 Investment in a Full Spectrum of Energy Research

EPSRC has invested £1.1bn within in-scope research areas since 2004 via 1,233 grants led by 695 Principal Investigators across 84 Research Organisations. Funding provided via the Energy programme exhibits a positive appetite for risk – often providing initial investment, acting as a catalyst for follow-on funding from both the public and private sectors, and accepting the degree of uncertainty that comes with early-stage investment in energy research. To date, EPSRC grants have secured follow-on funding of c.£2bn from a range of academic, charity, public and private contributors.

Every project reviewed as part of the study had the advancement of scientific, technical, technological knowledge and/or industrial capability for delivering climate change targets as central objectives. Funding supported a full spectrum of research, from more nascent research areas such as microbial fuel cells and hydrogen purification, through to projects with much broader research scope, such as whole energy systems and carbon capture and storage. The study also identified several examples of EPSRC funded projects that have delivered scientific and industrial advances in tandem.

The Programme portfolio has been balanced across Research Areas and is widely distributed across UK regions. Over time energy research and associated industrial specialisms have emerged that have the potential to be a powerful lever for delivering the levelling-up agenda.

1.4 Research Outputs & Policy Influence

Together, researchers supported by the Programme have produced c.23,500 research outputs and have delivered more than 1,000 tangible policy impacts, most notably in terms of energy economics, sustainability and energy regulation. Targeted EPSRC investments in projects that co-ordinate research across policy areas often feature heavily when it comes to research impacts on policy. Thematic case study research has provided illustrations of a breadth of policy impacts at various geographic levels. It demonstrates how the Energy Programme has provided extensive support for multi-disciplinary teams to devise new approaches to understanding energy challenges, and how it has also supported energy researchers to both influence and implement important UK energy policies and strategies.

1.5 Economic & Industrial Impact

Over time, the industrial partners involved in EPSRC Energy Programme activity have accounted for increasing proportions of UK employment and revenue. In 2005 project partners generated £233bn in UK revenues and employed c.1.1m people; by 2018 the employment figure had almost doubled and UK revenues had increased to c.£500bn. EPSRC funding also plays an important role in supporting UK start-ups and spin-outs across Research Areas. Analysis of secondary data demonstrates that in 2019 the spin-out companies supported by the Programme generated known UK revenues of £28.9m and employed 180 people. Since 2010 thirteen of these spin-out companies have secured a total of £49.3m of investment.

1.6 Research Skills & Networks

The study has highlighted various ways in which the Programme has contributed to advancing research skills and networks. It offers opportunities for the advancement of researcher skills and capabilities across a broad spectrum of research topics and associated skills, from fundamental science through mathematical modelling and software development to techno-economic assessment and social science research.

The Programme has invested approximately £13m directly into projects with specific training and skills development objectives via grants for Doctoral Training Centres and Fellowships and has also supported more than 800 secondments between UK universities and between UK universities and a range of other academic institutions and private-sector research teams nationally and internationally. More than 2,000 researchers involved in Energy Programme grants have moved between research institutions within the UK (72% of all researcher destinations, n=1,476) and internationally (n=619), including notable proportions having taken up positions in China, the United States, Australia, Canada, France, Germany and India.

The Energy Programme's positive contribution to skills development is also evidenced in responses to the online academic survey which indicate that EPSRC funding is successfully a) supporting the flow of academics into energy research fields and b) developing the skills and capabilities of UK energy research academics. Thematic case study research demonstrates how EPSRC investments in research skills and networks go beyond the stated objectives of direct awards and aggregated output indicators. They also support an array of 'softer' yet important skills and network development outcomes, most notably in terms of the effects that academic influence have within industry and on government policy.

I.7 UK International Standing

Throughout the study, consultation with Principal and Co-Investigators consistently highlighted the highly competitive nature of energy research on an international basis. In that respect, Energy Programme funding has frequently been cited as being critical for sustaining UK competitiveness within international research across numerous Research Areas.

In a smaller number of cases, Energy Programme funding is considered to have made a substantive contribution to securing the UK's position as internationally leading, particularly in respect of offshore renewable energy research and technology, scientific discovery and development of emergent Solar Technology, and Carbon Capture and Storage research. Further, study contributors believe that Energy Programme funding is creating new, leading-edge knowledge and increasing international visibility and collaboration.

I.8 Future Need

In addition to demonstrating considerable progress towards the Programme's overarching objectives and impact areas, the study highlights a significant ongoing need for investment in energy research. This future need is evidenced throughout the study, from the contribution that the Programme makes to the UK's strategic energy security and environmental objectives and the market failures that operate within the market for energy research, to the thematic case study research which demonstrates the complex, highly competitive and long-term nature of international energy research and the numerous benefits it derives.

Within its suite of net-zero reports, the Committee on Climate Change has stressed the extent of the challenge posed by the new 'stretched' net-zero 2050 target. It emphasises how the breadth of research currently funded under the Energy Programme will need to function together to achieve net-zero.

In addition to this environmental challenge, academic survey respondents frequently referred to the additional challenges that EU exit poses for energy research and the environmental, industrial and energy security benefits it can derive.

Ultimately the research compiled through this study serves as evidence of the considerable progress that the Energy Programme has made towards its strategic objectives and the range of benefits that the UK derives as a result. However, it also highlights the scale of the task required to achieve net-zero and the sustained investment that is required if energy research is to deliver maximum benefit to UK science and industry. It is feasible to suggest that future investment in UK energy is more important now than ever before.

1. Introduction

UK Research & Innovation's (UKRI's) Energy Programme was set up in 2004 to provide funding to UK academic researchers with a focus on energy research across the remit of multiple Research Councils. The Energy Programme's overarching mission is to position the UK to meet its energy and environmental targets and policy goals through high-quality research and post-graduate training. It seeks to tackle all aspects of the energy trilemma, including energy security, affordability and environmental sustainability. Perspective Economics was commissioned in May 2020 by the Engineering & Physical Sciences Research Council (EPSRC) to conduct a retrospective study into grants funded under EPSRC's Energy Programme (hereafter 'the Energy Programme' or 'the Programme') since 2004.
This report presents analysis and findings from a two-part study that comprised:

Part 1: Via an objective and independent review and selection process a total of 17 Energy Programme grants were identified as case study subjects. Each case study involved a combination of quantitative and qualitative research and seventeen individual case studies were produced.

Part 2: Following case study research and reporting, the study team undertook an aggregate analysis of data and documentation regarding the Programme in its entirety.

The objective of the study was to demonstrate the impact of EPSRC Energy Programme investments. Figure 1.1 provides a summarised overview of the study approach. More detail, including the case study framework, case study review notes and online academic survey questionnaire is available within the appendices to this report.

FIGURE 1.1. - OVERVIEW OF STUDY APPROACH

Stage 01: Project Initiation	Stage 02: Study Design	Stage 03: Case Study Research	Stage 04: Analysis	Stage 05: Reporting
- Project Initiation Meeting - Project Initiation Document - Rapid Evidence Assessment	- Study Co-Design - Impact Framework - Logic Models - Research Plan	- Case Study Research - Primary & Secondary Research - Progress Updates & Clarifications	- Analysis of Primary & Secondary Research - Case Study Development	- Draft Case Studies - Draft Report - Final Case Studies - Final Report

1.2. REPORT STRUCTURE

This report presents findings from Part 2 of the study – the aggregate analysis. It collates evidence from four main sources namely:

1. Analysis of EPSRC monitoring data including internal data regarding grant awards and wider Research Fish outputs and outcomes data.
2. Qualitative research and findings from across the 17 individual case studies reviewed within Part 1 of the study.
3. Analysis of secondary data from a range of sources including Gateway to Research in respect of supplementary project-level data, the Global Research Identifier Database (GRID) in respect of locational and network analysis, and a combination of Bureau van Dijk's FAME company database and Beauhurst's investment database to inform economic analyses.
4. Analysis of more than 150 responses to an online survey of EPSRC-funded academics.

The remainder of the report is structured as follows:

Section 2: presents an overview of the context surrounding the Energy Programme, including the strategic context within which it sits, the need and rationale for government intervention, and the Programme's mission and objectives.

Section 3: presents findings from an analysis of EPSRC monitoring data at aggregated and disaggregated levels including overall grant award numbers, associated EPSRC investment values, aggregated output data, and lower-level analyses by, for example, individual research areas and geography.

Section 4: discusses thematic findings that emerged from the case study research conducted in Part 1 of the study, triangulating findings from monitoring data analysis and the online academic survey where appropriate.

Section 5: concludes by setting findings from throughout the report against a) the high-level Energy Programme objectives, and b) the specific requirements of the study terms of reference.

1.2. LIMITATIONS

The study adopts a case study approach, combining comprehensive monitoring data held internally by EPSRC and within supporting databases such as Research Fish, with qualitative research into an independently and objectively identified sample of 17 case study projects. The methodology adopted for the study is reflective of the study parameters, particularly the timeframe and volume of activity that the study is required to cover.

However, the breadth of the study also presents some limitations, such as the ability to undertake more granular analysis that might inform narrower research questions within a reduced scope, or similarly the ability to construct more complex analyses that address questions of additionality. Finally, there are limitations associated with the fact that the study is the first to be conducted in many years, meaning it is unable to draw meaningful comparisons against a baseline position. In future aspects of this study may be used to construct baseline data against which future progress can be measured.

2. Energy Programme Context

The sub-sections below establish the strategic context within which the Energy Programme sits, including the prevailing (and current) policy context, the market failures that give rise to the rationale for government intervention in energy research, and finally the intervention rationale and associated Energy Programme mission and objectives.

2.1. STRATEGIC CONTEXT

Investment in energy research forms one part of the wider national policy agenda that has sought to drive decarbonisation of the economy and to make progress towards the UK's net-zero 2050 target. Here we discuss the strategic context within which the Energy Programme sits, including the prevailing policy context and related contextual factors including UK investment in energy research over time, and the current status of the UK's energy supply.

2.1.1 Policy Context

Since the 2007 White Paper on energy[1] various national policies have sought to contribute to the UK's strategic energy-related scientific, environmental, economic and industrial ambitions. More recent policies have provided the platform for investment in energy research, and associated industrial and economic growth, including but not limited to:

- The Department of Energy and Climate Change's (DECC) Carbon Plan (2011)[2] and White Paper for Secure, Affordable and Low Carbon Energy (2011)[3].
- The Department for Business, Energy and Industrial Strategy's (BEIS) Industrial Strategy (2017)[4], Clean Growth Strategy (2017)[5], Cost of Energy Review (2017)[6], Green Finance Strategy (2019)[7], and Industrial Strategy Sector Deals (2018 – 2020)[8].
- The Climate Change Act (2008) which introduced the 80% GHG emissions reduction target, the Carbon Budgets Order (2009) and subsequent Carbon Budget monitoring and reporting by the Committee on Climate Change (CCC), the IPCC's 1.5 degrees report (2019)[9] and the CCC's Net Zero Technical Report (2019)[10].

  The UK was the first country to set legally binding carbon budgets, and to date has set five such budgets, each with a five-year term, covering the period to 2032. Whilst GHG emissions have been within the first three of these budgets so far, meeting the fourth and fifth budgets will be very difficult unless more ambitious policies are implemented[11].

In November 2018 the then Secretary of State set out plans for a new white paper, planned to be published in 2019, and latterly in the first quarter of 2020. However, while the Government has indicated that the paper remains a high priority, the Coronavirus pandemic has led to a further delay.

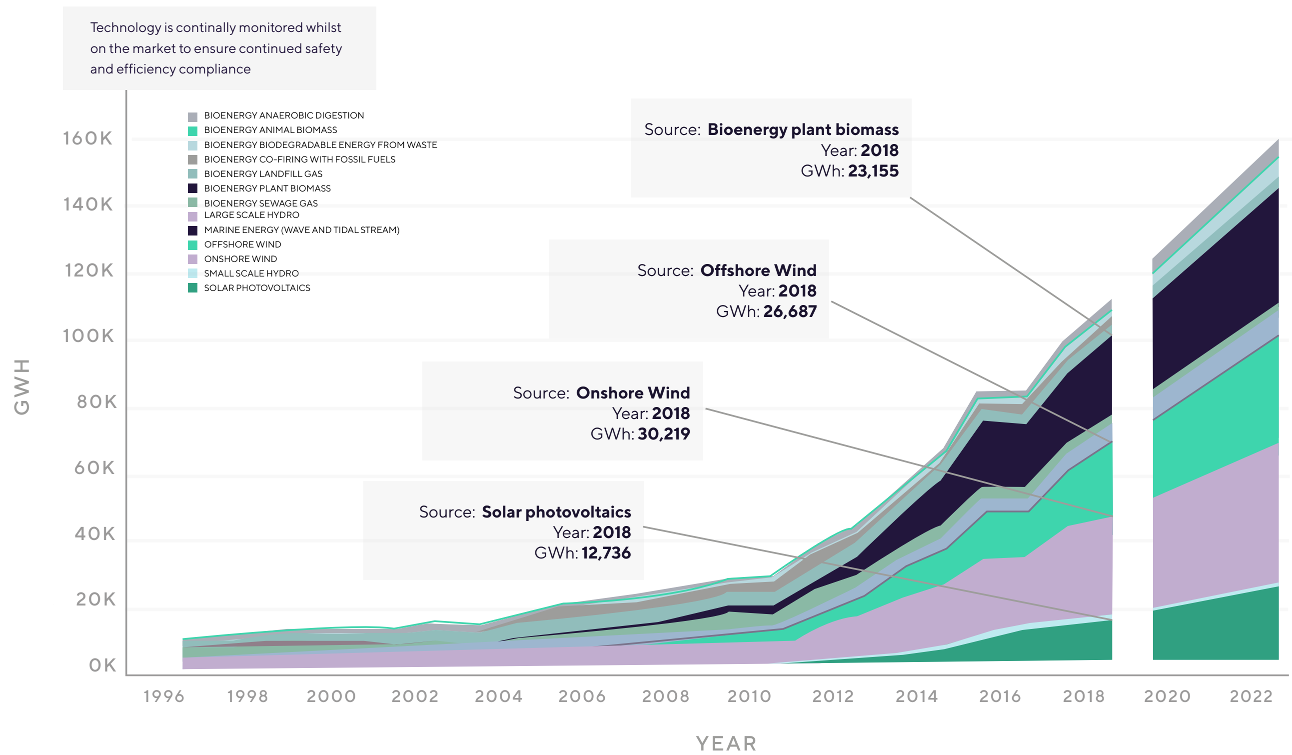
Further, the UK currently holds the joint presidency of the UN Framework Convention on Climate Change (UNFCCC) and will host the convention's 26th conference of parties (COP26) in late 2021. COP26 offers the UK a major opportunity to showcase UK prominence in energy research and climate change policy and action.

2.1.2 UK Electricity & Energy Supply

The UK's investment in energy research has contributed to rapid growth in the UK's share of electricity derived from low-carbon sources – which accounted for c.52% of the UK's electricity mix in 2019, and just under 20% for energy as a whole[12]. Increases have been driven by advances in Onshore and Offshore Wind, Bioenergy (plant biomass); and Solar Photovoltaics (Figure 2.1).

While trends in UK investment in energy research and the increasing role of low carbon energy sources within the past decade is encouraging, there remain a series of failures within the market for energy research that serve as strong justification for continued government intervention in terms of both investment and wider issues such as effective co-ordination.

FIGURE 2.1 - GROWTH IN ELECTRICITY FROM RENEWABLE SOURCES



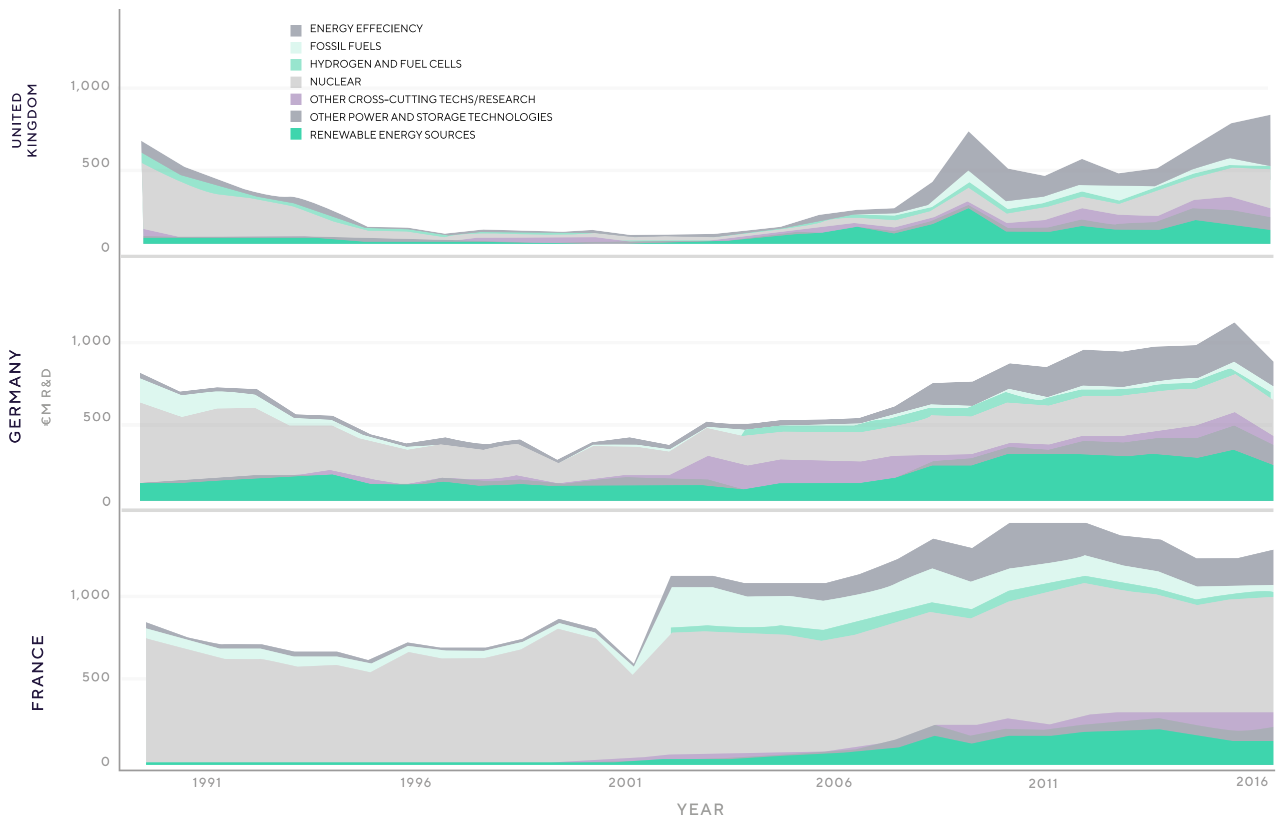
Source: Digest of UK Energy Statistics (DUKES), Electricity Generated from Renewable Sources 2020

2.1.3 UK Investment in Energy Research

Energy research has received increased funding in the UK since the early 2000s, spurred by the need to reduce emissions whilst ensuring energy security, resilience and affordability. Since 2004 the Energy Programme has invested significant sums of money into energy research at UK Universities, with EPSRC alone having committed c.£1.6bn between 2004 and the start of 2020[13].

In an international context, continuously increasing investment in the UK since 2014 has brought UK energy R&D spending in line with other major European economies. According to the International Energy Agency (IEA) data, the UK has also maintained a comparatively balanced energy research budget (Figure 2.2).

FIGURE 2.2 - UK ENERGY RESEARCH R&D INVESTMENT



However, the challenge for energy research has changed significantly in the last couple of years. The IPCC 1.5 degree report[14] and the Committee on Climate Change report on net-zero[15] contributed to a change in the UK target to net-zero greenhouse gas emissions by 2050. This means that all parts of the economy will need to reduce their emissions, including areas that are difficult to decarbonise (e.g. some industrial sectors, aviation, agriculture).

At the same time, energy research needs to continue to address other policy objectives such as security and resilience (e.g. cybersecurity as digitalisation of the energy sector starts to expand), affordability, and industrial/economic opportunities. Therefore, energy research needs to be intensified, with a greater emphasis on speed - and balancing 'blue skies' research with more applied research and innovation to commercialise low carbon technologies and systems.

Encouragingly the 2020 Budget signalled a significant increase in overall R&D funding by government, including for energy research. However, the more recent challenge of COVID19 gives rise to a degree of uncertainty regarding the potential scale and scope of future funding. Section 2.2 provides a summary of the market failures that continue to affect energy research, and therefore provide the underpinning rationale for continued government intervention. As illustrated later in this report, via several case studies including UK leadership in offshore renewable energy, and UK prominence in perovskite solar photovoltaics, investment in energy research is critical if the UK is to remain competitive both in terms of scientific research, and industrial strength.

2.2. ENERGY RESEARCH MARKET FAILURES

The rationale for any publicly-funded intervention can be based on strategic objectives, improvements to existing policy, market failure, or distributional objectives that the government wishes to meet[16]. The preceding section set out the strategic national objectives to which the Programme contributes. However, there are also various failures in the market for energy research which add further weight to the requirement for government intervention.
The sub-sections below present four of the key market failures (among many others) associated with energy research.

2.2.1 Negative Externalities

Greenhouse Gas (GHG) emissions represent a significant and detrimental global externality. However, the negative effects of GHG emissions do not fall on those producing the emissions. Therefore, historically they have been external to the market, with costs borne by future generations and corrections to the market-driven predominantly by moral and ethical rather than economic factors. As such markets have failed by overproducing GHG emissions. A focus on low carbon technologies in energy research, design and development is a partial response to this market failure, alongside measures to price or regulate activities that cause GHG emissions. Everything that investment in energy research seeks to do aims to address this most significant market failure.

2.2.2 Imperfect Information

Numerous factors associated with energy research are highly uncertain, including factors across the Technology Readiness Level (TRL) continuum, from uncertainties regarding the results of fundamental scientific research, through uncertainties about the performance of new technologies at pilot and demonstration scales, to uncertainties regarding lead-times to commercialisation.

This host of uncertainties makes investment in energy research highly unattractive to commercial entities and leads to a lack of inherent demand/appetite for energy research. It is often commercially unviable to invest in the capital and knowledge required to fully understand the potential commercial benefits of fundamental research advances, leading to imperfect information within industry.

2.2.3 Co-ordination Failure

In a similar vein, given the breadth and depth of research required to further energy products, services and policies, research can often be duplicated and / or complementary research findings are not effectively brought together. Co-ordination failures occur where there is inadequate organisation for collecting, analysing and sharing information about research, development and innovation opportunities[17]. Often it is too difficult to appropriate enough of the results of research or innovation to make private-sector investment worthwhile, and so a central organising entity is critical to help address market co-ordination failures.

2.2.4 Research Spill-Overs

Spill-over effects have implications for energy research in two main ways. First, spill-overs of knowledge into the market are hard to fully mitigate and therefore act as a disincentive to commercial organisations to invest in fundamental and early-stage research. Secondly, research spill-overs can refer to unintended benefits of research which, in the absence of government intervention, are unlikely to receive sufficient investment from the market to realise their potential. Therefore, research spill-overs generate a need for government intervention in terms of a) investment where it is commercially unviable and / or unattractive and b) maximising the research and potential future industrial and economic potential of unintended scientific advances.

2.3. ENERGY PROGRAMME INTERVENTION RATIONALE

The rationale for government intervention in energy research is firmly underpinned by the strategic policy alignment and market failures set out above. Providing a coordinated, long-term approach to investment in high-quality energy research is critical to addressing these strategic objectives and market failures. Specifically:

- Investment in research on low carbon sources of energy, energy-efficiency and more sustainable energy systems helps to develop and deploy technologies to reduce emissions and provides wider evidence to underpin the transition to a net-zero economy.

- Investment in research expertise, facilitated by a deep and broad network and understanding of that expertise, helps to maximise research quality and the wide-ranging benefits of research[18].

- Investment made in collaborative industry-academic research helps to incentivise commercial involvement in early-stage research, reduces uncertainty, and enhances the potential for deployment of new technology at scale. Evidence suggests that support for collaborative research which is driven by close industry-academia relationships and aligned objectives can derive scientific, societal, industrial and economic impact[19].

- Assuming appropriate checks and balances are in place, longer-term, centrally co-ordinated investment can help to minimise coordination failure, de-risking targeted early-stage research so that knowledge spill-over disincentives are mitigated, and unexpected advances due to research spill-overs are exploited[20].

2.4.

ENERGY PROGRAMME MISSION & OBJECTIVES

The Energy Programme was set up in 2004 to provide funding to UK academic researchers with a focus on energy research across the remit of multiple Research Councils. This overarching ambition for the Programme remained following the unification of the Research Councils into UK Research and Innovation as of April 2018. The Energy Programme[21] comprises twelve individual research areas, namely:

1. Energy Storage
2. Nuclear Fusion
3. Nuclear Fission
4. Solar Energy
5. Offshore Renewable Energy
6. Whole Energy Systems
7. Energy Networks
8. Hydrogen & Alternative Vectors
9. Fuel Cell Technology
10. End-Use Energy Demand
11. Bioenergy
12. Carbon Capture & Storage

The Energy Programme's overarching mission is to position the UK to meet its energy and environmental targets and policy goals through high-quality research and post-graduate training. It seeks to tackle all aspects of the energy trilemma, including energy security, affordability and environmental sustainability.

The Programme's original objectives were to:

1. Expand UK research capacity in energy-related areas.
2. Support a full spectrum of energy research to help the UK deliver the strategy elements set out in the 2007 Energy White Paper, in particular providing more support for low carbon technologies and ensuring the right conditions for investment.
3. Work in partnership to contribute to the research and post-graduate training needs of energy businesses and other key stakeholders.
4. Increase international visibility and level of international collaboration within the UK energy research portfolio.

A review of the economic and policy context surrounding the Energy Programme demonstrates close alignment between the underpinning rationale for the Programme, it's mission and objectives and a) increasing instance of national policy aimed at reducing emissions and helping the UK to achieve it's net-zero 2050 target; b) increasing UK investment in energy research and development, and c) significant growth in the UK's share of energy derived from low-carbon sources.

Nevertheless, while many of the fundamental policy drivers remain the same, the UK's strategic focus on climate change and green growth has intensified, emissions targets are now much tighter, specifically the net-zero target, and there is considerably more emphasis on a wider set of outcomes, spanning industrial advancement, economic development and job creation via the UK Industrial Strategy, as well as broader societal outcomes.

3. Energy Programme Statistics

The headline statistics presented here are based on monitoring data provided to the study in respect of 1,233 unique funding awards administered by EPSRC[22] under the Programme between 2004 and 2020.

3.1. GRANTS & INVESTMENT VALUE BY RESEARCH AREA

The number of unique awards made by Research Area ranges from 3 (UK Magnetic Fusion Research Programme) to 267 (End Use Energy Demand), with equivalent values ranging from c.£28m (Hydrogen and Alternative Energy Vectors) to c.£360m (UK Magnetic Fusion Research Programme). Overall investment in energy research apportioned to the twelve research areas amounts to just under £1.1bn. More broadly, grants included within the scope of the study make up seventy-seven per cent of the total value of associated awards[23]. Note that unless explicitly stated, analyses from this point forward do not include the UK Magnetic Fusion Research Programme due to its significantly different nature and scale compared to the rest of the Programme portfolio[24].

Data presented in Figure 3.1 shows that Energy Programme funding is very closely aligned with policy objectives on climate change, including demand and supply-side priorities such as End Use Energy Demand (EUED), Nuclear Fission, Solar and Offshore Renewables and Carbon Capture and Storage.

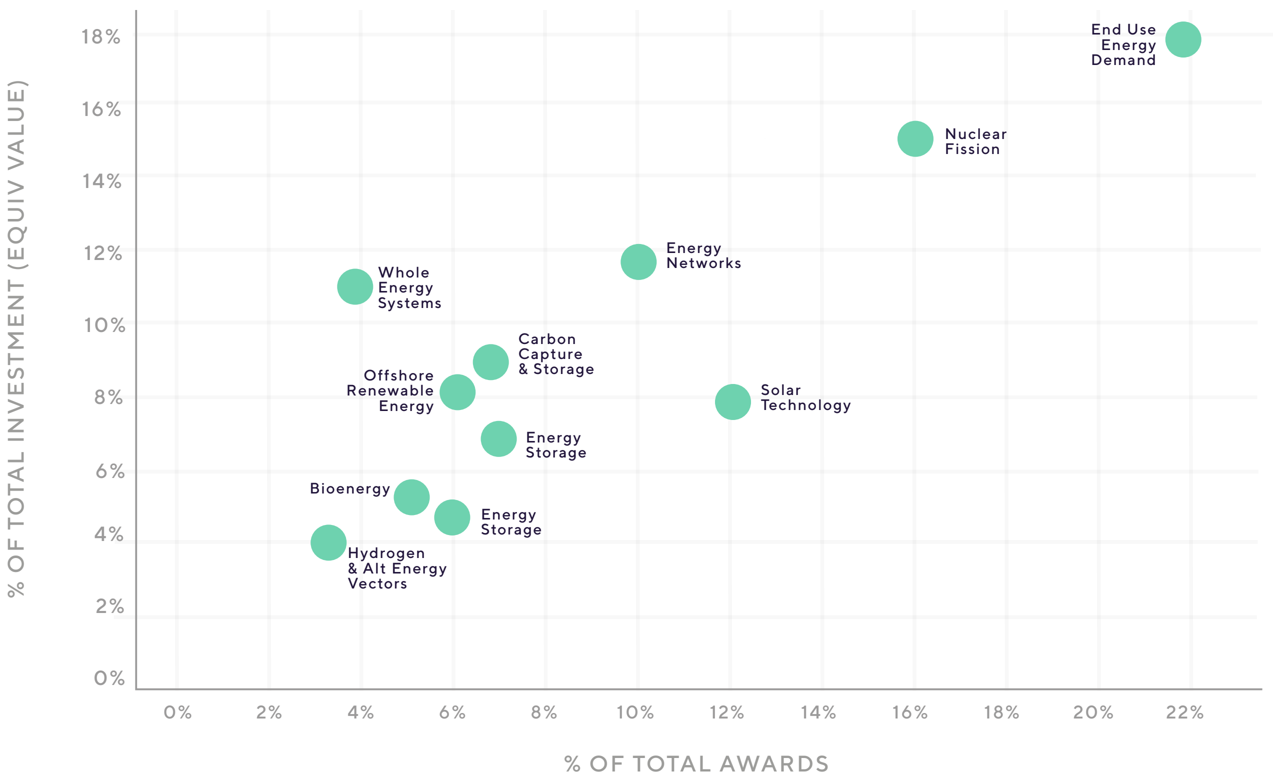
EUED has received just over one-fifth of the total number of grants made since 2005[25], and approximately 12 per cent of funding attributed to the in-scope research areas (referred to as equivalent value).

As might be expected, more nascent research areas such as Hydrogen and Alternative Energy Vectors, and Fuel Cell Technology account for smaller proportions in terms of both grant numbers and investment amounts. Average award values across Research Areas range from c.£336k (Solar Technology) to c.£771k (Offshore Renewable Energy) and point to a largely balanced research portfolio.

It is also worth highlighting that a significant share of the Energy Programme budget is now devoted to networks and systems research (Energy Networks and Whole Energy Systems) which complements the funding for individual technologies, and enables the programme to support research into how the energy system as a whole might need to change.

FIGURE 3.1 - PROGRAMME FUNDING OVERVIEW

RESEARCH AREA	NUMBER OF GRANTS	% OF TOTAL GRANTS	EQUIVALENT VALUE	AVG. EQUIVALENT VALUE	% OF EQUIVALENT VALUE
Bioenergy	67	5.4%	£35,475,474	£529,485	4.8%
Carbon Capture and Storage	86	7.0%	£61,350,813	£713,382	8.8%
End Use Energy Demand	267	21.7%	£130,412,302	£488,436	17.7%
Energy Networks	125	10.2%	£90,141,708	£721,134	11.5%
Energy Storage	86	7.0%	£50,655,175	£589,014	7.1%
Fuel Cell Technology	76	6.2%	£33,368,890	£439,064	4.5%
Hydrogen & Alt Energy Vectors	45	3.7%	£28,317,911	£629,287	3.8%
Nuclear Fission	199	16.2%	£111,141,650	£558,501	14.8%
Offshore Renewable Energy	79	6.4%	£60,920,438	£771,145	8.1%
Solar Technology	150	12.2%	£50,389,402	£335,929	7.9%
Whole Energy Systems	50	4.1%	£86,306,722	£1,726,134	10.9%
Grand Total	1,230	100.0%	£738,480,488	£600,391	100.0%

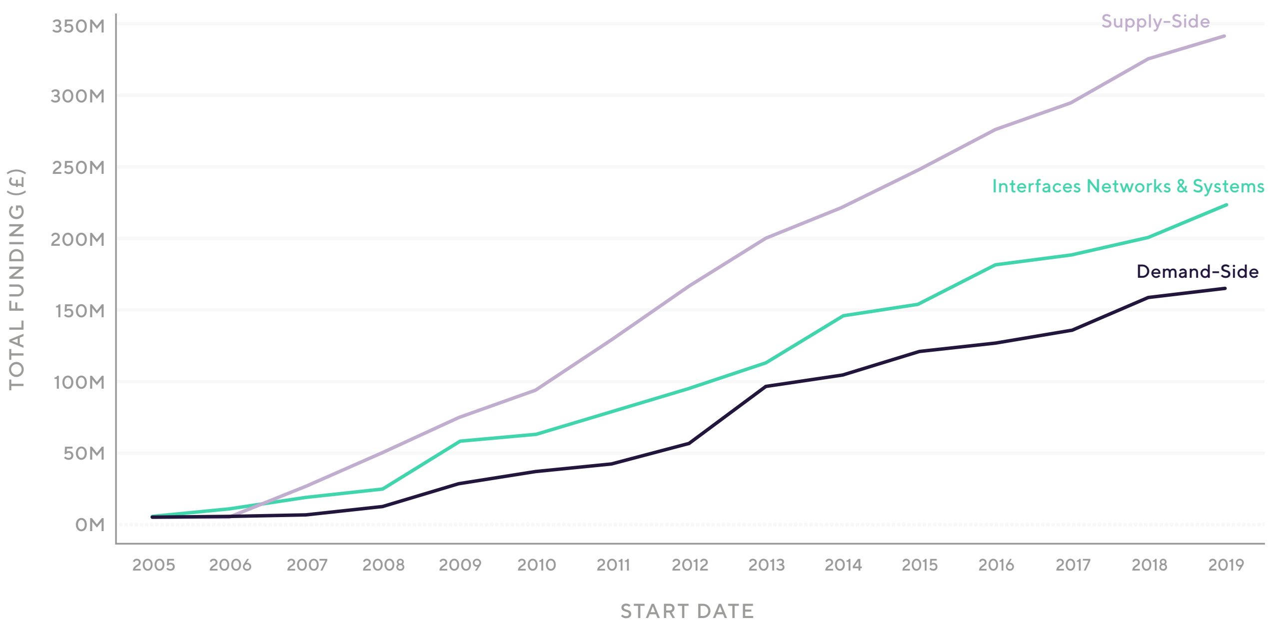


Source: EPSRC Monitoring Data

Figure 3.2 charts the level of funding directed to demand and supply-side aspects of the Energy Programme. In the Figure below 'Demand-Side' funding includes EUED and Fuel Cell Technology; 'Supply-Side' funding includes Bioenergy, CCS, Hydrogen and Alternative Energy Vectors, Nuclear Fission, Offshore Renewable Energy and Solar Technology. Other funding referred to as 'interfaces, networks and systems' includes funding that supports research into technologies that operate in the space between supply and demand, and projects that support whole energy systems thinking and solutions i.e. Energy Networks, Energy Storage, and Whole Energy Systems.

Over time a majority of funding has understandably been directed towards supply-side research. More recently increases in demand-side research, and research that targets the interface between demand and supply, and whole-systems research have helped to balance the Programme portfolio.

FIGURE 3.2 - DEMAND & SUPPLY-SIDE FUNDING OVER TIME



Source: EPSRC Monitoring Data

3.2. GEOGRAPHIC DISTRIBUTION OF ENERGY PROGRAMME GRANTS

Analysis of the geographic distribution of Energy Programme grants indicates that the number of grants awarded have been distributed throughout the UK. Outside of London (which has received less than one-fifth of the total number of grants) the overall proportion of grants by region ranges from 4% (Wales), 1% (Northern Ireland) to 12% (Scotland and the South East).

Just under 200 grants have been awarded to London universities including Imperial College London, University College London, Brunel and King's College.

In Scotland, almost 100 grants have been awarded to the Universities of Edinburgh and Strathclyde, and in the South East c.70 awards have been made to energy researchers at Oxford and Surrey.

3.3. RESEARCH OUTPUTS & POLICY INFLUENCE

The Programme has supported 695 Principal Investigators across 84 Research Organisations. On average each Principal Investigator supported by the Programme has received c.1.5 grants. Analysis of the number of grants awarded to individual Research Organisations (ROs) by Research Area (RAs) provides some indication of institutional research specialisms over time. Figure 3.4 identifies the top three ROs by number of awards across the Energy Programme RAs.

By way of example, the University of Manchester has been prominent in Bioenergy and Nuclear Fission research, the University of Edinburgh has received more CCS grants than any other Research Organisation, Imperial College London has been prominent in Solar Technology and Energy Storage research, and University College London has received the most awards for End-Use Energy Demand and Whole Energy Systems.

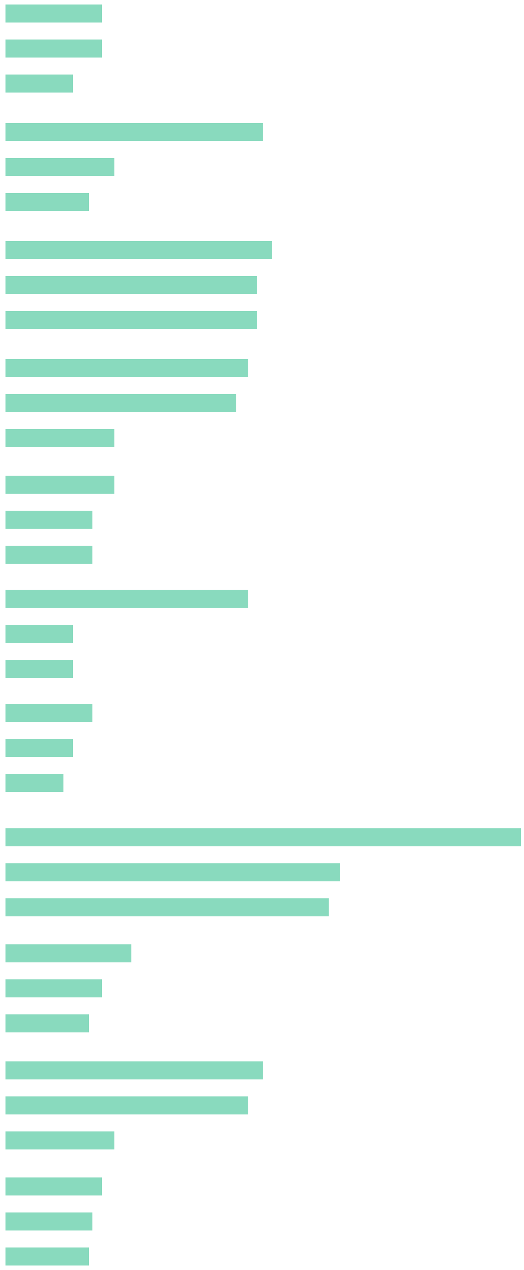
It is important to note here that specialisms within Research Organisations are dynamic and therefore that these aggregate figures do not necessarily provide an accurate view of current research specialisms.

FIGURE 3.3 – GEOGRAPHIC DISTRIBUTION OF GRANTS

Source: EPSRC Monitoring Data

FIGURE 3.4 - GRANT AWARDS BY RA AND RO

Bioenergy	University of Manchester	8
	University of Leeds	8
	University of Nottingham	5
Carbon Capture & Storage	University of Edinburgh	19
	University of Nottingham	10
	Imperial College London	9
End Use Energy Demand	University College London	20
	University of Cambridge	18
	Newcastle University	18
Energy Networks	Imperial College London	17
	University of Strathclyde	16
	University of Southampton	10
Energy Storage	Imperial College London	10
	University of Oxford	7
	University of Birmingham	7
Fuel Cell Technology	Imperial College London	17
	University of St Andrews	5
	University of Birmingham	5
Hydrogen & Alt Energy Vectors	University of Nottingham	7
	Newcastle University	5
	University College London	4
Nuclear Fission	University of Manchester	39
	University of Sheffield	24
	Imperial College London	23
Offshore Renewable Energy	University of Edinburgh	12
	University of Strathclyde	8
	Plymouth University	6
Solar Technology	Imperial College London	19
	Loughborough University	18
	University of Warwick	10
Whole Energy Systems	University College London	8
	Imperial College London	7
	University of Leeds	6



Source: EPSRC Monitoring Data

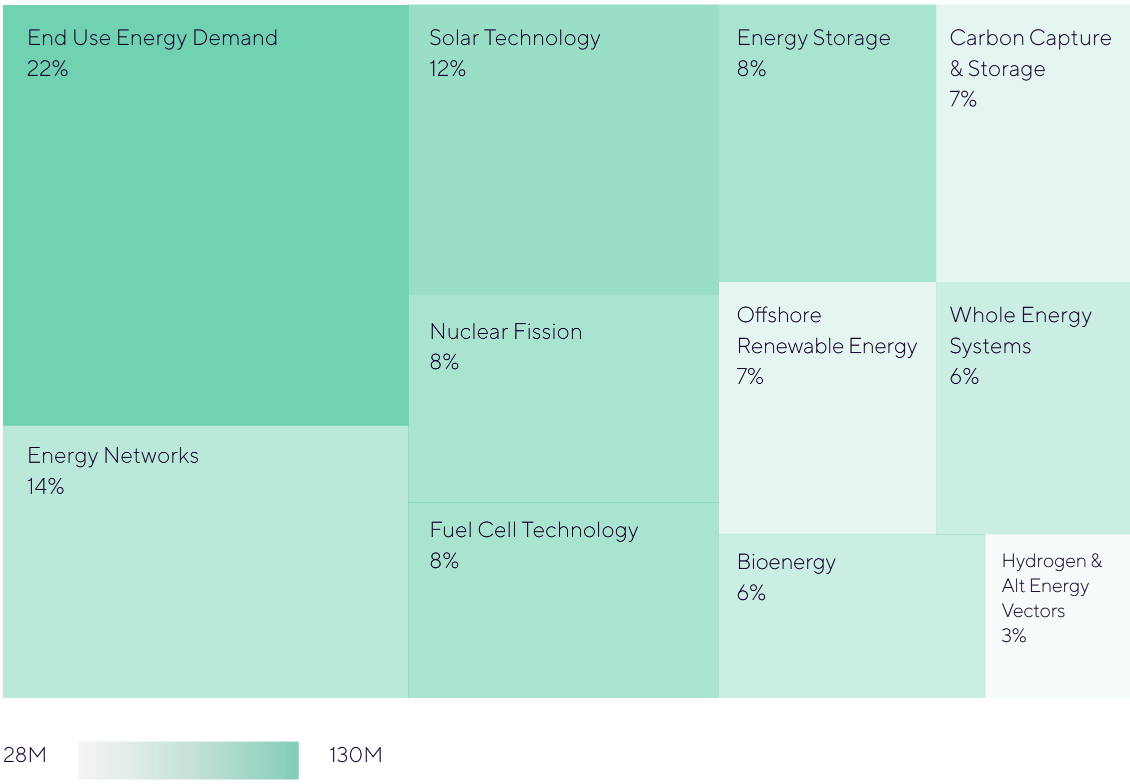
3.3.1 Research outputs

The Programme-supported grants have together produced c.23,500 research outputs of which more than c.13,500 (58%) are research publications with Digital Object Identifiers (DOIs) i.e. publications that are available online and expected to be widely used. Twenty-two percent of all research outputs are associated with EUED research. Approximately 14% of all research outputs are within the Energy Networks Research Area, and the distribution of research outputs across remaining RAs is broadly even (Figure 3.5).

3.3.2 Policy influence

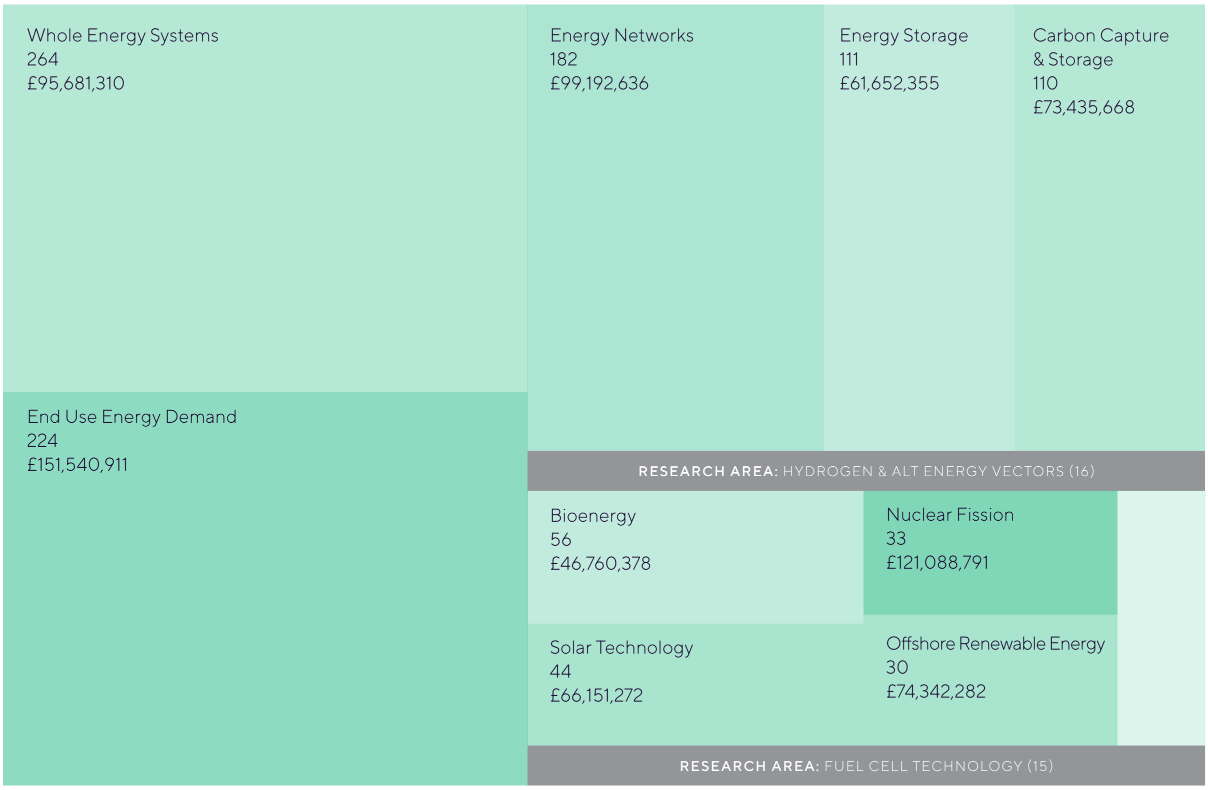
Since 2005, the Programme has recorded more than 1,300 instances in which funding has, or is expected to result in positive policy influences. Of these c.1,000 tangible instances of policy influence have been recorded across Research Areas (Figure 3.6)[26]. Most instances of policy influence have been recorded against grants within the Whole Energy Systems and End-Use Energy Demand Research Areas (24% and 21% of recorded instances of policy influence respectively). Both of these Research Areas have a focus on addressing important policy issues, which is likely to be one driver of their strong showing. Another is the breadth of research that is carried out, which is very interdisciplinary and includes a strong element of social science alongside more 'core' EPSRC disciplines.

FIGURE 3.5 - RESEARCH OUTPUTS BY RA



Source: EPSRC Monitoring Data (depth of colour = investment value)

FIGURE 3.6 - INSTANCES OF POLICY INFLUENCE BY RESEARCH AREA



Source: EPSRC Monitoring Data

Within these figures EPSRC's targeted investments in co-ordinating Centres across Research Areas feature heavily. For example, within the Whole Energy Systems Research Area the UK Energy Research Centre accounts for sixty-eight per cent of all policy influence (n=180), and within the CCS Research Area the UK Carbon Capture and Storage Research Centre is responsible for eighty-five per cent of policy influence outputs (n=94). There are noticeable concentrations of policy influence within other Research Areas, although these are more distributed, for example within EUED approximately one-fifth of all policy influence is linked to the UK Centre for Research on Energy Demand and approximately ten per cent is linked to the 'Shipping in Changing Times' grant (EP/K039253/1), and within the Energy Networks Research Area approximately sixteen per cent of instances of policy influence are attributable to the UK Infrastructure Transitions Research Consortium (ITRC, n=30) and approximately twenty per cent (n=36) are linked to the 'Electrical Energy Infrastructure to 2020', Research Leadership and Networking for Energy Networks' and 'Grid Economics, Planning and Business Models for Smart Electric Mobility' grants.

3.4. ENERGY RESEARCH SKILLS & NETWORKS

Data presented in Section 3.1 demonstrates the breadth and depth of Energy Programme funding, which in itself plays an important role in exposing UK academic researchers to a broad base of research topics and skills needs. Academic survey data supports the assertion that EPSRC funding supports energy research across the research spectrum, from fundamental research to deployment and commercialisation. For example, 83% of respondents (n=151) indicated that Energy Programme funding 'allows space and time for fundamental research' and 87% believe that the Programme is enhancing applied research.

In addition to the skills and network benefits derived as a consequence of the scale and breadth of Programme funding, the Energy Programme has invested approximately £13m directly into projects with specific training and skills development objectives. For example, seven grants with a value of just under £10m have supported Doctoral Training Centres in EUED, Fuel Cell Technology, Offshore Renewable Energy and Whole Energy Systems.

The most substantive awards include the Doctoral Training Centre in Wind Energy Systems (£5.8m), and the Doctoral Training Centre in Hydrogen, Fuel Cells and their Applications (£2.6m). Four grants with a value of approximately £3.5m have supported fellowship initiatives including, most notably, the RCUK Energy Strategy Fellowship (c.£1.9m).

The Programme has also supported more than 800 secondments between UK universities and between UK universities and a range of other academic institutions and private-sector research teams nationally and internationally. Nuclear Fission, EUED and Energy Networks Research Areas account for a majority of Programme-supported secondments (24%, 17% and 13% respectively). The largest proportion of secondments (c.12%, n=99) have been from Imperial College London. Approximately 60% of Energy Programme-supported secondments have been from the ten Universities presented in Table 3.1 below.

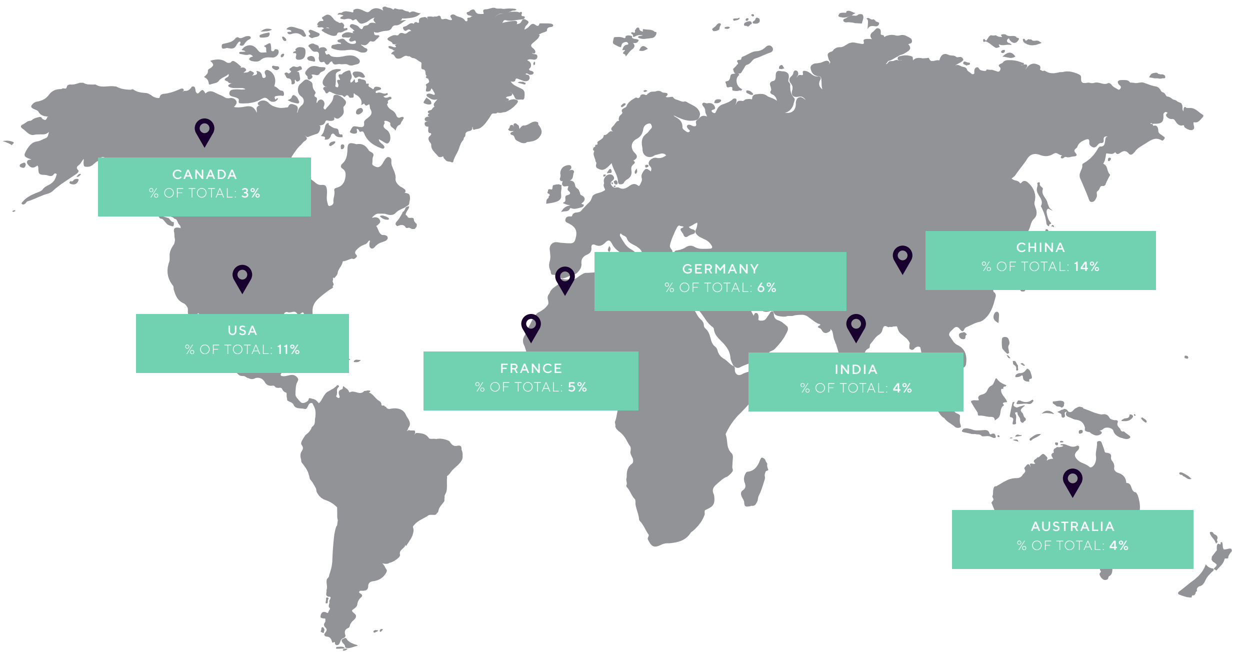
TABLE 3.1 - SECONDMENT ORIGIN UNIVERSITIES

Research Organisation	# Secondments	% Secondments
Imperial College London	99	12.3%
University of Sheffield	71	8.9%
University of Leeds	66	8.2%
Lancaster University	44	5.5%
University of Manchester	42	5.2%
University of Bath	35	4.4%
University of Nottingham	34	4.2%
University of Birmingham	33	4.1%
University of Edinburgh	31	3.9%
Loughborough University	31	3.9%
Total	486	60.6%

Source: Research Fish

Data regarding the 'next destination' of academics and researchers involved in Energy Programme grants indicates the extent to which the Programme has contributed to building networks within the UK and internationally. More than 2,000 researchers involved in Energy Programme grants have moved between research institutions within the UK (72% of all researcher destinations) and internationally. The map below shows the proportion of researchers that have moved to public and private sector research entities internationally. The largest single proportion (14%) moved to China, eleven per cent moved to the United States and between three and six per cent moved to Australia, Canada, France, Germany and India.

FIGURE 3.7 - INTERNATIONAL RESEARCH NETWORKS



Source: Research Fish

The Energy Programme's positive contribution to skills development is also evidenced in responses to the online academic survey through which 81% and 85% of respondents respectively indicated that EPSRC funding is successfully a) supporting the flow of academics into energy research fields and b) developing the skills and capabilities of UK energy research academics.

FIGURE 3.8 - ENERGY PROGRAMME CONTRIBUTION TO ENERGY RESEARCH SKILLS & NETWORKS

	Small Extent	Somewhat	Large Extent | Significantly
Supporting the flow of academics into energy research fields	14%	25%	56%
Developing skill & capability of UK energy research academics	11%	24%	61%

Source: EPSRC Energy Programme Academic Survey

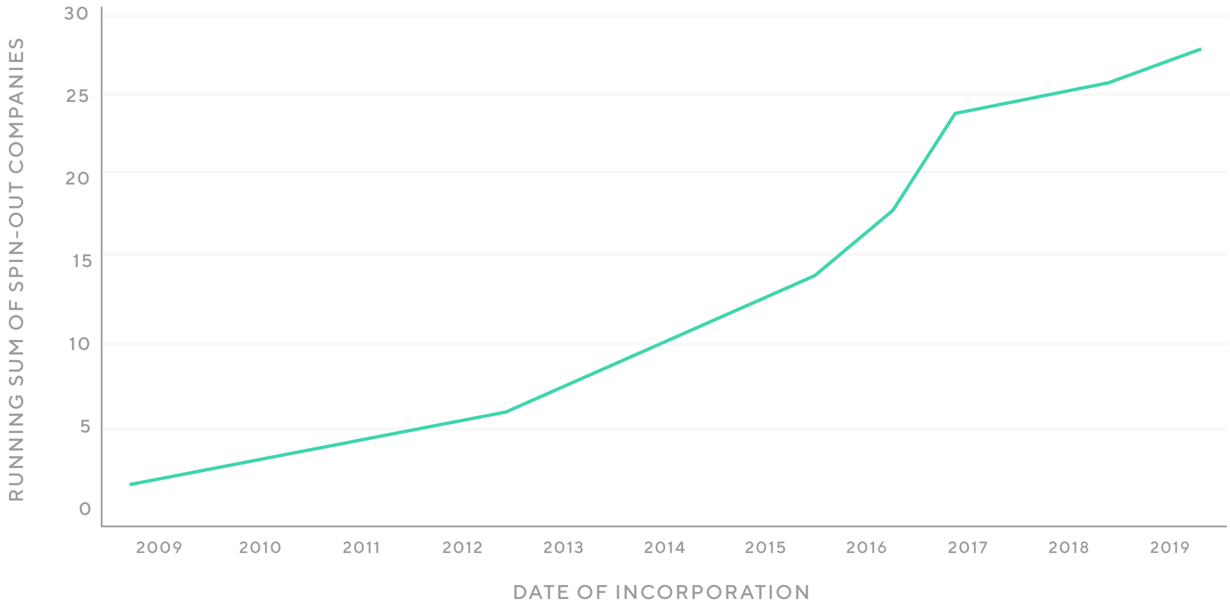
EPSRC investments in research skills and networks go beyond the direct awards and aggregated output indicators presented here. They also support an array of 'softer' yet important skills and network development outcomes. Thematic case study findings presented in Section 4 further illustrate the various ways in which EPSRC funding permeates research skills and network development.

3.5. SPIN-OUT COMPANIES & INTERNATIONAL COLLABORATION

The Programme has contributed to the set-up and / or growth of thirty-five spin-out companies across nine of the twelve research areas in scope[27] - more than two per year on average (Figure 3.9). Thirty-three of those companies could be matched to company data[28], and are distributed across Research Areas as illustrated in Figure 3.10.

A majority of spin-out companies are linked to End Use Energy Demand research (n=8), Solar Technology (n=7), and Energy Networks, Energy Storage and Fuel Cell Technology (n=4 per Research Area).

FIGURE 3.9 - SPIN-OUT COMPANIES INCORPORATION DATES



Source: Research Fish, Bureau van Dijk

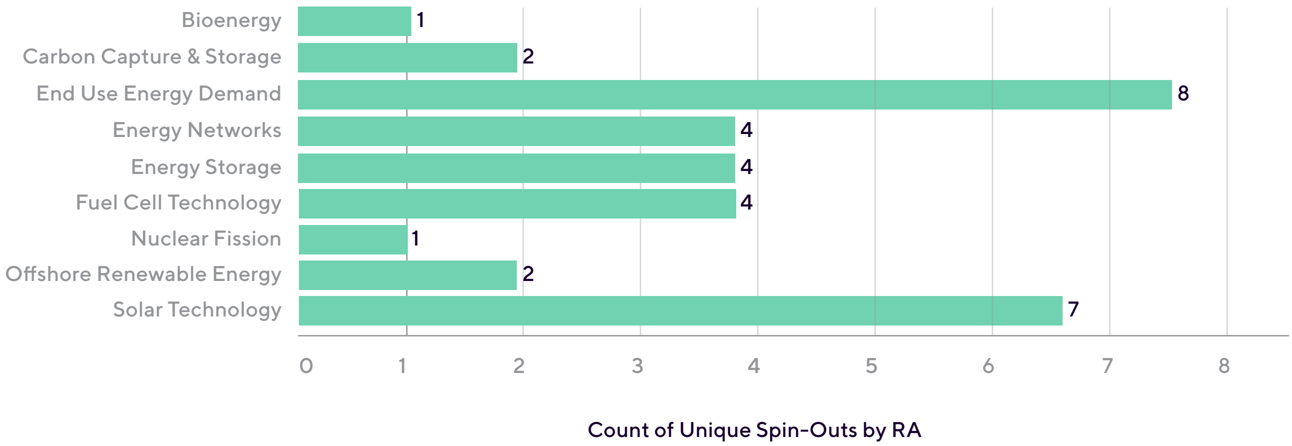
In 2019 the spin-out companies supported by the Programme generated known UK revenues of £28.9m and employed 180 people (averages of £1.4m and 8 employees). The three largest spin-out companies include Ossila Limited (40 employees), ECONIC Technologies Limited (36 employees) and Upside Energy Limited (31 employees). Together, since 2010 thirteen of these spin-out companies have secured a total of £49.3m of investment from thirty-two funds. Fundraising examples include:

- **Econic Technologies** – a venture stage firm founded in the North West in 2011 that is developing catalysts to produce polyurethanes and polycarbonates from carbon dioxide;

- **Eight19** – a mature firm founded in the East of England in 2010 that develops solar cell technology for low cost, high-speed manufacture; and

- **Upside Energy** – a venture stage firm founded in the North West in 2014 that has developed technology to aggregate energy stored in devices owned by households and businesses (such as heating systems) to help manage electricity demand on the national grid at peak times.

FIGURE 3.10 - SPIN-OUT COMPANIES BY RA



Source: Research Fish, Bureau van Dijk

The Programme has supported extensive international collaboration. Research Fish monitoring data identifies c.1,350 unique collaborating organisations, from other UK universities to international universities and research institutes across the globe. Of the collaborating organisations contained within the Research Fish data, approximately 400 could be matched to geospatial data available via the Global Research Identifier Database (GRID). Figure 3.11 uses geospatial data on lead research organisations, and the sample of collaborating organisations to illustrate the extent of the Programme's global reach.

FIGURE 3.11 - INTERNATIONAL COLLABORATION

Source: Research Fish, Global Research Identifier Database (GRID)

Analysis of the number of collaborating organisations across international locations shows that just under twenty per cent of international collaborators are within the United States, with c.14% in China, 6% in both India and Japan, and between 3% and 5% in other high-instance countries such as (in ascending order) Australia, France, Spain, Italy, Germany, and South Korea.

4. Thematic Case Study Findings

4.1. INTRODUCTION

This Section presents thematic findings that emerged from the case study research conducted in Part 1 of the study. The data is largely qualitative, supplemented where relevant by findings from an online survey of academics supported by the Programme to date.

4.2. CHARACTERISTICS OF EPSRC FUNDING

Throughout the case study research, study participants highlighted a series of benefits associated with the operational and logistical aspects of EPSRC funding, ranging from EPSRC's 'appetite for risk', to the comparatively long-term nature of EPSRC funding. Findings in support of these perceived benefits are presented in the sub-sections.

4.2.1 Appetite for risk and acting as a catalyst for research funding

Several case studies suggested that EPSRC grant funding exhibits a positive appetite for risk – often providing initial investment, acting as a catalyst for follow-on funding from both the public and private sectors, and accepting the degree of uncertainty that comes with early-stage investment in energy research. Analysis of internal monitoring data shows that EPSRC grants have secured follow-on funding of c.£2bn from a range of academic, charity, public and private contributors.

Case study research into projects such as the Infrastructure Transition Research Consortium (ITRC, EP/I01344X/1) and Energy Storage for Low Carbon Grids (ESLCG, EP/K002252/1) provide useful illustrations of how EPSRC funding is effectively used to secure follow-on funding. Excerpts from these case studies are set out below.

CASE STUDY EXCERPT: EPSRC FUNDING AS A CATALYST FOR ENERGY RESEARCH INVESTMENT

Infrastructure Transition Research Consortium (ITRC, EP/I01344X/1)

Initial EPSRC funding was awarded to ITRC in January 2011, totalling £4,730,842 and lasted until December 2015. During this period c.£375k in additional funds were awarded to ITRC, of which c.30% came from non-EPSRC funded projects. During a second phase of funding (between February 2016 and August 2020) the ITRC academic team secured an additional £1.2m in funding (over and above a second EPSRC award) of which 70% came from a combination of private sector organisations (36%) and Foreign Direct Investment (34%).

The proportion of non-EPSRC grants increased from 30% of the total additional grant value during the 2011 – 2015 period to 79% in the 2016 – 2020 period, demonstrating the role that EPSRC funding plays as a catalyst for additional investment in energy research. Consultations with ITRC academics indicated that support from EPSRC was fundamental to their initial work – creating confidence and credibility that helped to secure additional investment.

CASE STUDY EXCERPT: EPSRC FUNDING AS A CATALYST FOR ENERGY RESEARCH INVESTMENT

Energy Storage for Low Carbon Grids (ESLCG, EP/K002252/1)

The ESLCG project ran between October 2012 and June 2018. It received just over £5.6m in initial investment from EPSRC and subsequently secured more than £3.25m in additional funding from a combination of Foreign Direct Investment from both public and private sector sources in China, and via private sector in-kind contributions.

Foreign Direct Investment supported collaborative research with a Chinese manufacturer of locomotives and rolling stock, to assess the feasibility of including Thermal Energy Storage (TES) devices for waste heat-capture on its trains. Further, consultation with participating academics highlighted how successive grants have built a 'critical mass' of expertise required to deliver extensive energy storage research projects.

Consultations with Principal and Co-Investigators often indicated that research would either not have gone ahead at all, or would have gone ahead at reduced scale or slower pace in the absence of EPSRC funding, largely due to the uncertainties and level of risk involved. This perceived counterfactual was supported via the online academic survey, where more than three-quarters of respondents (n=113) suggested that UK energy research would be largely or significantly worse off in the absence of EPSRC funding.

"EPSRC is very good at funding risky areas of research that may prove to be important in future. I have been predominantly funded by EPSRC, and have been well supported right from the start. The primary reason for my [early academic research] was because of an EPSRC / Japan joint project. That enabled research with Japanese academics, without which my own work might not have happened at all."

Co-Investigator, Solar Technology

"We had no alternative to EPSRC funding, we didn't have the facility or the systems for testing, and investment wouldn't have come from the private sector."

Carbon Capture & Storage Academic

4.2.2 Substantive, Long-Term Funding

The case studies referenced above, and others such as MAXimizing wind Farm Aerodynamic Resource via advanced Modelling (MAXFARM, EP/N006224/1), and Effective Adsorbents for Establishing Solids Looping as a Next Generation NG PCC Technology (CCA, EP/J020745/1) also highlighted the importance of both the scale of EPSRC funding, and it's comparatively long-term nature.

Excerpts from the MAXFARM and CCA case studies are provided below to illustrate how the scale and long-term nature of Energy Programme funding have benefitted UK research.

CASE STUDY EXCERPT: BENEFITS OF SUBSTANTIAL, LONG-TERM FUNDING

Maximizing Wind Farm Aerodynamic Resource Via Advanced Modelling (Maxfarm, EP/N006224/1)

A top-down case study regarding EPSRC's investment in Offshore Renewable Energy (ORE) (using MAXFARM as a starting point) demonstrated how EPSRC's long-term commitment to ORE research has helped position the UK as an international leader in the deployment of offshore wind farms. Following a period during which publicly-funded wind energy research declined substantially in the UK (between the 1990s and early 2000s) EPSRC investment in a formal programme for wind energy research in 2006 effectively reignited UK wind energy research.

Since then EPSRC has invested £13.5m in the Supergen Wind Hub, and the UK now: a) has the highest level of installed wind capacity in the world, amounting to over one-third of global capacity; b) has delivered research efforts that have reduced the cost of wind energy, and c) is now one of the foremost contributors to international wind energy research. Consultations to inform the ORE case study indicated that the UK's current position as global leaders in wind energy research is, in large part, attributable to EPSRC's 2006 funding. The impact of EPSRC's ORE investment is further supported by academic survey responses. Of 18 respondents who indicated that their primary research area was ORE, almost 80% believe that EPSRC funding has enhanced applied research to either a 'large' or 'significant' extent.

CASE STUDY EXCERPT: BENEFITS OF SUBSTANTIAL, LONG-TERM FUNDING

Effective Adsorbents For Establishing Solids Looping As A Next Generation Ng Pcc Technology (CCA, EP/J020745/1)

The capital investment required to conduct applied research and demonstrations at scale makes it unattractive to the private sector. Case study research into an EPSRC-funded Carbon Capture and Adsorbents (CCA) project provides a useful illustration of how substantial EPSRC funding can stimulate the level of investment required to deliver important demonstration projects. Following an initial EPSRC award of c.£750k, the academic team at Nottingham University secured £160k from the Korean Institute of Energy Research (KIER), and a further £500k from Innovate UK to build large scale testing and demonstration facilities. Consultation with the researchers at Nottingham indicated that in the absence of EPSRC funding, the team would not have been able to scale-up the production of a baseline PEI/silica adsorbent to 100kg. This in turn would have limited their potential to collaborate with KIER, which would ultimately have put the £500k investment from Innovate UK at risk.

Further, substantive awards made by EPSRC are deemed to provide wider, more generic benefits. Larger investments enable multidisciplinary and interdisciplinary projects, where outcomes are often greater than the sum of individual research activities. They have also been confirmed as providing stability and security for researchers, allowing a 'critical mass' of research expertise to be built-up.

4.2.3 Flexibility And Facilitating Breadth of Research

Research undertaken to inform the case studies highlights the often unbound, unpredictable, and incremental nature of early-stage research. These findings are particularly evident within case studies regarding more nascent research such as microbial fuel cells (MFCs) / bio-electrochemical systems (BES) and hydrogen research. Evidence gathered in respect of three particular case studies serves to demonstrate how EPSRC funding enables creativity and innovation through flexibility (SPECIFIC, EP/I019278/1), and supports a breadth of research including important early-stage incremental research (LifesCO2R, EP/N009746/1 and RTH2P, EP/L018330/1). Illustrative excerpts from each of these case studies are presented overleaf.

CASE STUDY EXCERPT: FLEXIBILITY OF EPSRC FUNDING

Sustainable Product Engineering Centre For Innovative Functional Industrial Coatings (Specific, EP/I019278/1)

Research undertaken to inform the SPECIFIC case study indicated that one of the key factors in the project's success is the flexibility that was a feature of EPSRC funding. Consultations highlighted how EPSRC funding allowed the project to explore more tangential ideas that have given rise to many of the project's more technically complex advances.

This approach is deemed to offer an alternative to other funding approaches, which generally have more process-driven methodologies that focus on iterative testing and incremental developments, and which are less conducive to an innovative project focusing on emerging technology.

"The flexibility of EPSRC funding is brilliant. As long as your idea is within scope, you can put some resource into it and have a go. The reality is that without the EPSRC funding we would have continued to look at different ways of drying paint [i.e. been constrained to much more iterative research activity]."

Solar Technology Academic Researcher

CASE STUDY EXCERPT: BREADTH OF EPSRC FUNDING

Liquid Fuel And Bioenergy Supply From Co2 Reduction (Lifesco2r, EP/N009746/1)

The LifesCO2R grant is multi-faceted, focussing on advancing fundamental chemical, biological and material science and associated technologies, in areas that could have wide-ranging implications across various aspects of the decarbonisation agenda, including sustainable biofuels that reduce reliance on fossil fuels, low power energy as part of more efficient distributed energy solutions, and sustainable production of important platform chemicals from biological sources. LifesCO2R sought to develop breakthrough technology with integrated low-cost bio-electrochemical processes to convert CO2 into liquid fuels for transportation, energy storage, heating and other applications.

The grant supported 12 leading academics (PI and Co-Is) and many more researchers across five UK Universities (Newcastle, Oxford, South Wales, Surrey and Sheffield). It has led to advances in knowledge and technology that bring the potential of a) using industrial waste for low power generation, b) conversion of CO2 to formate and important base chemicals and c) production of sustainable synthetic biofuel closer to industrial relevance.

The LifesCO2R group is also the first to have closed the electricity-formate-electricity loop using electrochemical reduction approaches. They have been able to produce the necessary amount of formate to put into a fuel cell, and also the concentration of formate required to produce electricity and for energy storage. Through the LifesCO2R project, EPSRC funding has effectively brought together disparate UK teams working within nascent, fundamental research areas. In doing so, it has created a critical mass of UK research which is helping to accelerate the rate of research progress regarding bio-electrochemical systems, is providing opportunities for the research group to apply for new sources of funding and is effectively heightening the UK's presence within the international research community. While the research area remains highly fundamental, there are ever-increasing examples of its application at scale. The UK is at the forefront of research advances, and there is scope now to support increased industrial interest so that future economic benefits can be returned to the UK.

CASE STUDY EXCERPT: BREADTH OF EPSRC FUNDING

Real-Time H2 Purification And Monitoring For Efficient And Durable Fuel Cell Vehicles (RTH2P, EP/L018330/1)

Having received just over £1m in EPSRC funding, the RTH2P award brought together a multi-disciplinary team from University College London and the University of Warwick spanning molecular sorption, storage, and catalysis and microsensors and bioelectronics.

The grant supported more than 30 researchers across the two institutions and achieved its original objectives by advancing low-cost and high performance in-situ H2 purification systems, and developing low-cost, robust gas sensors for real-time impurity monitoring.

Hydrogen research has received increasing attention in recent years, yet deriving power from hydrogen remains complex, requiring multiple research advances that help to improve catalytic effectiveness and reduce cost. The EPSRC-funded RTH2P grant has supported incremental and multi-faceted research that is essential if advances are to be made in complex energy technology.

The incremental research advances derived, regarding catalytic and sorption materials and designs, could have important implications for the advancement of hydrogen power technology far beyond fuel cell vehicles, and via linkages to related EPSRC grants, the RTH2P grant has also supported research that is closer to commercial application.

The RTH2P is an example of how EPSRC funding allows for flexibility that enables broader incremental advances (those that are the focus of current international research efforts) to be achieved, while at the same time successfully delivering against narrower objectives that are the specific focus of the award.

4.3. ADVANCING UK ENERGY POLICY

The past five years have seen major and rapid developments in energy-related policies and strategies. In June 2019 the UK became the first major economy to pass net-zero emissions law, which represents a significant stretching of the original 80% reduction target[29]. The new net-zero target is recognised as being highly ambitious and is expected to contribute to driving the UK's 'green recovery' and 'green growth' agendas. However, it is also accepted that while feasible, the net-zero target is only credible if new supporting strategies and policies are introduced.

> *"Existing ambitions must be delivered in full, challenges that have so far been out of scope must now be confronted. The UK must make firm plans for housing and domestic heat; for industrial emissions; carbon capture and storage; road transport; agriculture; aviation and shipping."*
>
> **Committee on Climate Change**

Energy research has an important role to play in advancing UK energy policy; from devising entirely new ways of thinking about energy challenges, to evidencing the feasibility of policies, strategies and technologies, and effectively influencing key actors within academia, industry and government. Evidence generated to inform this study demonstrates how Programme funding helps to advance UK energy policy from idea formation through to policy implementation.

4.3.1 Encouraging New Ways Of Thinking

EPSRC's Energy Programme has provided extensive support for devising new approaches to understanding energy challenges. Much of this research activity has taken place within the EUED and Whole Energy Systems Research Areas, into which EPSRC has invested a total of more than £330m[30]. Sixty per cent of academics responding to the online survey (n=109) agreed that EPSRC funding allowed space and time for academics to explore fundamental research.

Several case studies produced as part of this research had the development of new approaches to, and new frameworks for understanding energy challenges as central objectives. These case studies help to demonstrate how EPSRC funding has supported new ways of thinking about and understanding major energy challenges.

CASE STUDY EXCERPT: ENCOURAGING NEW WAYS OF THINKING

Realising Transition Pathways - Whole Systems Analysis For A UK More Electric Low Carbon Energy Future (RTP, EP/K005316/1)

In May 2012 a consortium of multi-disciplinary researchers from 10 UK universities was awarded c.£3.2m from EPSRC under the Whole Energy Systems research area, to produce a set of 'transition pathways' towards a low carbon UK electricity system. Via an iterative and multi-disciplinary approach that included the development of analytical tools; assessment of the role of future demand; and techno-economic assessments, the project produced a whole-system framework for understanding current and future energy challenges. The RTP team successfully created, collated and curated an extensive repository of research and wider evidence that highlights the benefits of a whole systems approach, and in the years subsequent to the grant, the whole system approach to understanding energy use has been an area of continually increasing research interest. The RTP project helped give traction to whole energy systems thinking within research, policy and industry spheres. As a result, the energy sector's understanding of energy as a whole-system, and its view of energy in whole system terms have taken substantive steps forward.

The RTP team ultimately comprised 50% engineers and 50% economists and social scientists. The increased inclusion of social scientists will help to more effectively account for actor dynamics and social change as well as roles of the public and civil society in realising the UK transitions pathways[31].

CASE STUDY EXCERPT: ENCOURAGING NEW WAYS OF THINKING
Dynamics Of Energy, Mobility & Demand (Demand, EP/K011723/1)

The DEMAND Centre challenges pre-existing attitudes in the energy sector, which was previously considered to have provided insufficient weight to the social aspects of energy use. The Centre developed a range of partnerships, held a range of dissemination events (linked to publications), and helped to develop the skills required to conceptualise the issues, carry out empirical research and engage with policymakers.

Core research activity has focussed on trends and patterns in energy demand, domestic IT use, business travel, older people and mobile living, energy in daily life, and the adaption of infrastructure for a lower carbon society (among others). The project has developed and promoted new practices that could help the government achieve its overall energy efficiency and environmental policy aims. The concepts put forward by the Centre could also help to improve operational energy efficiency within the public and private sectors and, in time, subsequent competitiveness within industry. This impact could be amplified via further engagement in the UK's new national Centre for Research into Energy Demand Solutions (CREDS).

Consultations with a number of academics in the EUED and Whole Energy Systems research areas indicated that, while EPSRC has been a major catalyst for new energy research thinking and multi-disciplinary approaches, further work is still required to bring together expertise from within and across disciplines to maximise knowledge transfer, scientific advance, and industrial relevance. This sentiment was echoed in responses to the academic survey, where almost three-quarters of respondents (73%, n=114) indicated that there is further scope to more effectively support whole systems collaboration.

4.3.2 Influencing Policy Development & Implementation

Beyond bringing together multi-disciplinary teams and devising new ways of thinking about major energy challenges, EPSRC funding has also supported energy researchers to both influence and implement important UK energy policies and strategies. Three case studies in particular (CIE-MAP, EP/N022645/1; UKCCSRC, EP/K000446/1 and ITRC, EP/I01344X/1) provide useful insights into EPSRC's contribution.

CASE STUDY EXCERPT: INFLUENCING POLICY DEVELOPMENT

Centre For Industrial Energy, Materials, Energy And Products (Cie-Map, EP/N022645/1)

The Centre for Industrial Energy, Materials and Products (CIE-MAP) received funding of c.£3.2m via the EPSRC Energy Programme between 2015 and 2018. The grant was awarded against a backdrop of multiple decarbonisation policy directives that sought to achieve the UK's 2050 net-zero target.

CIE-MAP conducted research to identify opportunities along entire product supply chains that could ultimately deliver a reduction in industrial energy use, including via i) industrial efficiency gains including the use of heat and process improvements; ii) changing the materials used in production; and iii) changing the way end-consumers (industry, households or government) use products to reduce energy demand.

Research outputs (comprising more than 100 academic publications and several policy reports) address a range of energy-related challenges, including sector-specific challenges; waste reduction; resource efficiency; and consumer behaviour. Examples of the Centre's thematic research include a whole-life approach to carbon reduction within the construction sector; research efficiency and the circular economy; and a series of technology roadmaps for energy-intensive industries such as steel, chemicals, food and drink, and paper and pulp.

The CIE-MAP team worked with a range of government stakeholders and departments, and these engagements (particularly in respect of the technology roadmaps) have had a notable influence on how end-use energy is perceived within policy development. The research has also led to the adoption of a new UK Carbon Footprint indicator, and effectively connected the development of the government's Resource and Waste Strategy and the Industrial Strategy, taking account of the need for material efficiency and decarbonisation, whilst still developing opportunities for economic growth through efficient use of resources.

CASE STUDY EXCERPT: INFLUENCING POLICY DEVELOPMENT

United Kingdom Carbon Capture & Storage Research Centre (UKCCSRC, EP/K000446/1)

Carbon Capture and Storage (CCS) has the potential to save the UK tens of billions of pounds (1% GDP) in the annual cost of low carbon energy by the 2040s. As the UK's national centre for UK research into Carbon Capture and Storage, the UK Carbon Capture and Storage Research Centre (UKCCSRC or 'the Centre') co-ordinates and helps to fund research that advances carbon capture knowledge and application within power generation and wider industry clusters. The Centre received £14m across two grants from EPSRC between 2012 and 2017, which has allowed the UKCCSRC to support a range of CCS related activities in the UK.

There are clear examples of where UKCCSRC's work has pre-empted and/or influenced government policy. In 2018 the Carbon Capture, Usage and Storage Cost Challenge Taskforce produced a Cost Challenge Report and a Pathway to Deployment Action Plan. One of the cost-saving mechanisms outlined in the action plan involves the development of CCS clusters, which provide economies of scale that can lower CCS unit costs within industrial centres.

UKCCSRC was at least partly responsible for establishing the importance of CCS clusters in advance of the Deployment Action Plan and has supported the early development of clusters via its "Delivering Cost-Effective CCS in the 2020s" initiative – which included a series of regional meetings that were well-attended by industry, government and academia. Each meeting produced a summary report that outlined capabilities and improvements required within each UK region. An associated national report set out overarching findings and has spurred the development of six regional CCS clusters, of which two are directly attributed to UKCCSRC support.

UKCCSRC's expertise provided the basis for developing practical, feasible policy interventions; facilitated by the capacity that EPSRC funding provided. Effective engagement of CCS stakeholders across industry, policy and academia, and the subsequent development of six CCS clusters demonstrates how EPSRC funding influences policy development and implementation.

CASE STUDY EXCERPT: INFLUENCING POLICY DEVELOPMENT

UK Infrastructure Transitions Research Consortium (ITRC, EP/I01344x/1)

The Infrastructure Transition Research Consortium (ITRC) is a consortium of seven UK universities (Oxford, Newcastle, Leeds, Southampton, Cardiff, Cambridge, University College London), and 55 private and public sector partners, founded in 2012 against the backdrop of the UK's National Infrastructure Plan (2011). Within the UK's National Infrastructure Plan government acknowledged the need to take a joined-up approach to address existing and emerging issues within what was widely considered to be a largely fragmented and reactive UK infrastructure network. The ITRC set out to change how strategic planning, infrastructure design and investment decisions are made via a combination of national infrastructure system analysis; development and shared access to a national infrastructure database; and networking to engage a wide range of stakeholders in understanding infrastructure performance and choices. The ITRC received support from the EPSRC through two grants, valuing £4.73m (January 2011 – December 2015) and £5.37m (February 2016 – August 2020).

The ITRC has delivered notable impacts in terms of infrastructure analysis, design and strategy at regional, national, and international levels. Regionally the ITRC has supported England's Economic Heartland and the Oxford Cambridge Arc to develop and evaluate a significant transport decarbonisation strategy. Nationally ITRC's modelling tool was used to support the National Infrastructure Commission's (NIC's) 'first-of-a-kind' resilience study assessing both security and industrial threats and infrastructure needs in the UK – producing options that can reduce disruptions estimated to impact up to 8 million users in the UK and cost up to £6.7 million/day. Internationally, ITRC's analytics work has helped the United Nations to inform construction work post-conflict and to build infrastructure resilience.

The ITRC case study therefore serves as evidence of how EPSRC funding helps to deliver tangible policy impact regarding nationally significant public investment issues, at every geographic level.

4.4. BUILDING TECHNICAL & ECONOMIC CAPABILITY TO DELIVER CLIMATE CHANGE TARGETS

The Committee on Climate Change Net-Zero Report explains how difficult it will be to achieve net-zero 2050. Delivering against the UK's climate change targets will require continued scientific advances both in technical know-how and technological development. However, achieving net-zero will also require advances in the UK's economic and industrial capability – building an industrial base that can both commercialise and make effective use of new energy technology. Recent research by the European Institute for Innovation and Technology (EIT) Climate Knowledge and Innovation Community (Climate-KIC) highlights how critical industrial capacity, investment and innovation is to delivering climate change objectives.

"Policymakers and companies have a major task ahead. There is an urgent need to clarify what it would take to reconcile a prosperous industrial base with net-zero emissions, and how to get there in the 30 remaining years to 2050. There is no doubt that significant innovation and entrepreneurship will be required, by companies, policymakers, cities, and a range of other actors."[32]

4.4.1 Building Technical & Industrial Capability In Tandem

Every project reviewed as part of the study had the advancement of scientific, technical, technological knowledge and/or industrial capability for delivering climate change targets as central objectives. Funding that supported more nascent research areas (such as microbial fuel cells and hydrogen purification, for example) are more focussed on scientific, technical and technological advancement. However, there are also several examples of EPSRC funded projects that have delivered scientific and industrial advances in tandem.

The case study extracts below evidence how EPSRC funding has helped to build technical and economic capability to achieve climate change targets.

CASE STUDY EXCERPT: BUILDING TECHNICAL & INDUSTRIAL CAPABILITY

Advancing The Efficiency & Production Potential of Excitonic Solar Cells (APEX, EP/H040218/2)

The APEX project sought to deliver high-efficiency, low cost excitonic solar cell (ESC or XSC) technologies that were capable of being manufactured on flexible substrates, compatible with high-throughput roll-to-roll fabrication methods. It had a series of technical objectives that sought to deliver improvements in dye-sensitised solar cell conversion on solid and flexible substrates. The project received a total of just under £6m in funding from EPSRC via three grants between 2010 and 2016 and contributed to the discovery and development of new perovskite solar cell technology.

In addition to the scientific and technical advances derived from EPSRC investment, the discovery of perovskite solar cell technologies creates industrial opportunities for the UK economy. In the same way as silicon solar cell advances led to an increase in the number of UK firms exploiting commercialisation opportunities since 2009, it is realistic to expect a similar pattern of commercial exploitation associated with new perovskite technology in the next decade. Since 2009, the cost of silicon-based solar PV has declined rapidly (by more than 80% between 2009 and 2018), which has unlocked innovation and investment, leading to a significant expansion of the UK PV business base[33]. Between 2011 and 2013 more than one-fifth of all solar-related businesses registered in the UK focused specifically on photovoltaics, and in 2013 that proportion was more than one-quarter of all solar-related businesses registered in the UK. By 2018, the UK[34] was home to more than 230 solar PV firms, providing more than 20,000 high-value jobs.

Private investment in perovskite technology, and particularly in Oxford PV since it was founded in 2010 gives credence to the technology's commercialisation and market development potential. Beauhurst (a proprietary private investment data platform) records twelve fundraisings by Oxford PV between 2011 and 2019 to the value of almost £110m, of which sixty per cent (£65m) was secured in 2019. According to Oxford PV, its perovskite-on-silicon heterojunction tandem solar cell manufacturing line is expected to be complete and installed in the firm's Brandenburg facility this year. A wider search for private investment in perovskite technology internationally identifies a dozen firms (including Oxford PV), most of which have been established since 2014, in the United States, China, Canada (two firms in each location) and in Australia, Denmark, Japan, Poland and Saudi Arabia.

Consultation with APEX academic representatives highlighted that major global firms including Tata in India and UK firms including NSG-Pilkington, DuPont Teijin Films, G-24i, and Solar Press will continue to be involved in any future APEX phases, providing an opportunity for complementary industrial exploitation nationally and internationally. The economic potential derived from this EPSRC investment is significant in and of itself, however, it also plays a critical role in building UK industrial capability that will be required if challenging net-zero targets are to be achieved.

CASE STUDY EXCERPT: BUILDING TECHNICAL & INDUSTRIAL CAPABILITY

Response of Tidal Energy Converters To Combined Tidal Flow, Waves & Turbulence (Flowturb, EP/No21/487/1)

The UK's considerable tidal resources mean that tidal stream technology has the potential to make a significant contribution to power sector decarbonisation. The UK's practical tidal resource is estimated to be approximately 15GW, and the Offshore Renewable Energy (ORE) Catapult considers that deploying 1GW of tidal stream by 2030 is a realistic aim, given the right policy support.

The FlowTurb project received c.£800k in EPSRC funding and was driven by a collaboration between the University of Edinburgh, tidal developers Nova Innovations – a spinout company established by an Edinburgh University PhD student – and Scottish Renewables (now called Orbital), which both operate in Orkney and had a shared objective of better understanding turbulence in the Pentland Firth and Orkney Waters (PFOW). FloWTurb had three main objectives: 1. Develop an enhanced understanding of wave-current turbulence interaction in laboratory conditions; 2. Develop methodologies to estimate 'turbulence intensity' (TI) in PFOW; 3. Provide design solutions for marine energy devices located at PFOW.

By making datasets available to researchers and tidal developers, and using industry-standard commercial software, the project aimed to make these research advancements readily available for commercial partners. FloWTurb collected a significant amount of laboratory and field data which was analysed to develop a better understanding of the wave-current-turbulence interactions in PFOW. It developed a robust numerical model for predicting turbulence intensity (TI) in the region and adapted a wind turbine design tool created by the National Renewable Energy Laboratory (NREL) to simulate the dynamic response of tidal turbines to turbulence.

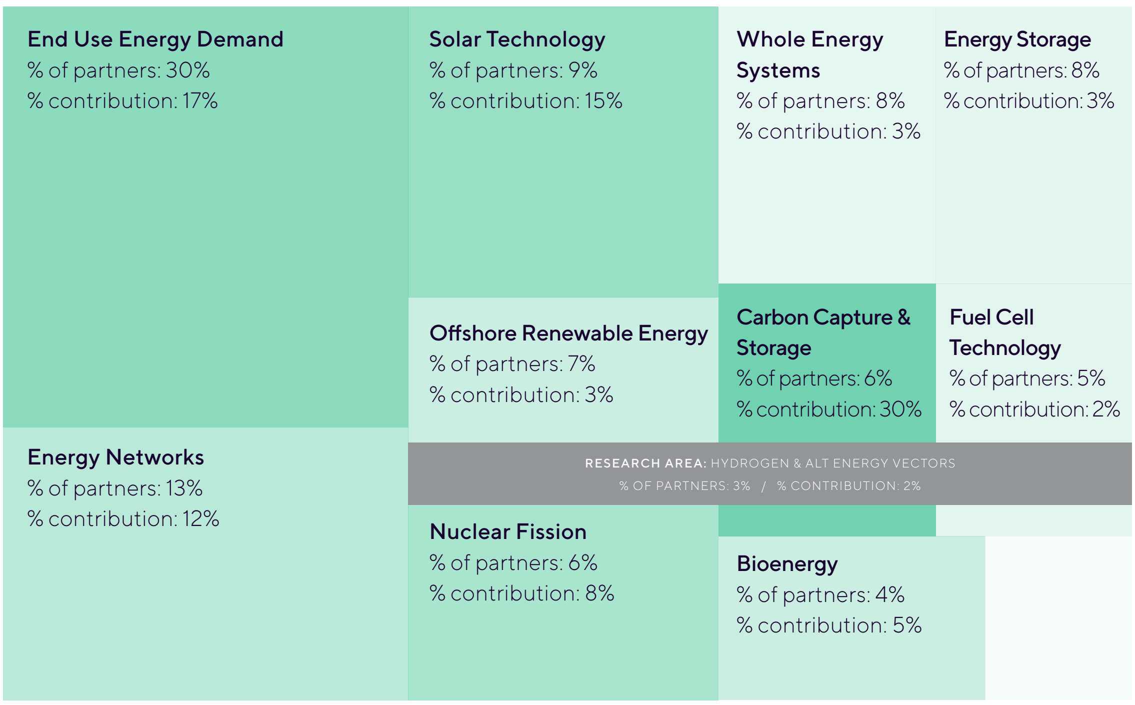
There are several ways in which the project could generate savings for the tidal industry including via greater understanding of turbulence leading to reduced developer risk and avoidance of unnecessary development costs; and optimisation of tidal array layouts. While the impact of the research advancements cannot yet be robustly quantified, desk research has shown that this type of research is important for driving the many incremental cost reductions in tidal stream technology that will be required for it to become commercially viable, and thereby make an increasingly substantive contribution to the UK's technical and economic capability to deliver climate change objectives.

4.4.2 Wider industrial capability building

More broadly, EPSRC funding has supported extensive collaboration with a range of project partners, including industrial partners. Since 2005, the Programme has engaged at least 1,600 unique partners in project activity, spanning the academic, public, private and charitable sectors[35]. Approximately 1,400 project partners have been engaged via grants that are within the scope of the study. Figure 4.1 shows the proportion of project partners (box size) and financial contributions (depth of colour) across in-scope research areas. EUED accounts for 30% of all project partners and 17% of financial contributions. CCS accounts for just six per cent of project partners but 30% of the financial contribution – which aligns to known challenges associated with capital investment for delivering CCS solutions.

Of the 1,427 project partners engaged, 819 could be matched to registered company data and 619 are currently registered as active. Over time, the project partners involved in EPSRC Energy Programme activity have accounted for increasing proportions of employment and revenue. In 2005 the total employment recorded against project partners involved in the Energy Programme was 1.1m. In 2018 the same figure was almost double that, at 2.1m employees. In 2005 EPSRC project partners contributed more than £233bn in UK revenues, and by 2018 this figure was almost £500bn.

FIGURE 4.1 - PROJECT PARTNERS & CONTRIBUTIONS BY RESEARCH AREA



Total Contribution: 2,084,437 – 38,388,266

Source: EPSRC Monitoring Data

4.5. CEMENTING THE UK'S POSITION AS INTERNATIONALLY LEADING

Throughout the study, consultation with Principal and Co-Investigators has consistently highlighted the highly competitive nature of energy research on an international basis. In that respect, Energy Programme funding has frequently been cited as being critical for sustaining UK competitiveness within international research across numerous Research Areas. In a smaller number of cases, Energy Programme funding has been cited as making a substantive contribution to securing the UK's position as internationally leading. Excerpts from Offshore Renewable Energy (MAXFARM, EP/N006224/1), Solar Technology (APEX, EP/H040218/2) and CCS (UKCCSRC, EP/K000446/1) case studies illustrate the Programme's contribution to international research leadership.

CASE STUDY EXCERPT: INTERNATIONALLY LEADING RESEARCH

Maximizing Wind Farm Aerodynamic Resource Via Advanced Modelling (Maxfarm, EP/N006224/1)

As already referenced in Section 4.2.2, substantive Energy Programme investment in wind energy research in 2006 re-ignited UK research following a period of scarcity. The UK now has the highest level of installed wind capacity in the world, amounting to over one-third of global capacity. The UK has also contributed research that has reduced the cost of wind energy and is now one of the foremost contributors to international wind energy research. Consultations to inform the ORE case study indicated that the UK's current position as internationally leading in wind energy research is, in large part, attributable to EPSRC's 2006 funding.

CASE STUDY EXCERPT: INTERNATIONALLY LEADING RESEARCH

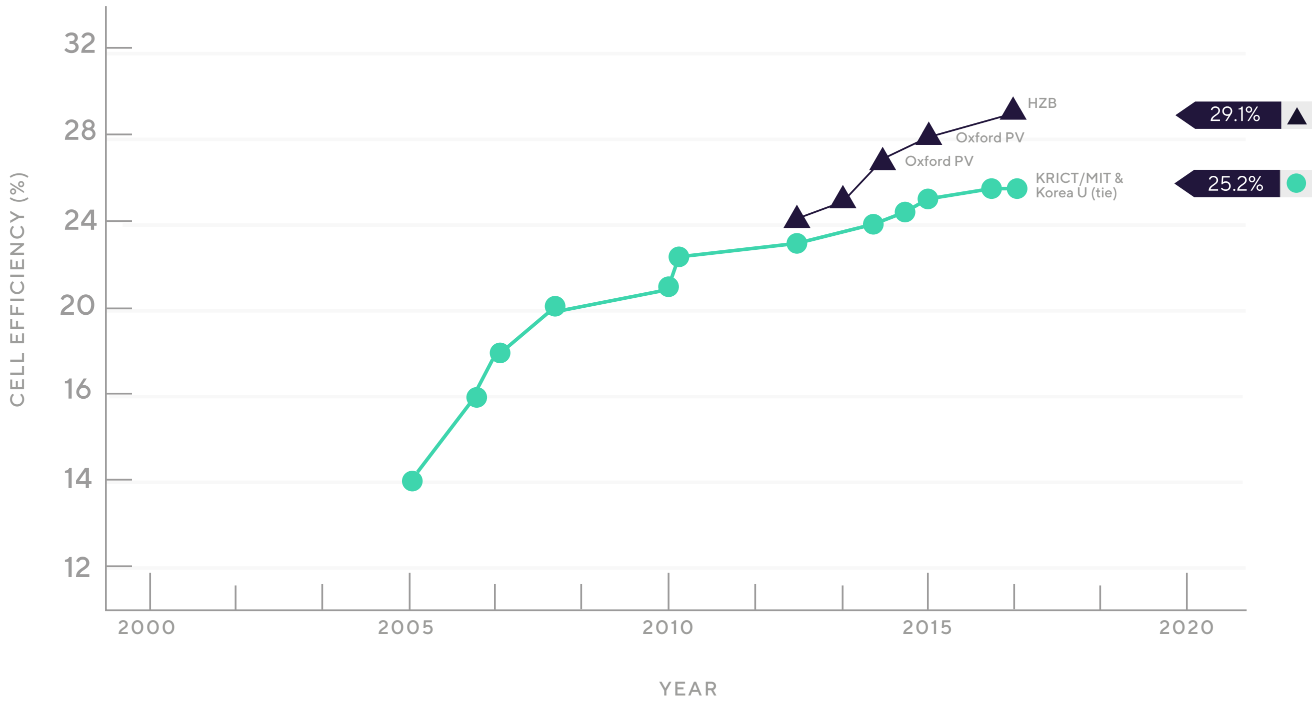
Advancing The Efficiency And Production Potential Of Excitonic Solar Cell (APEX, EP/H040218/2)

In addition to supporting industrial advances and economic opportunities in solar technology (referred to in Section 4.4) Energy Programme solar research investment has also positioned the UK at the leading edge of emerging perovskite solar cell technologies. In 2012 Professor Snaith at Oxford University (a member of the APEX consortium) discovered a breakthrough technology referred to as 'Perovskite Solar Cells' through a material 'methylammonium lead iodide' (MAPI). The Oxford team's research led to an unprecedented achievement of power conversion efficiency from ~4% to ~20%.

The discovery has placed the UK at the leading edge of both perovskite solar research and commercialisation via an associated patent and spin-out firm Oxford PV.

The UK has been the driving force behind subsequent technological advancement, as evidenced by the National Renewable Energy Laboratory's charting of solar technology efficiency records illustrated in Figure 4.2 below.

FIGURE 4.2 - UK LEADERSHIP IN PEROVSKITE PV TECHNOLOGY



Source: National Renewable Energy Laboratory, Best Research-Cell Efficiencies, 2020

CASE STUDY EXCERPT: INTERNATIONALLY LEADING RESEARCH

United Kingdom Carbon Capture & Storage Research Centre (UKCCSRC, EP/K000446/1)

Section 4.3.2 illustrates how Energy Programme funding has enabled UKCCSRC to contribute to advancing UK energy policy. The UKCCSRC case study also demonstrates how EPSRC funding has contributed to establishing the UK's position as internationally leading in CCS research. Comprehensive bibliometric academic studies have charted CCS research outputs internationally highlighting that post-climate change abatement legislation, 55 countries have engaged in CCS technologies and related research. Of these countries, the UK ranks second behind only the US, and ahead of China in terms of research output volume[36]. UKCCSRC has been closely involved in a significant proportion of UK CCS research since 2012, and this recent bibliometric analysis suggests that UK research output is effectively positioning the UK as internationally leading in CCS. These statistics are supported by primary case study research with UKCCSRC MoU partners, which highlights positive international perspectives on UK expertise, and more specifically UKCCSRC's international standing among international MoU holders.

In addition to these thematic case study findings, results from the online academic survey offer further evidence in support of the programme's contribution to the UK's international research standing. Eighty-seven per cent of respondents were of the view that Energy Programme funding is creating new, leading-edge knowledge. Eighty-four per cent believed that the Programme is increasing international visibility, and a marginally lower proportion (79%, n=120) believed that the Programme is increasing international collaboration.

4.6. PERMEATING RESEARCH SKILLS & NETWORKS

Section 3.4 presented aggregate statistics regarding the Energy Programme's support for research skills and network benefits, including investment in doctoral training and fellowships and outputs such as secondments and next destination of researchers. However, case study research has highlighted how Programme funding permeates skills and network development through almost every facet of project activity. The case study excerpts below (drawn from case studies into Offshore Renewable Energy and Energy Storage Research Areas) illustrate just some of the less tangible ways in which EPSRC funding supports skills and network development beyond the headline facts and figures.

CASE STUDY EXCERPT: RESEARCH SKILLS & NETWORK DEVELOPMENT

Supergen Wind Hub (EP/L014106/1)

Data from a 2016 Supergen Wind Hub report showed that 77 students received a PhD through the Doctoral Training Centre in Wind Energy Systems (awarded £5.9m between 2009 and 2018) in addition to 28 PhDs funded through the Supergen consortium. Researchers supported to obtain qualifications via the training centre and the Supergen consortium took up positions within industry, in research institutions outside of the academic sector, as well as within the academic sector. The most common destination for CDT-funded researchers was industry (47%, n=32) which serves to highlight the role that EPSRC plays in developing the UK offshore wind industry's skills base.

CASE STUDY EXCERPT: RESEARCH SKILLS & NETWORK DEVELOPMENT

Energy Storage for Low Carbon Grids (ESFLCG, EP/K002252/1)

The ESFLCG project started in 2012, at a time when the UK Government was developing Electricity Market Reform (EMR) which aimed to create the policy framework to deliver the huge investment in low carbon electricity technologies required to meet the UK's decarbonisation targets, whilst maintaining security of electricity supply and affordability for consumers. ESFLCG sought to better understand the various roles and values of energy storage on a whole-system basis and develop new technologies that would mitigate unique security of supply risks to the UK. Sixteen researchers from across nine universities were involved in the project, which also established an advisory board consisting of 19 organisations from the public and private sectors, including National Grid, DECC/BEIS, Ofgem and major utilities companies. The project delivered scientific advances in systems modelling and storage technology that formed the basis for reports commissioned by a variety of policy stakeholders. For example, Imperial College London's electricity system modelling was used to conduct modelling for reports commissioned by BEIS and Ofgem as part of the development of their 'Smart Systems and Flexibility Plan'. Other analyses of the role of energy storage and other flexibility technologies have influenced various aspects of policy and regulatory frameworks including the RIIO-2 regulatory framework and a review of Distribution Network Security Standards among others.

The collaboration between ESFLCG academics and policy stakeholders facilitated via the project and its advisory group builds research networks in and of itself. However, most notably in respect of this particular illustration, the advances made in energy storage technologies from three of the CI's was key to underpinning the case for the Faraday Institution, which invests substantively in collaborative research that brings together academics, industry and government to make advances in electrochemical storage, and develop the academic and industrial skills in the UK. All three academics now sit on the expert panel that provides direction to the Institution, demonstrating one of the much less direct and less tangible ways in which EPSRC Energy Programme funding contributes to research skills and network development.

CASE STUDY EXCERPT: RESEARCH SKILLS & NETWORK DEVELOPMENT

Response Of Tidal Energy Converters To Combined Tidal Flow, Waves & Turbulence Research (Flowturb, EP/No21/487/1)

The FloWTurb project sought to develop an enhanced understanding of wave-current turbulence interaction in laboratory conditions and to develop estimation methodologies and technology solutions for marine energy devices located at Pentland Firth and Orkney Waters (PFOW). By making datasets available to researchers and tidal developers, and using industry-standard commercial software, the project aimed to make these research advancements readily available for commercial partners.

The FloWTurb project provided training for six PhD students and two post-doctoral researchers at Edinburgh University. All of these students have gone on to obtain high-skilled positions in industry or academia in the marine energy sector. Moreover, the experience that one of the CI's gained during the FlowTurb project helped him to gain a senior position at the ORE Catapult, further facilitating knowledge sharing between academia and industry.

4.7. FUTURE PROGRAMME CONSIDERATIONS

In addition to highlighting the breadth of benefits that Energy Programme investments have had across Research Areas, the thematic case study research also identified a limited number of future programme considerations including:

- Follow-on funding to support post-discovery incremental research advances: as outlined in Section 4.2, the Energy Programme has been recognised as being good at funding early stage research and accepting the associated risks. However, a number of consultees also noted the importance of sustaining investment in emerging technology post-discovery. The decrease and subsequent reinvigoration of wind energy research described in the Offshore Renewable Energy case study, and the highly competitive nature of emergent solar technology research provide useful examples of where sustained investment has been or will be important for maximising scientific and industrial benefits to the UK.
- Closer collaboration with complementary research institutions: Energy Programme funding has been recognised as effectively supporting a breadth of nascent research across Research Areas. However, a number of consultees involved in some of the more nascent Energy Programme research projects suggested scope for further collaboration between EPSRC and other research institutions such as the Royal Society and Research Academies, and between Research Councils such as the Natural Environment Research Council, for example.

- Continued focus on whole-system and multidisciplinary research: thematic research has highlighted how EPSRC has driven more multi-disciplinary approaches to energy research across a vast majority of the case study grants over the past decade. This multidisciplinary focus is typically accepted as having derived better, more holistic research outcomes. Nevertheless, a notable minority of case study participants suggested that to fully embed multi-disciplinary approaches will require sustained focus within future Energy Programme grants. In a similar vein, the vast majority of case study subjects highlighted productive collaboration with industry partners, yet in a small number of cases, scope was identified for further industry involvement at both strategic and operational levels.
- Supporting opportunities for developing skills and capabilities of those in academic support roles: the case study research has emphasised both the very tangible and less tangible ways in which Energy Programme funding supports the development of UK energy research, academic skills and capabilities. However, findings from the academic survey pointed to scope for enhancing support for also developing the skills and capabilities of those in academic support roles, such as technicians and laboratory assistants for example. Compared to c.80% of respondents who believed that Energy Programme funding was positively contributing to the flow of academics into energy research and development of UK academic researcher skills and capabilities, just 51% were of the same opinion when it came to academic support roles.

In addition to these thematic findings, responses to the online academic survey provided a wealth of constructive opinions regarding future Programme considerations.

- Investment in a revised model for doctoral training: a notable proportion of qualitative responses to the academic survey referenced potential improvements within the pipeline for doctoral research students. Respondents suggested that the current doctoral training model could be revised to allow for greater flexibility and variety of PhD opportunities. Reference was also made to difficulties faced by new academics to access PhD students who are no longer funded by grants or scholarships. Increased flexibility within the current model for doctoral training is also expected to provide an additional benefit of increasing access to and/or visibility of high-quality supervisors/researchers within the breadth of UK universities.
- Attracting higher-level international students and researchers: Section 4.5 highlights the positive sentiment among UK academics regarding the Programme's contribution to international visibility and collaboration. However, survey responses also suggest some scope for improving the way in which UK research is currently positioned to a) attract higher-level international students and researchers, and b) establish more structured international energy research networks. Sentiment regarding both of these international components is clearly influenced by the UK's exit from the EU, with references to 'Europe'/'EU' and 'Brexit' featuring heavily.
- More effective use of existing research facilities: a notable proportion of survey respondents suggested that there is scope for more effective strategic use of existing EPSRC-funded research facilities. This may be enabled via a combination of clearer signposting to existing facilities, support for preparing and evaluating proposals to use existing facilities, and provision of training for researchers wishing to use existing facilities.

- Further alignment of industry-academia collaboration: academics highlighted a range of existing industry-academic collaborative projects that have assisted in supporting knowledge exchange and application of research. Specifically, those referenced include: the UK Catalysis Hub, EDF Energy, the Energy Research Accelerator, the Faraday Battery Exchange, the Industrial Strategy Challenge Initiative, the LabVIEW Academy, Midlands ERA, BEIS Reactor Programmes, and Wave Energy Scotland's programmes. However, survey responses also reiterated a number of issues associated with collaborative research that require continued focus. For example, ongoing work is required to more routinely align academic and industry objectives and expectations. The long-term strategic planning required to facilitate effective energy research is often challenging when industrial partners are headquartered outside the UK. Investment in targeted collaboration with UK-owned SME clusters and increased opportunities for researcher placements and secondments was considered to be worth exploring.

While it should be stressed that the majority sentiment regarding the impact of Energy Programme funding was by far a positive one, these future considerations may be of some value for deriving future operational objectives.

5. Conclusions

Through this study EPSRC sought to demonstrate the contribution that its Energy Programme investments have made to the advancement of research, research-led collaboration, innovation and skills. This section draws together findings gathered throughout the study as they align to the key study questions posed. It demonstrates the Programme's contribution to expanding UK research capacity across a full spectrum of energy research, its contribution to research and post-graduate training needs and the ways in which it has increased the UK's international visibility in energy research. It also highlights the ongoing need for substantive investment in energy research to achieve several UK objectives including energy security, decarbonisation and environmental sustainability, industrial advancement and economic recovery and growth.

5.1. STRATEGIC ALIGNMENT & ONUS ON RESEARCH INFRASTRUCTURE

Before discussing each impact area in turn, it is important to first highlight that, overall, the study demonstrates a clear alignment between the challenges and opportunities associated with energy research and the stated objectives of the Programme. There is strong evidence (from case study research, and via the online survey) to suggest that EPSRC funding is critical for a) ensuring that the UK achieves net-zero by 2050; b) positioning the UK as a global leader in various aspects of energy research and c) stimulating economic growth via national and international industrial expansion.

The discussion contained in Section 2 establishes that UK government legislative and policy developments since the 2007 Energy White Paper, spanning environmental sustainability (net-zero), green growth and the industrial strategy, are placing an ever-increasing onus on the UK's energy research infrastructure and networks to deliver the scientific and technological advances required to achieve the UK's strategic ambitions. Findings from Section 2 also reiterate the significance of the market failures that drive environmental sustainability, and consequently the energy research agenda. These market failures continue to provide robust justification for government intervention in energy research, both in terms of funding and an overarching coordinating function.

5.2. RESEARCH IMPACT

EPSRC has invested £1.1bn in in-scope research areas since 2004 via 1,233 grants. Funding provided via the Energy Programme exhibits a positive appetite for risk – often providing initial investment, acting as a catalyst for follow-on funding from both the public and private sectors, and accepting the degree of uncertainty that comes with early-stage investment in energy research. To date, EPSRC grants have secured follow-on funding of c.£2bn from a range of academic, charity, public and private contributors.

Every project reviewed as part of the study had the advancement of scientific, technical, technological knowledge and/or industrial capability for delivering climate change targets as central objectives. Funding supported a full spectrum of research, from more nascent research areas such as microbial fuel cells and hydrogen purification, through to projects with much broader research scope, such as whole energy systems and carbon capture and storage. The study also identified several examples of EPSRC funded projects that have delivered scientific and industrial advances in tandem.

The Programme portfolio has been balanced across Research Areas and is widely distributed across UK regions. The study has identified where, over time, research specialisms have secured above-average numbers of grants, and together with regional industrial specialisms these have the potential to be a powerful lever within the levelling-up agenda.

5.3. POLICY IMPACT

Together, researchers supported by the Programme have produced c.23,500 research outputs and have delivered more than 1,000 tangible policy impacts, most notably in terms of energy economics, sustainability and energy regulation. Targeted EPSRC investments in projects that co-ordinate research across policy areas often feature heavily when it comes to research impacts on policy. This is evidenced particularly via the UK Energy Research Centre which accounts for sixty-eight percent of all instances of policy influence within the Whole Energy Systems Research Area (n=180), and within the CCS Research Area where the UK Carbon Capture and Storage Research Centre is responsible for eighty-five percent of policy influence outputs (n=94).

Thematic case study research has provided illustrations of a breadth of policy impacts at various geographic levels. It demonstrates how the Energy Programme has provided extensive support for multi-disciplinary teams to devise new approaches to understanding energy challenges, particularly within the EUED and Whole Energy Systems Research Areas (Realising Transition Pathways, EP/K005316/1; DEMAND, EP/K011723/1) and how it has also supported energy researchers to both influence and implement important UK energy policies and strategies (CIE-MAP, EP/N022645/1; UKCCSRC, EP/K000446/1 and ITRC, EP/I01344X/1).

For example, Realising Transition Pathways successfully created, collated and curated an extensive repository of research and wider evidence that highlights the benefits of a whole systems approach, and in the years subsequent to the grant, the whole system approach to understanding energy use has been an area of continually increasing research interest. At a much more practical level, UKCCSRC was at least partly responsible for establishing the importance of CCS clusters and has spurred the development of six regional CCS clusters, of which two are directly attributed to UKCCSRC support. The UK ITRC has delivered notable impacts in terms of infrastructure analysis, design and strategy at regional, national, and international levels, including the National Infrastructure Commission's (NIC's) 'first-of-a-kind' energy and infrastructure resilience study.

5.4. INDUSTRIAL & ECONOMIC IMPACT

EPSRC funding has supported extensive collaboration with a range of project partners, including industrial partners. Since 2005, the Programme has engaged at least 1,600 unique partners in project activity, spanning the academic, public, private and charitable sectors. Over time, the industrial partners involved in EPSRC Energy Programme activity have accounted for increasing proportions of UK employment and revenue. In 2005 the total employment recorded against project partners involved in the Energy Programme was 1.1m. In 2018 the same figure was almost double that, at 2.1m employees. In 2005 EPSRC project partners contributed more than £233bn in UK revenues, and by 2018 this figure had more than doubled to c.£500bn. Given the breadth of the study, it is not possible to robustly determine either causality or additionality in respect of these economic statistics, but they do serve to demonstrate the Energy Programme's involvement with large and economically significant swathes of the UK economy.

Consultations with participating academics also highlighted the important role that EPSRC funding plays in supporting UK start-ups and spin-outs across Research Areas. This assertion is borne out in monitoring and supplementary secondary data which demonstrates that in 2019 the spin-out companies supported by the Programme generated known UK revenues of £28.9m and employed 180 people (averages of £1.4m and 8 employees). Since 2010 thirteen of these spin-out companies have secured a total of £49.3m of investment.

5.5. RESEARCH SKILLS & NETWORKS IMPACT

The study has highlighted various ways in which the Programme has contributed to advancing research skills and networks. The Programme portfolio is wide-ranging and largely balanced in terms of both Research Areas and geography. As such, it offers opportunities for the advancement of researcher skills and capabilities across a broad spectrum of research topics and associated skills, from fundamental science through mathematical modelling and software development to techno-economic assessment and social science research.

Analysis of aggregate Programme statistics identifies investment of approximately £13m directly into projects with specific training and skills development objectives via grants for Doctoral Training Centres and Fellowships. The Programme has also supported more than 800 secondments both between UK universities and between UK universities and a range of other academic institutions and private-sector research teams nationally and internationally. More than 2,000 researchers involved in Energy Programme grants have moved between research institutions within the UK (72% of all researcher destinations, n=1,476) and internationally (n=619), including notable proportions having taken up positions in China, the United States, Australia, Canada, France, Germany and India.

The Energy Programme's positive contribution to skills development is also evidenced in responses to the online academic survey through which 81% and 85% of respondents respectively indicated that EPSRC funding is successfully a) supporting the flow of academics into energy research fields and b) developing the skills and capabilities of UK energy research academics.

Thematic case study research demonstrates how EPSRC investments in research skills and networks go beyond the stated objectives of direct awards and aggregated output indicators. They also support an array of 'softer' yet important skills and network development outcomes, most notably in terms of the effects that academic influence have within industry and on government policy.

5.6. INTERNATIONAL IMPACT

Throughout the study, consultation with Principal and Co-Investigators consistently highlighted the highly competitive nature of energy research on an international basis. In that respect, Energy Programme funding has frequently been cited as being critical for sustaining UK competitiveness within international research across numerous Research Areas. In a smaller number of cases, Energy Programme funding has been cited as making a substantive contribution to securing the UK's position as internationally leading. Excerpts from Offshore Renewable Energy (MAXFARM, EP/N006224/1), Solar Technology (APEX, EP/H040218/2) and CCS (UKCCSRC, EP/K000446/1) case studies illustrate the Programme's contribution to international research leadership.

The Programme has also supported extensive international collaboration, including collaboration with organisations in the United States, China, India, Japan, and with organisations in Australia, France, Spain, Italy, Germany, and South Korea.

Results from the online academic survey offer further evidence in support of the programme's contribution to the UK's international research standing. Eighty-seven percent of respondents were of the view that Energy Programme funding is creating new, leading-edge knowledge. Eighty-four percent believed that the Programme is increasing international visibility, and a marginally lower proportion (79%, n=120) believed that the Programme is increasing international collaboration.

5.7. FUTURE NEED

In addition to demonstrating considerable progress towards the Programme's overarching objectives and impact areas, the study highlights significant ongoing need for investment in energy research. This future need is evidenced throughout the study, from the contribution that the Programme makes to the UK's strategic energy security and environmental objectives and the market failures that operate within the market for energy research, to the thematic case study research which demonstrates the complex, highly competitive and long-term nature of international energy research and the numerous benefits it derives.

Within its suite of net-zero reports, the Committee on Climate Change has stressed the extent of the challenge posed by the new 'stretched' net-zero 2050 target. It emphasises how the breadth of research currently funded under the Energy Programme will need to function together to achieve net-zero. In addition to this significant environmental challenge, academic survey respondents frequently referred to the additional layer of challenge that EU exit poses for energy research and the environmental, industrial and energy security benefits it can derive. Fundamentally, it is feasible to suggest that future investment in UK energy is more important now than ever before.

Energy research academics responding to the online survey also provided useful insight into some of the more specific future energy research investment needs which include:

- Access to critical UK owned and operated research facilities: academics highlighted future need for a range of specialist energy research facilities, including for example a facility akin to the National Renewable Energy Lab, combined wind and wave test facilities, more whole energy facilities, heat pump system test facilities, and living labs (used to experiment human-energy system interactions in the area of low carbon energy systems). Survey findings frequently cited the extent to which current research is reliant upon EU facilities via, for example, the European Transnational Access schemes for wave and tidal energy research facilities (such as MARINET and HYDROLAB) and the significant risk that these facilities may soon become unavailable to UK researchers.

- Investment in multi-disciplinary energy research skills: in order for the UK to keep pace with international energy research, academics highlighted a major need for continued investment in researcher skills, including investment in fundamental scientific research skills but also broader skills particularly IT, advanced data analytics, modelling, programming and software engineering. More generally energy research academics emphasised the need for increased focus on and investment in multidisciplinary skills that are increasingly required to deliver research projects of ever-increasing complexity.

- Further investment in virtual research infrastructure: in an increasingly digital and remotely configured research environment, many academic researchers have highlighted the need for exploration and future investment in virtual research infrastructure. Examples offered through the academic survey included online resources such as the Natural Environment Research Council's Vocabulary Server curated by the British Oceanographic Data Centre (BODC) and the UKCCSRC's CCS database. Once again, academics highlighted the role that EU funding has played in the provision of virtual research infrastructure that may become harder to access or unavailable post-UK/EU transition.

Ultimately the research compiled through this study serves as evidence of the considerable progress that the Energy Programme has made towards its strategic objectives and the range of benefits that the UK derives as a result. It demonstrates how EPSRC Energy Programme funding delivers a wide range of economic and industrial benefits to the UK and therefore the potential that future investment in the Energy Programme has to drive economic recovery via the Green Growth agenda. However, it also highlights the scale of the task required to achieve net-zero and the additional layer of challenge that the UK's transition out of the EU presents.

1 Department of Trade and Industry (2007) Meeting the energy challenge: a White Paper on energy. Accessible at: https://www.gov.uk/government/publications/meeting-the-energy-challenge-a-white-paper-on-energy

2 DECC (2011) Carbon Plan. Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47621/1358-the-carbon-plan.pdf

3 DECC (2011) 'Planning our electric future: a white paper for secure, affordable, and low carbon energy'. Retrievable from: https://www.gov.uk/government/publications/planning-our-electric-future-a-white-paper-for-secure-affordable-and-low-carbon-energy

4 BEIS (2017) 'Industrial Strategy White Paper'. Retrievable from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf[5] Committee on Climate Change (2019) Net Zero Technical Report. Retrievable from: https://www.theccc.org.uk/publication/net-zero-technical-report/

5 BEIS (2017) Clean Growth Strategy. Retrievable from: https://www.gov.uk/government/publications/clean-growth-strategy

6 BEIS (2017) 'Cost of Energy Review'. Retrievable from: https://www.gov.uk/government/publications/cost-of-energy-independent-review

7 BEIS (2019) 'Green Finance Strategy: Transforming Finance for a Greener Future'. Retrievable from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820284/190716_BEIS_Green_Finance_Strategy_Accessible_Final.pdf

8 Various sector deal publications retrievable from: https://www.gov.uk/government/publications/industrial-strategy-sector-deals/introduction-to-sector-deals

9 Ibid

10 Committee on Climate Change (2019) Net Zero Technical Report. Retrievable from: https://www.theccc.org.uk/publication/net-zero-technical-report/

11 Committee on Climate Change annual progress reports, most recently 2020

12 Department for Business Energy & Industrial Strategy UK Energy in Brief, 2020. Accessible at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904503/UK_Energy_in_Brief_2020.pdf

13 Note that this figure includes investment in aspects of the programme that do not fall within the scope of this study.

14 Intergovernmental Panel on Climate Change, 2019 'Special Report on Global Warming of 1.5oC', IPCC, 2019[15] Ibid

15 UK Committee on Climate Change, 2019 'Net Zero – The UK's Contribution to Stopping Global Warming', CCC, 2019

16 HM Treasury (2018) 'The Green Book: Central Government Guidance on Appraisal and Evaluation', HM Treasury, 2018.

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18 See for example the European Commission's Research, Innovation and Science Policy Experts (RISE), 2015 'Value of Research' report. Accessible at: https://ec.europa.eu/futurium/en/system/files/ged/60_-_rise-value_of_research-june15_1.pdf

19 See for example the Institute for Innovation & Knowledge Exchange's (IKE Institute) 2018 report 'Are University-Industry Collaborations in the UK Really Working to Deliver Innovation Impact'. Accessible at: https://ikeinstitute.org/asset/resource/%7B6DFF369C-0929-4534-8A0C-DAE161480091%7D/file.pdf

20 See for example the Office of Fair Trade's (OFT) 2009 'Government in Markets Guide for Policy Makers' which recognises where government can play a positive role in markets, including through effective co-ordination. Accessible at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/284451/OFT1113.pdf

21 As it relates to the scope of this study

22 Awards made under the twelve Research Areas within the scope of this study, to which EPSRC contributed at least 50% of the funding award.

23 Monitoring data apportions funding across Research Areas, using fractions to denote the alignment between research activity and funding allocations. The proportions of funding allocated to Research Areas are referred to as 'Equivalent Values'. In some cases, funding is apportioned across Research Areas both within, and outside of the scope of the review. The total amount of funding (including both in and out of scope Research Areas) is referred to as 'Reporting Value'.

24 The UK Magnetic Fusion Research Programme has received just under £360m via three grants awarded between 2010 and 2019. It is subject to its own governance and review process and therefore the level of resource required to credibly include it in this study was not deemed to represent value for money with respect to the broader Programme portfolio.

25 While some records within the monitoring dataset date back to 2004, none are within the Research Areas in scope.

26 Note: figures presented here are based on unique rows within the Research Fish dataset. They are intended to provide an indication of the balance of Programme derived policy influence. However, in many cases more than one instance of policy influence is referred to within descriptive text linked to individual policy impact rows. The totality of policy influence linked to individual RAs may therefore be higher than presented for some RAs.

27 Nine out of twelve because the analysis does not include the Nuclear Fusion Research Area as previously stated, and no spin-out companies are recorded as being linked to the Hydrogen and Alternative Energy Vectors or Whole Energy Systems Research Areas.

28 Using Bureau van Dijk's FAME company database: https://www.bvdinfo.com/en-gb/

29 Department for Business, Energy & Industrial Strategy, UK becomes first major economy to pass net zero emissions law, 27 June 2019, GOV.UK, retrieved 16 September 2020, www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law

30 Figures presented here reflect the total value of EPSRC investment into both in-scope and linked Research Areas.

31 Higginson S, et al. (2015) Diagramming social practice theory: An interdisciplinary experiment exploring practices as networks. Retrievable from: https://journals.sagepub.com/doi/10.1177/1420326X15603439

32 Material Economics (2019), Industrial Transformation 2050, EIT Climate-KIC. Accessible at: https://www.climate-kic.org/wp-content/uploads/2019/04/Material-Economics-Industrial-Transformation-2050.pdf

33 International Renewable Energy Agency (IRENA), "Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid-Integration, and Socio-Economic Aspects", IRENA, 2019

34 Data derived from Bureau van Dijk using key word searches for a) solar and b) photovoltaics

35 1,658 unique records within EPSRC monitoring data

36 Osaze Omoregbe, Abdullah Naseer Mustapha, Robert Steinberger-Wilckens, Ahmad El-Kharouf, Helen Onyeaka., Carbon capture technologies for climate change mitigation: A bibliometric analysis of the scientific discourse during 1998–2018, Energy Reports, 2020, ISSN: 2352-4847, Vol: 6, Page: 1200-1212

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