Research Councils UK Energy Programme Strategy Fellowship

ENERGY RESEARCH AND TRAINING PROSPECTUS: REPORT NO 7

Wind, Wave and Tidal Energy

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Dr. Matthew Hannon
Prof. Jim Skea
Dr Aidan Rhodes
Centre for Environmental Policy
Imperial College London
14 Princes Gardens
London SW7 1NA

http://www3.imperial.ac.uk/rcukenergystrategy

Research Councils Energy Programme

The Research Councils UK (RCUK) Energy Programme aims to position the UK to meet its energy and environmental targets and policy goals through world-class research and training. The Energy Programme is investing more than £625 million in research and skills to pioneer a low carbon future. This builds on an investment of £839 million over the period 2004-11.

Led by the Engineering and Physical Sciences Research Council (EPSRC), the Energy Programme brings together the work of EPSRC and that of the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC), and the Science and Technology Facilities Council (STFC).

In 2010, the EPSRC organised a Review of Energy on behalf of RCUK in conjunction with the learned societies. The aim of the review, which was carried out by a panel of international experts, was to provide an independent assessment of the quality and impact of the UK programme. The Review Panel concluded that interesting, leading edge and world class research was being conducted in almost all areas while suggesting mechanisms for strengthening impact in terms of economic benefit, industry development and quality of life.

Energy Strategy Fellowship

The RCUK Energy Strategy Fellowship was established by EPSRC on behalf of RCUK in April 2012 in response to the international Review Panel's recommendation that a fully integrated 'roadmap' for UK research targets should be completed and maintained. The position is held by Jim Skea, Professor of Sustainable Energy in the Centre for Environmental Policy at Imperial College London. The main initial task is to synthesise an Energy Research and Training Prospectus to explore research, skills and training needs across the energy landscape. Professor Skea leads a small team at Imperial College London tasked with developing the Prospectus.

The Prospectus contributes to the evidence base upon which the RCUK Energy Programme can plan activities alongside Government, RD&D funding bodies, the private sector and other stakeholders. The Prospectus highlights links along the innovation chain from basic science through to commercialisation. It is intended to be a flexible and adaptable tool that takes explicit account of uncertainties so that it can remain robust against emerging evidence about research achievements and policy priorities.

One of the main inputs to the Prospectus has been a series of four high-level strategic workshops and six in-depth expert workshops which took place between October 2012 and July 2013. The main report, *Investing in a brighter energy future: energy research and training prospectus*, was published in November 2013. This is one of nine topic-specific documents supporting the main report. All reports can be downloaded from: www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports. This first version of the Prospectus will be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This report is the product of work conducted independently under EPSRC Grant EP/K00154X/1, Research Councils UK Energy Programme: Energy Strategy Fellowship. The draft report was reviewed by Nicola Beaumont of the Plymouth Marine Laboratory, David Quarton of Garrad Hassan and Robin Wallace of the University of Edinburgh. While the report draws on extensive consultations, the views expressed are those of the Fellowship team alone.

Contents

Executive Summary

This report examines research and training needs for wind, wave and tidal energy, covering a range of engineering, environmental and social science research challenges. The conclusions from a two-day facilitated expert workshop, attended by academics along with representatives from the private sector and public sector organisations, constitute one of the most important inputs to this report. The report sets these conclusions in the context of the UK's scientific and industrial capabilities, policy ambitions, global and UK developments and outputs from existing roadmaps and innovation needs assessments. The main findings are:

- Wind, wave and tidal energy accounts for a small percentage of the UK's electricity generation. Wind is the most mature of the technologies, contributing over 5% of the UK's electricity generation in 2012, the majority of it onshore. Marine renewables meet a negligible proportion of the UK's electricity generation needs.
- Investment in offshore wind is proceeding rapidly and it is likely to account for a larger share of generation than onshore wind in the near future. There has been little commercial investment so far in wave and tidal energy technologies, which are much less mature. However, some major companies have recently invested in tidal current technology, suggesting that it holds commercial promise.
- There is a large degree of uncertainty as to the role of wind, wave and tidal technologies in the future generation mix. Whilst wind energy, particularly offshore, is expected to play the most important role over the coming years, this will largely be driven by public policy. The future for marine energy is less certain. The TINA on marine energy sees a very wide range of potential deployment by 2050, with near zero deployment being possible. Past projections of marine energy deployment, especially for wave technology, have proved to be over-optimistic. The value of research into wave and tidal energy is closely aligned with its prospects for commercial deployment and it is important to keep these under review.
- The priority research areas fall into eight categories: **device and array design; foundations and support structures; grid integration; system reliability; asset management; monitoring and mitigating environmental impacts; resource characterisation and assessment**; and **economic, social and governance factors.** The first four categories have a strong technology and engineering focus, concerned with improving the performance of technologies at multiple scales, e.g. device components, devices, device 'fixings', arrays and grid integration. **Asset management** focuses on maximising performance via appropriate management. **Monitoring and environmental impacts** examines how the deployment of technologies will impact ecosystem, either positively or negatively, and how any negative impacts maybe avoided. **Resource assessment** is concerned with assessing the extent and distribution of wind, wave and tidal resources in the UK at various spatial and temporal scales. Finally, the last category underlines the importance of research into the governance and planning of wind, wave and tidal development, and the associated economic and social factors.
- The offshore wind and marine energy sectors face some common research challenges. However, there are also many important differences. Therefore, they should be considered jointly in a research context only when there are genuine overlaps.
- Research challenges in the wind, wave and tidal energy area are generally 'application-inspired' rather than 'science-inspired'. Consequently, close linkages between the research councils and innovation bodies such as the Technology Strategy Board (TSB) and the Energy Technologies Institute are essential and could be nurtured via joint-funding calls (e.g. Natural Environment Research Council-TSB), knowledge exchange networks or possibly establishing a central organisation responsible for coordinating such collaboration. Wind, wave and tidal research also

demands an interdisciplinary approach, which would benefit from greater coordination between the research councils, for example through joint research calls. International collaboration via collaborative networks (e.g. the European Energy Research Alliance) will also play a key role in facilitating high quality research. Making resources available to utilise these networks and using research consortia as the interface for exchange could help to support international engagement.

- There is a critical need for access to large-scale test facilities such as test beds, wave tanks, wind tunnels, and wind turbines, as well as high-performance computational facilities. Data from wind, wave and tidal research should be curated centrally and disseminated to maximise research opportunities. Attention should however be paid to the confidentiality and commercial sensitivity of this data. The development of new *in situ* and remote sensing technology would also be helpful for data collection as current technology is at or beyond its limit in terms of resource characterisation and environmental impacts. Regulation may be needed to help support the growth of this market but this is outside the remit of RCUK.
- The report identifies the need for PhD training via both Centre for Doctoral Training and project-based funding models, some of which should be interdisciplinary in nature. Industrial PhD support could also provide PhD students with a richer learning experience, as well as helping to foster academic-industry collaboration.

Acronyms

2/4/6DS	two/four/six degree scenarios
BBSRC	Biotechnology and Biological Sciences Research Council
CCS	Carbon capture and storage
CDT	Centre for Doctoral Training
CFD	computational fluid dynamics
DC	direct current
DECC	Department of Energy and Climate Change
DSM	Demand side management
EERA	European Energy Research Alliance
EMEC	European Marine Energy Centre
EngD	Engineering Doctorate
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
ETP	Energy Technology Perspectives
EUREC	Association of European Renewable Energy Research Centres
EWEA	European Wind Energy Association
EWETP	European Wind Energy Technology Platform
GHG	greenhouse gas
GWh	gigawatt hours
HVAC	high voltage alternative current
HVDC	high voltage direct current
IDCORE	Industrial Doctoral Centre for Offshore Renewable Energy
IEA	International Energy Agency
IP	intellectual property
ISSMER	International Network for Social Studies in Marine Energy
LC	low carbon
LCA	life cycle assessment
LCICG	Low Carbon Innovation Coordination Group
MARKAL	Market Allocation (Model)
MW	megawatt
NAREC	National Renewable Energy Centre
NCIL	no clear international lead
NERC	Natural Environment Research Council
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
OEM	original equipment manufacturer
ORE	Offshore Renewable Energy (Catapult centre)
ORECCA	Offshore Renewable Energy Conversion platforms Coordination Action
PV	Photovoltaics
R&D	research and development
RCUK	Research Councils UK
RD&D	research, development and demonstration

REF	reference scenario
STFC	Science and Technology Facilities Council
TINA	Technology Innovation Needs Assessment
TRL	Technology Readiness Level
TSB	Technology Strategy Board
TWh	terawatt hour
UKCMER	UK Centre for Marine Energy Research
UKERC	UK Energy Research Centre
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

This document is one of a series of reports that identifies UK research and training needs in the energy area. The focus of this report is **wind, wave and tidal energy**. The primary audience is Research Councils UK (RCUK), which supports energy research in UK higher education institutions through the RCUK Energy Programme.[1] However, other bodies involved in funding energy research and innovation, notably those involved in the UK's Low Carbon Innovation Carbon Group (LCICG),[2] may also find the content useful. The report is being disseminated widely throughout the UK energy research and innovation community to encourage debate and raise awareness of the work conducted under the Energy Strategy Fellowship.

The most important input to this report has been an expert workshop held on 25 September 2013. There were 20 participants at the workshop (excluding the Fellowship team), most of whom were academics and researchers falling within the communities supported by the Engineering and Physical Sciences Research Council (EPSRC) and the Natural Environment Research Council (NERC). A number of attendees were from government organisations and funding agencies and one participant came from a commercial background.

This subject of wind, wave and tidal energy is one of three areas where a light-touch approach has been taken.[3] This is because innovation bodies have already expended considerable effort on identifying R&D needs in this area, notably Technology and Innovation Needs Assessments (TINAs) developed through LCICG. A one-day workshop was organised using a cut-down version of the facilitation methods used in six previous residential expert workshops.

A full report of the workshop has previously been published as a working paper.[4] The working paper constitutes a document of record and has acted as an intermediate step in the production of this report, which focuses on key messages and recommendations. The workshop also drew on the outcomes of a series of 'strategy' workshops that addressed the following topics: **energy strategies and energy research needs; the role of the environmental and social sciences;** and **the research councils and the energy innovation landscape**. Reports of all of these workshops are available on the Fellowship website.[5]

The conclusions respond to a recommendation of the 2010 International Panel for the RCUK Review of Energy[6] that the research supported by the research councils should be more aligned with the UK's long-term energy policy goals. The key criteria used in developing this report have been the three pillars of energy policy – environment, affordability and security – coupled with potential contributions to UK growth and competitiveness.

The Fellowship team is using the EU/International Energy Agency (IEA) energy Research and Development (R&D) nomenclature[7] to map out the energy research landscape. This report covers **Area**

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[1] http://www.rcuk.ac.uk/research/xrcprogrammes/energy/Pages/home.aspx

[2] http://www.lowcarboninnovation.co.uk/

[3] The others are **Industrial Energy** and **Nuclear Fission**

[4] https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Light%20Touch%20workshop/Light%20Touch%20Report%203%20-%20Wind,%20Wave%20and%20Tidal.pdf

[5] http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports

[6] http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/ReviewOfEnergy2010PanelReportFinal.pdf

[7] http://ec.europa.eu/research/energy/pdf/statistics_en.pdf

III.2, Wind Energy and **Area III.3 – Ocean Energy**. The wind energy sector covers convertor development, system integration, onshore and offshore applications, whilst the ocean energy sector covers tidal power, wave energy, ocean current power and ocean thermal power.

This report is structured as follows. **Sections 2-4** provide the wider context within which research and training challenges are identified. Section 2 focuses on the possible role of wind, wave and tidal energy in future energy systems both globally and in the UK. Section 3 describes the current UK research landscape and capability levels. Section 4 reviews existing roadmaps and assessments of research and training needs. The sections that follow, **Sections 5-8**, draw heavily on the expert workshop. Section 5 sets out high-level research challenges across eight key research areas. Section 6 focuses on the ways in which the research councils operate, how the research they support is conducted and underlying needs for research infrastructure and data collection/curation. Many of the conclusions are generic in the sense that they may be applicable across the energy domain or even more widely. Section 7 addresses training provision. Section 8 addresses generic issues about the role of the research councils within the wider UK energy innovation system as well as EU/international engagement. **Section 9** presents key conclusions and recommendations.

2 Current and future role of wind, wave and tidal energy

2.1 Global perspectives on wind, wave and tidal energy

At present wind, wave and tidal electricity generation accounts for an extremely small portion of the global electricity mix. In 2011, wind accounted for approximately 2% and marine 0.003% respectively.[8] Wind energy accounted for 10% of renewable electricity generation, whilst marine energy[9] accounted for only 0.01% (Figure 1).

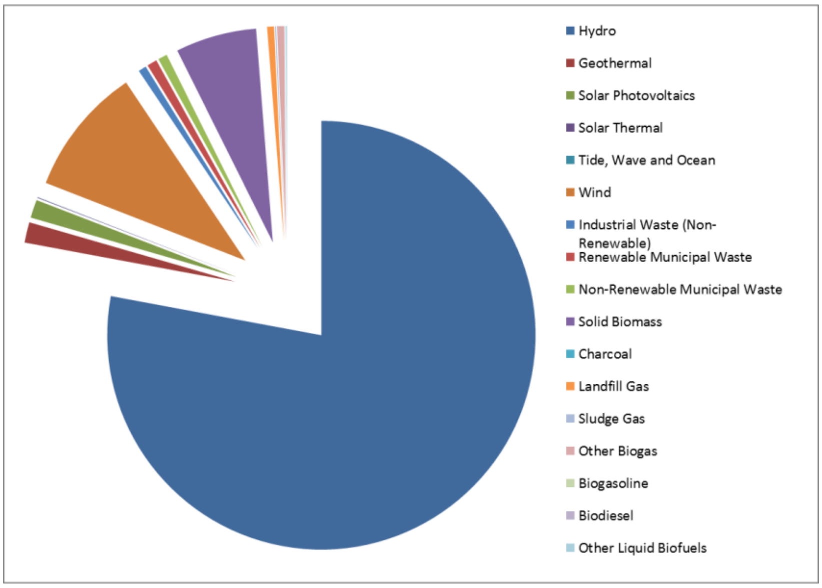

Figure 1: The balance of renewable electricity supply in 2011
Source: IEA

There is a stark contrast in terms of the increases in electricity generation from wind and marine energy between 1990 and 2011. The amount of energy generated by wind increased by a factor of 112,

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[8] http://esds80.mcc.ac.uk/wds_iea/TableViewer/tableView.aspx?ReportId=790
[9] This encapsulates tidal, ocean and wave energy

with much of this increase taking place since 2000, whilst the output from marine energy actually dropped by 4%. These statistics demonstrate how wind energy technology has matured and been deployed at a commercial scale over the last 20 years, whilst marine remains an early stage technology.

Uncertainty surrounds the extent to which wind, wave and tidal technologies will contribute to global energy generation in the future. Figure 2 compares the output of onshore wind, offshore wind and marine renewable technologies in 2050 in three long-term International Energy Agency (IEA) scenarios.[10] The **2DS** scenario is compatible with meeting the United Nations Framework Convention on Climate Change (UNFCCC) goal of keeping global temperature increases to no more than 2°C above pre-industrial levels; the **4DS** scenario assumes that countries fulfil the pledges they made at the Copenhagen climate conference in 2009; and the **6DS** scenario is ‘business-as-usual’ with no new policies.

There is a significant expansion of onshore wind in all scenarios. Offshore wind makes a significant contribution by 2030, but marine renewable technologies emerge only by 2050. The deployment of each type of technology increases with the ambition of climate policies. In the **2DS** scenario, wind energy accounts for 15% of electricity generation by 2050 and marine energy for 1%. Under this scenario, wind energy would be one of the largest sources of electricity generation, behind only nuclear and hydro-electricity generation. While marine energy would account for only a small proportion of electricity supply, its share would be larger than geothermal and only slightly less than natural gas with carbon capture and storage (CCS). The contribution of wind, wave and tidal energy would be significantly lower should no further action be taken on climate change, or even if action is restricted to the Copenhagen pledges.

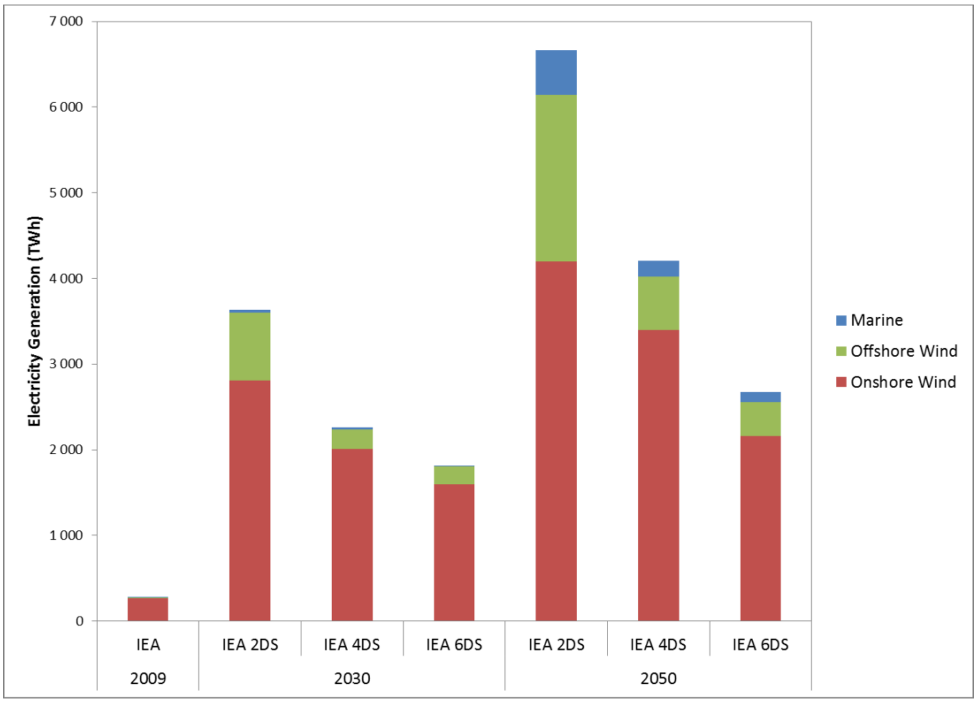

Figure 2: Projected future electricity generation by wind and marine energy technologies
Source: IEA Energy Technology Perspectives (ETP)[11]

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[10] http://www.iea.org/w/bookshop/add.aspx?id=425
[11] http://www.iea.org/w/bookshop/add.aspx?id=425

In summary, these scenarios indicate: a) that wind energy is expected to make a much more significant contribution to the global electricity supply mix than marine energy; and b) that, whilst both technologies are expected to capture a much larger market share than at present, the extent of deployment is very uncertain and depends primarily on policy drivers.

2.2 UK perspectives on wind, wave and tidal energy

Wind, wave and tidal energy accounted for only 5.4% of electricity generation in 2012.[12] Wind energy was responsible for the vast majority of this contribution, accounting for almost half of total renewable electricity generation. Of this, nearly two thirds was onshore and a just over a third was offshore.[13] Onshore wind started to make a significant contribution during the mid-1990s. In recent years there has been a rapid growth in offshore wind, particularly since the mid-2000s (Figure 3). In contrast, marine energy technologies supplied 4 GWh of electricity generation in 2012,[14] or 0.01% of renewable electricity generation.

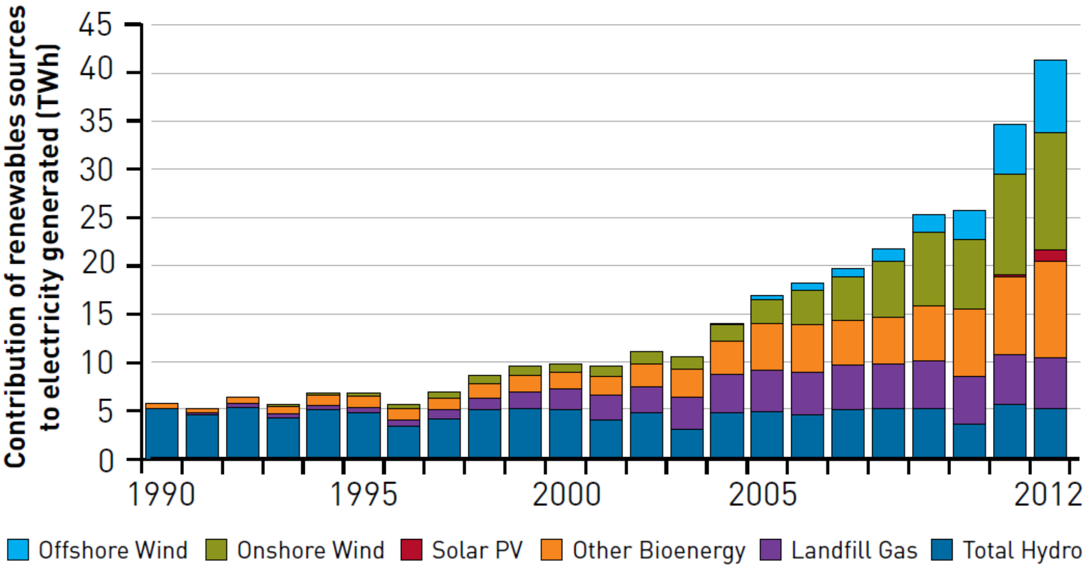

Figure 3: Electricity generation from renewable sources since 1990
Source: Department of Energy and Climate Change (DECC)[15]

To understand how UK wind and marine energy generation might change in the future, two scenario sets were consulted. The first was the revised UK Energy Research Centre (UKERC) Energy **2050** scenario set,[16] which used the UK Market Allocation (MARKAL) model,[17] a bottom-up, technology-rich cost optimisation model. The two scenarios reviewed from this set were a reference scenario (**REF**), which assumes that current policies extend into the future and a low carbon (**LC**) scenario, which is compatible with the 2050 greenhouse gas (GHG) target. Current policies in **REF** include the assumption that the carbon price floor will rise to £30/tonne of CO_2 by 2020 and £70/tonne by 2030 in line with

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[12] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/249679/et_sep_13.PDF

[13] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/249679/et_sep_13.PDF

[14] Marine energy in this figure is subsumed by the category 'hydro'

[15] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224130/uk_energy_in_brief_2013.PDF

[16] UKERC, **Energy 2050 Scenarios: Update 2013**, http://www.ukerc.ac.uk/support/ES_RP_UpdateUKEnergy2050Scenarios

[17] UCL Energy Institute, 'UK MARKAL model', http://www.ucl.ac.uk/silva/energy-models/models/uk-markal

current government intentions. This provides a significant incentive for low carbon technologies even in the absence of other measures.

The second scenario set was derived using the DECC **2050 Pathways Calculator**[18], which integrates user-specified assumptions about the level of effort expended on different energy technologies. Two pathways, reference (**REF**) and pathway alpha (**ALPHA**), were selected.[19] The former assumes minimal efforts to decarbonise or diversify energy supply, whilst the latter assumes a balanced effort to decarbonise across all sectors resulting in compliance with the 80% GHG reduction target.

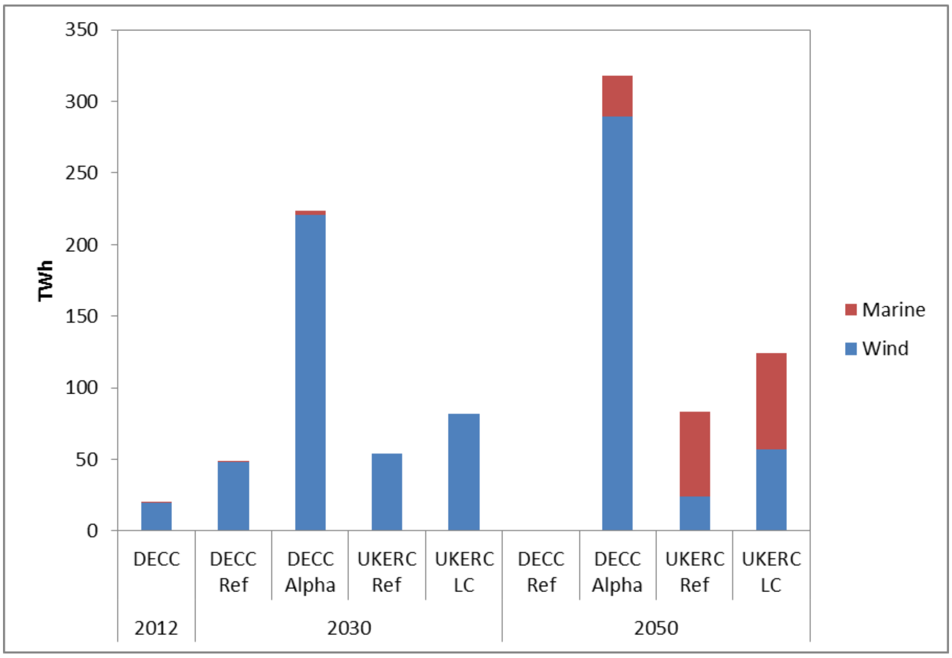

Figure 4: Projected UK marine and wind electricity generation
Sources: DECC[20] and UKERC

Figure 4 illustrates the large degree of uncertainty around the future deployment of wind and marine energy technologies. The DECC's **ALPHA** pathway is more optimistic than UKERC's **LC** scenario about the prospects for wind, suggesting that it could account for approximately 50% of total electricity generation by 2050, compared to 12% in the UKERC's scenario. In both reference scenarios, wind would play a less prominent role, with wind generation falling post-2030 as decommissioned wind farms are not replaced. DECC's **REF** pathway has almost no wind electricity generation by 2045.

Both sets of scenarios indicate that the marine energy sector is unlikely to have reached commercialisation by 2030, regardless of the extent to which climate change targets are met. Post-2030, DECC's **REF** pathway has no marine electricity generation, whilst marine generation accounts for 3% of electricity generation output by 2050. The UKERC scenarios are more optimistic about marine energy's role, with marine energy contributing 13-14% of electricity generation in both the **REF** and **LC** scenarios. This is a higher contribution than that of wind. However, marine energy is not deployed until the 2030s, whereas wind makes a significant contribution from around 2015.

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[18] DECC, **2050 Pathways Calculator**, https://www.gov.uk/2050-pathways-analysis

[19] DECC, **2050 Pathways Analysis Report**, 2010, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/68816/216-2050-pathways-analysis-report.pdf

[20] 2010 levels taken from DECC's DUKES report

2.3 Energy aspirations and expectations

The Fellowship strategy workshop **Energy strategies and energy research needs** explored the role that different technologies might make across a range of different energy futures. Participants were invited to consider various key features of a future UK energy system and specify what technology mix they **wanted** to see in 2050 (aspiration) and what they **expected** to happen, given their knowledge of barriers, policy directions, technology limitations and other factors (Figure 5).

Participants' preference was that wind would account for a larger share of electricity generation than they actually expected. Offshore wind was expected **and** preferred to capture a larger market share of the market than onshore wind by 2050. Participants' preference was that offshore wind would account for the largest share of the UK's generation mix. They expected it to account for a slightly smaller share than gas and coal with CCS but a larger share than unabated gas and nuclear.

There was less agreement about the role of marine energy. On average, the participants both hoped and expected that marine renewables would a supply a similar amount of electricity to onshore wind and photovoltaics (PV) by 2050, and would contribute significantly more than unabated coal generation.

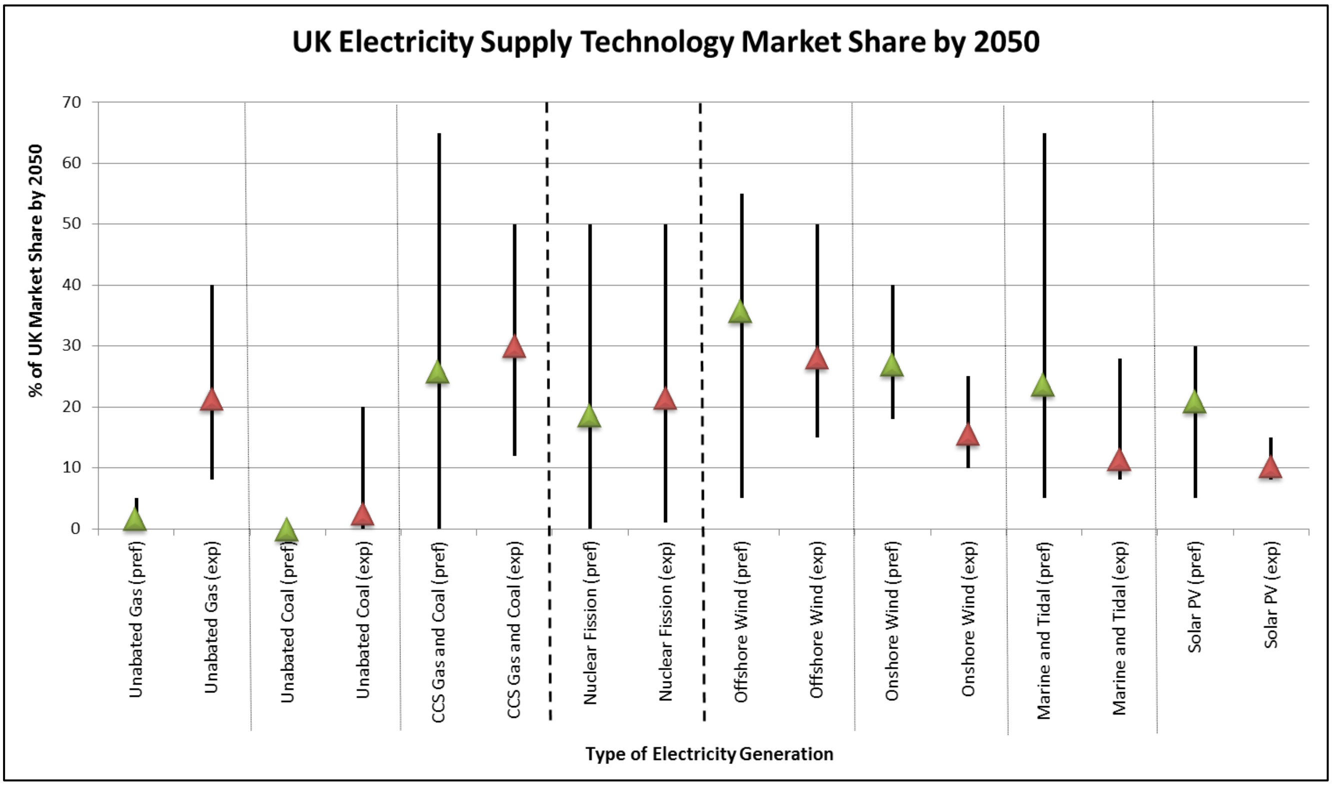

Figure 5: Preferred (green) and expected (red) ranges and mean average values for electricity supply technologies

3 Current UK research capabilities

3.1 Overview

Evidence on UK research capabilities in relation to wind, wave and tidal energy comes from three main sources: the Fellowship strategic workshop on **Energy strategies and energy research needs;**[21] the one-day 'light-touch' Expert Workshop on **Wind, wave and tidal energy;**[22] and the UKERC Energy Research Landscape documents on **Wind energy**[23] and **Ocean energy**[24]. Other evidence comes from the LCICG TINAs covering **Offshore Wind**[25] and **Marine Energy.**[26]

3.2 Strategic level workshop

Figure 6 is one of the key outputs of the strategic workshop on **Energy strategies and energy research needs**. It plots subjective judgments relating to the UK's level of industrial capability in various fields (x-axis) against the 'relevance' of these research areas to the UK's energy future, e.g. in terms environment, affordability, security, economic opportunity (y-axis). The size of the circles represents a subjective judgment about the level of scientific capability in the UK. The circles located to the left of the vertical axis represent areas where there is thought to be no clear international lead in industrial capability, or where one has yet to be established. The research areas relevant to this report are mapped in green and are labelled wind energy and ocean energy.

Figure 6 shows that participants expected marine energy (or 'ocean energy') to play a relatively minor role in the UK's future energy system even though participants recognised that the UK possessed strong scientific capabilities. There was some disagreement in relation to industrial capabilities in this sector. Some participants regarded the UK as a global leader in marine energy, whilst others believed the industry was not yet sufficiently mature for a global leader to have emerged.

Participants believed that wind energy was likely to play a major part in the UK's future energy system. They viewed the UK as having strong research capabilities in this area but only moderate industrial capabilities.

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[21] http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/workshops/workshop0

[22] https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Light%20Touch%20workshop/Light%20Touch%20Report%203%20-%20Wind,%20Wave%20and%20Tidal.pdf

[23] http://ukerc.rl.ac.uk/Landscapes/Wind.pdf

[24] http://ukerc.rl.ac.uk/Landscapes/Marine.pdf

[25] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48279/4467-tina-offshore-wind-summary.pdf

[26] http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/marine/

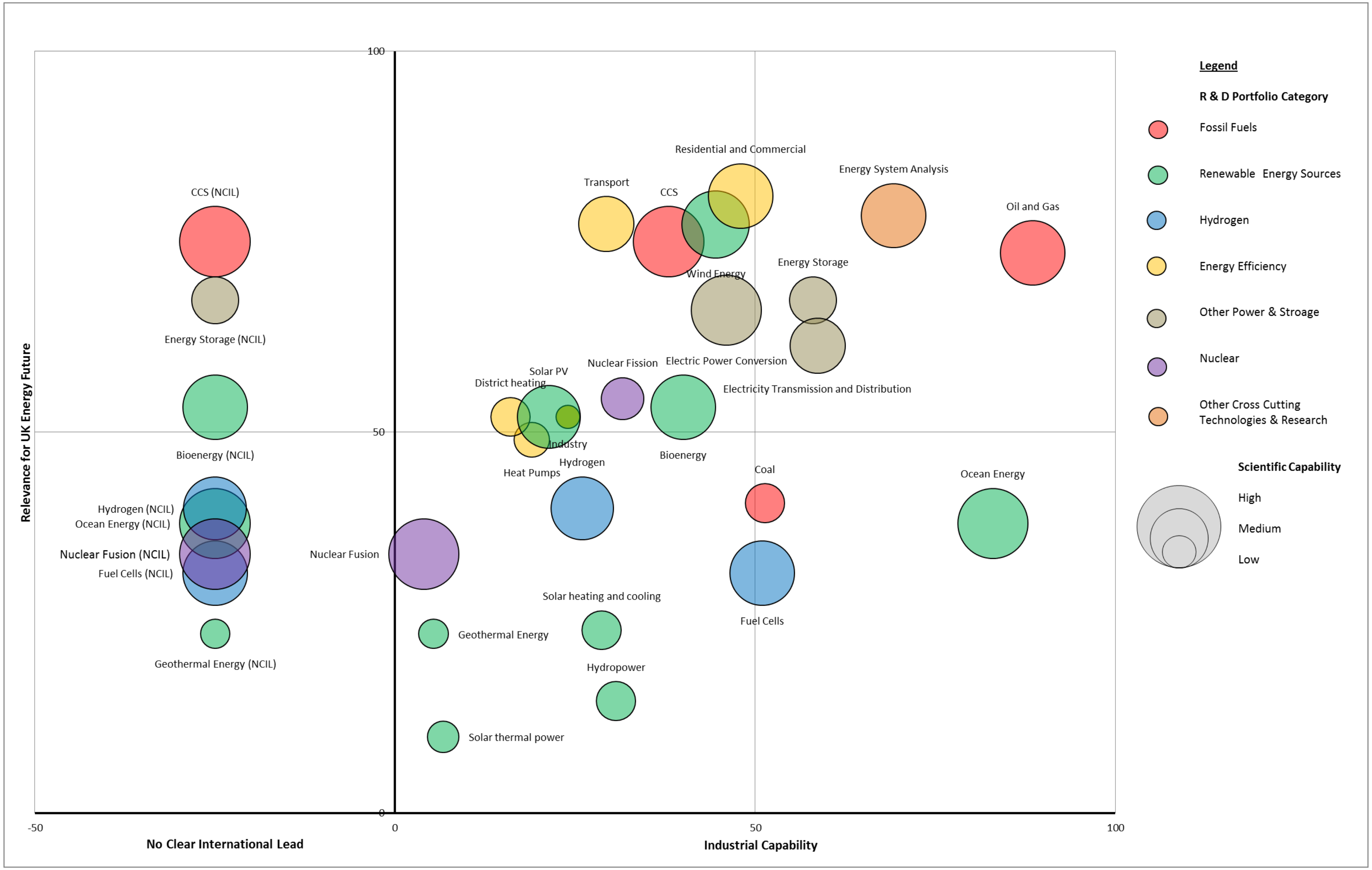

Figure 6: The UK's current and future energy R&D portfolio

3.3 Expert workshop

Participants at the expert workshop were asked were asked to identify how well placed they considered the UK to be at present in terms of wind, wave and tidal energy research capabilities. They were invited to score these on a scale of 0-10 (0 = no chance, 10 = well setup). Participants' scores were remarkably close to a normal distribution with an average score of 6.0 +/- 2.5 (Figure 7). This represents among the highest ratings given in any of the workshops run in this series.

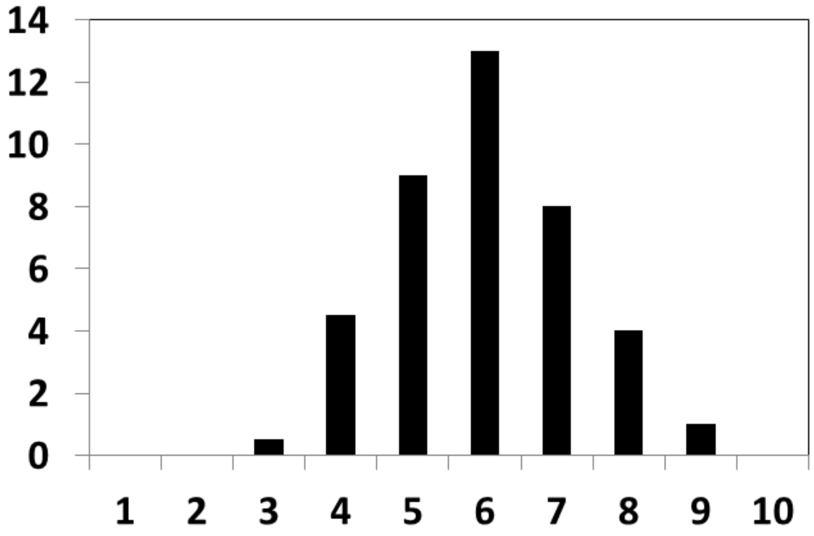

Figure 7: Distribution of perceived UK research capabilities in wind, wave and tidal energy

There were some differences between wind and marine energy. Wind energy scores from individual participants were in the range 5 to 8 with an average of 6.2. Marine energy scored 6.0 with scores ranging from 3 to 9. These scores suggest that the UK may have slightly stronger research capabilities in wind energy compared to marine and that there is greater uncertainty around the UK's capabilities in marine energy.

Other key themes emerging from the expert workshop included: 1) a strong research community in terms of technology, environmental resource/impacts and socio-economic aspects; 2) good investments in testing facilities; 3) major challenges in terms of cost reduction; 4) the need for greater integration/co-operation between groups; 5) the need for better joining up between basic research and applied R&D; 6) a related concern that EPSRC work might become disconnected from more commercial activity; and 7) a perception of lower levels of support at the higher Technology Readiness Levels (TRLs).

3.4 UKERC Research Landscapes

UKERC has produced two research landscape reports relevant to this Prospectus covering **Wind Energy** and **Ocean Energy**.

3.4.1 Wind energy

The UKERC research landscape report on wind energy notes that UK public support for wind energy R&D has risen substantially in recent years, prompted by the drive to cut the costs of offshore wind power and accelerate its deployment.

Industry, universities and research institutions all play a role. The UK has some important strengths in this domain, drawing on a wide range of disciplines ranging from engineering to the environmental, geological and social sciences (Table 1). The table also shows that the UK is not considered to be weak in any area of wind energy research.

Table 1: UK Wind Energy Research Capabilities

UK Capability	Area
High	Wind farm development and exploitation
	Grid Integration
	Wind power prediction
	Direct drive generators and power converters
	Monitoring and control
	Small wind turbines
	Blade materials technology and lifetime prediction
Medium	Resource assessment
	Offshore wind technologies including connection and foundations
	Wind turbine design and manufacture

Source: UKERC[27]

The most important delivery mechanism for wind energy research in universities has been the SUPERGEN initiative, funded by the RCUK Energy Programme. The SUPERGEN **Wind Consortium**[28] consists of seven academic research groups with expertise in wind turbine technology, aerodynamics, hydrodynamics, materials, electrical machinery and control, and reliability and condition monitoring. The Consortium has the active support of 19 industrial partners, including wind farm operators, manufacturers and consultants. There have also been important initiatives supporting more applied wind energy R&D, such as the £40m initiative announced jointly in 2008 by the Energy Technologies Institute (ETI) and the Carbon Trust and the £30m initiative for offshore wind innovation announced in 2011 by DECC.

In terms of training, EPSRC funds Centres for Doctoral Training (CDTs) in **Wind Energy Systems** at the University of Strathclyde, the **E-Futures Centre for Doctoral Training for Interdisciplinary Energy Research** at the University of Sheffield, and the **Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE)** at the University of Edinburgh. CDTs represent a relatively new approach to training PhD students, aiming to create new working/training cultures, build relationships with teams in industry and forge lasting links.

3.4.2 Marine energy

The UKERC research landscape report on ocean energy[29] notes that the level of investment in wave energy, which was high in the 1970s, was scaled down in the 1980s as a result of concerns about cost. Marine energy research in the 1980s was mostly university led but, since the 1990s, commercial device developers have begun to engage in marine energy R&D, developing and testing prototypes at various scales for both wave **and** tidal stream applications. Marine energy research has been predominantly been engineering focused. However, in recent years, there has been a growth in economic, social and environmental research relevant to marine energy.

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[27] http://ukerc.rl.ac.uk/Landscapes/Wind.pdf

[28] http://www.supergen-wind.org.uk/

[29] http://ukerc.rl.ac.uk/Landscapes/Marine.pdf

The UKERC report concludes that the UK has high capabilities in a wide range of marine energy areas and can be considered to be the world leader (Table 2). The table also suggests that the UK is strong in most areas of marine energy research with no areas of weakness. These strong research capabilities are complemented by relevant activities in other areas, such as electrical system design, grid connection, device installation and offshore engineering.

Environmental monitoring of marine devices was highlighted as an important growth area for the UK, with work being undertaken at a number of institutes and facilities including the: **SUPERGEN UK Centre for Marine Energy Research** (UKCMER), **Sea Mammal Research Unit, Scottish Association for Marine Science** and **Peninsula Research Institute for Marine Renewable Energy**. The report also highlights the UK's strengths with regards to testing and demonstrating facilities through University laboratories and testing tanks, as well as major marine testing facilities such as the **European Marine Energy Centre (EMEC)** and the **National Renewable Energy Centre (NAREC).**

Table 2: UK Marine Energy Research Capabilities

UK Capability	Area
High	Wave device development
	Tidal stream device development
	Electrical system design
	Tank and offshore testing
	Resource assessment
	Device installation
	Grid connection
	System demonstration
	Power train demonstration
	R&D
	Environmental monitoring
Medium	Manufacturing

Source: UKERC

The key marine research investment in the UK is the EPSRC funded marine SUPERGEN consortium, UKCMER, which is currently in its third funding phase.[30] There have also been a number of smaller funding initiatives, such as NERC's Marine Renewable Energy Research Programme.

3.5 Other

The LCICG TINA reports aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. These assessments focus on the UK's energy innovation chain as a whole and not just RCUK's activities.

The TINA for wind energy provides little detail on the UK's basic research capabilities but emphasises that UK research, development and demonstration (RD&D) wind energy programmes are leading edge in the field of offshore wind. It would take some time for major programmes in other countries to catch up with the UK.

The TINA on marine energy indicates that the UK possesses strong competitive advantage in nearly all areas with the exception of power off-take systems. This is attributed to a strong R&D base, leading device developers and experience accumulated in the offshore oil and gas and offshore wind industries.

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[30] http://www.supergen-marine.org.uk/drupal/

The UK's strengths in wind, wave and tidal energy, especially at the more applied end of the research spectrum, are likely to be reinforced by the recent establishment of the **Offshore Renewable Energy Catapult (ORE).**[31] The centre's aim is to support the identification, development and rapid commercialisation of innovative offshore technology solutions, by bringing together key stakeholders from industry, government and academia.

4 Existing roadmaps and innovation needs assessments

This section reviews existing roadmaps and innovation needs assessments relating to wind and marine energy. It highlights not only priority research challenges but also what resources or arrangements are needed to address these challenges.

4.1 Summary

This section highlights a number of common research challenges facing the marine and offshore wind energy sectors. There are engineering challenges around device and device component design. There are also technical questions that lie beyond the device-level, for example: improving device support structures; array installation; operation and maintenance; and grid integration. There are also environmental challenges relating to: resource characterisation; and device/array interaction with the natural environment, including environmental impacts on device performance and the health of the wider ecosystem. There are also social science questions relating to public engagement with wind, wave and tidal energy and potential social and economic impacts, both positive and negative.

The review identified a number of issues relating to the types of resources and arrangements required to deliver this research. These include: 1) testing facilities to undertake device development and demonstration; 2) the option of having a single innovation coordination body; 3) greater availability of 'real' data to facilitate further research; 4) stronger industrial and wider stakeholder engagement; and 5) stronger international research collaboration.

4.2 Wind energy

UK

A number of UK specific reports highlight priority wind energy research challenges, **for** both onshore and offshore applications. These include the LCICG's TINA for **Offshore Wind,**[32] the report of the UKERC **Wind Energy Research Road Mapping Meeting**[33] and Scottish Enterprise's **Offshore Wind Power: Priorities for R&D and Innovation**[34] and the UK Government's 2013 report **Offshore Wind Industrial Strategy Summary: Business and Government Action.**[35] These reports identify the following research challenges:

- **Device:**
  - novel support structures;
  - advanced drive train and device component research; and
  - high performance, lightweight blades through use of innovative materials and designs.

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[31] https://ore.catapult.org.uk/home

[32] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48279/4467-tina-offshore-wind-summary.pdf

[33] http://ukerc.rl.ac.uk/Roadmaps/Wind/UK_wind_research_road_map_publication_version.pdf

[34] http://www.scottish-enterprise.com/resources/reports/foresighting/offshore-wind-power-priorities.aspx

[35] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/226457/bis-13-1092ES-offshore-wind-industrial-strategy-summary.pdf

- **Arrays:**
    - array installation, operation and maintenance;
    - new vessels, float-out concepts and access systems for offshore turbine and support; and
    - remote controls to assess and manage the reliability, condition and performance of arrays.
- **Wind Energy Resource Assessment:**
    - modelling, measuring and monitoring of wake effects to improve yield of arrays; and
    - understanding the two-way causal interaction between wind arrays and the wider environment (e.g. seabed, waves, complex terrain, lower atmospheric boundary etc.).
- **System Integration:**
    - wind power plant capabilities (e.g. power quality, control, flexibility etc.);
    - design and infrastructure for grid integration (e.g. offshore HVDC networks);
    - wider grid system management (e.g. demand side management (DSM); and
    - short term power prediction/forecasting.
- **Wind Energy Policy:**
    - supply chain development;
    - incentives and tariffs;
    - cost benefit analysis;
    - capacity building via education and training;
    - improving knowledge transfer; and
    - planning that accommodates public attitudes.

A key theme that emerges regarding resources is the need for test and demonstration sites to support the commercialisation and deployment of innovative turbines, blades and foundations at both onshore and offshore locations. There was also a perceived need for a body capable of coordinating collaboration between industry, academic and public sector stakeholders. Finally, programmes could be established to coordinate and incentivise the collection and dissemination of wind energy technology testing data (e.g. turbine, foundations etc.) to facilitate further research and innovation at relatively low cost.

Europe

A number of research and training needs assessments have been conducted at the European level, including: the Offshore Renewable Energy Conversion platforms - Coordination Action (ORECCA) project's **European Offshore Renewable Energy Roadmap;**[36] the European Wind Energy Technology Platform's (EWETP) **Strategic Research Agenda: Market Deployment Strategy;**[37] European Renewable Energy Research Centres (EUREC) **Agency's Research priorities for renewable energy technology by 2020 and beyond;**[38] and the European Wind Energy Association's (EWEA) **The European Wind Initiative: Wind Power Research and Development to 2020.**[39]

The priority research areas identified in these reports are similar to those identified at the UK level. However, there is a stronger focus on the development of industry standards for wind energy, particularly in relation to testing, installation and health and safety. The European reports also identify research challenges specific to onshore wind, such as assessing wind resources within complex rural locations (e.g. forests) and urban environments, and how these resources might be best captured. There is also a call for research into more accurate forecasting techniques to predict wind output levels.

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[36] http://www.orecca.eu/c/document_library/get_file?uuid=1e696618-9425-4265-aaff-b15d72100862&groupId=10129

[37] http://www.windplatform.eu/fileadmin/ewetp_docs/Bibliography/SRA_MDS_July_2008.pdf

[38] http://www.energy.eu/publications/a06.pdf

[39] http://www.ewea.org/fileadmin/files/library/publications/reports/EWI_2013.pdf

Finally, the need to understand the adverse environmental impacts of wind power, especially offshore, and to identify solutions, is also identified.

International

At the international level, the IEA **Wind Implementing Agreement** produced the report **Long-Term Research and Development Needs for Wind Energy for the Time Frame 2012 to 2030.**[40] That report and the US National Renewable Energy Laboratory (NREL)[41] identify a set of research priorities similar to those identified at the UK and European levels. The IEA report does however have a greater focus on improving the social and environmental acceptability of wind energy.

4.3 Marine energy

UK

A number of UK specific reports highlight priority wind energy research challenges. The LCICG's **Marine Energy** TINA highlighted the following priority research areas:

- **Structure and prime mover:**
    - use of alternative materials;
    - manufacturing methods;
    - evolution of component level capabilities (e.g. high integrity tidal turbine blades); and
    - new and better design concepts and structural configurations.
- **Power take-off:**
    - improved yield through control systems; and
    - developing disruptive new technologies to advance approaches to drivetrain and power take-off systems.
- **Foundations and moorings:**
    - moorings and seabed structures require design optimisation to improve durability and robustness and reduce costs, particularly for deep water tidal; and
    - improved station-keeping technologies.
- **Connection:**
    - developing next generation cables, connectors and transformers, including using higher voltage high voltage alternative current (HVAC) or high voltage direct current (HVDC) and developing 'wet mate' connectors.
- **Installation:**
    - installation techniques including vessels that are suited for deeper water and large scale installations at lower costs.
- **Operation and Maintenance:**
    - improved lifecycle design;
    - access technologies;
    - retrieval rather than on-site intervention; and
    - remote monitoring.

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[40] http://www.ieawind.org/index_page_postings/100313/IEA%20Long%20Term%20R_D_Approved%20July%2023%202013.pdf

[41] http://www.nrel.gov/wind/offshore_wind.html

The **Marine Energy Technology Roadmap**[42] produced by UKERC and ETI identifies research challenges similar to those in the TINA. It also identified research needs relating to guidelines and standards for marine energy development and operation. It also recommended research into the development of tools capable of assessing the availability of marine energy resources, the performance of marine devices and their potential impacts on the wider environment. Other relevant documents include the House of Commons Energy and Climate Change Committee's report **The Future of Marine Renewables in the UK**[43] and the UKERC landscape report for **Ocean Energy.** [44]

A common theme is that the marine energy research landscape is currently too crowded and complex, creating the risk of overlaps and inefficiencies in the way the programmes are funded. Drawing on these reports, the following needs are identified:

- development of open-sea testing facilities for experimentation and demonstration purposes;
- feeding-back data and experience on prototype performance and operating experience into earlier phases of the innovation;
- drawing on lessons learnt from other energy industries, such as the offshore oil and gas industry;
- greater collaboration between industry and academia; and
- access to 'real' data from prototype deployments to verify resource models and design codes.

Europe

A number of research and training needs assessments have been conducted at the European level including ORECCA's **European Offshore Renewable Energy Roadmap** and EUREC's report **Research priorities for renewable energy technology by 2020 and beyond**. The challenges are broadly similar to those identified at the UK level. The EUREC report does however identify some specific challenges relating to wave **and** tidal energy technologies. These are:

- **Tidal:**
    - downscaling marine current resource atlases;
    - modelling water flow in channels and headlands;
    - modelling and measuring device performance; and
    - testing and developing new marine current devices.
- **Wave:**
    - developing short, medium and long time scale wave energy forecasting systems to better forecast electricity generation, as well as suitable operation and maintenance (O&M) timing and device protection;
    - advanced control techniques to optimise performance and reliability of single devices; and
    - wave propagation, including interaction between devices.

International

The Offshore Energy Research Association of Nova Scotia recently produced the report **Marine Renewables Energy Research Targeted Research Priorities.**[45] This report largely mirrors the priorities highlighted by the European and UK reports. However, it places greater emphasis on the need to monitor and optimise operational and life-cycle cost performance of turbines and related equipment. It

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[42] http://eti.co.uk/downloads/related_documents/ETI_UKERC_Roadmap.pdf
[43] http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/1624/1624.pdf
[44] http://ukerc.rl.ac.uk/Landscapes/Marine.pdf
[45] http://www.oera.ca/wp-content/uploads/2013/07/11-Tidal-Research-Programs-02-July-2013.pdf

also calls for additional research into the social and economic impacts of marine energy at the community, provincial and national levels.

The social and economic research focus is echoed in the International Network for Social Studies in Marine Energy's (ISSMER) report **Establishing an Agenda for Social Studies in Marine Renewable Energy: Research Priorities.**[46] The report identifies the following three priority research areas:

- **Values, community benefits, and public understanding:**
    - developing models for community benefit from marine renewable development;
    - minimising value conflict in the development of marine renewable energy projects; and
    - understanding the economic impacts of commercialisation of marine energy technology.
- **Consultation, communication, and knowledge flow:**
    - improving the process of consultation within consenting and planning processes.
- **Innovation, futures, uncertainty, and planning processes:**
    - integrating marine and terrestrial planning and regulatory processes within EU, national and regional frameworks and ensuring these are sensitive to present and (uncertain) future challenges and opportunities for marine energy development; and
    - understanding the drivers of innovation within the marine energy sector and translating this into economic development policy.

5 High-level research challenges

Drawing primarily on the outputs from the expert workshop on wind, wave and tidal energy, eight broad categories of priority research challenges were identified:

- device and array design;
- foundations and support structures;
- grid integration;
- system reliability;
- asset management;
- monitoring and mitigating environmental impacts;
- resource characterisation and assessment; and
- economic, social and governance factors.

The eight research themes are outlined in the following tables, with detailed research questions set out in Annex B.

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[46] https://ke.services.nerc.ac.uk/Marine/Members/Documents/Events%20section%20documents/ISSMER%20workshop.pdf

Table 3: Research challenges in the area of device and array design

Sub-Topic	Challenge	Notes
Device design	Step-change system (device) and sub-system (device component) innovation across wind, wave and tidal energy technologies	
	Improving power output of devices	wind turbines >6MW
	Improving the flexibility of devices	floating wind turbines
	Improving performance of devices	low speed tidal turbines, low and variable head tidal barrage turbines
Array design	'Whole-system' array design and operation	
	Validated software tools to model performance of marine energy arrays	
	Developing operation strategies to manage array faults	

Table 4: Research challenges in the area of foundations and support structures

Sub-Topic	Challenge	Notes
Foundations and support structures	Designing tools for reaction sub-systems that account for dynamic loads	
	Developing foundations for large offshore wind turbines	> 6 MW
	Cost-effective floating foundations for deep water	Depth > 50m

Table 5: Research challenges in the area of grid integration

Sub-Topic	Challenge	Notes
Grid integration	Engineering challenge of offshore wind, wave and tidal integration	
	Resource assessment to identify location and load of connection	
	Market and regulatory conditions to facilitate grid integration	
	Solutions to manage intermittency of wind, wave and tidal energy generation	DSM, energy storage, grid reinforcement
	Offshore grid connections as interconnector starting points	
	Component innovation to facilitate grid connection	cables, circuit breakers, transformers

Table 6: Research challenges in the area of system reliability

Sub-Topic	Challenge	Notes
System reliability	Whole-system reliability assessment and modelling of wind, wave and tidal energy system	component – device – array
	Duty cycle analysis of devices under standard and extreme loads	
	Assessing the future reliability of devices	
	Economic analysis of differing degrees of reliability	
	Improving reliability through use of innovative materials	light-weight, more durable
	Use of innovative control system to improve reliability	

Table 7: Research challenges in the area of asset management

Sub-Topic	Challenge	Notes
Asset management	Collecting and rapidly communicating high-quality device/array data to maximize performance via asset control	
	Short term power output forecasting	
	Automating asset data collection and interpretation	
	Device-to-array scale asset management	
	Assessing single device performance via array-scale modelling	
	Modelling future device performance	
	Verification of condition monitoring systems	
	Identifying key ancillary services and the best method and timing to provide these	

Table 3: Research challenges in the area of monitoring and mitigating environmental impacts

Sub-Topic	Challenge	Notes
Monitoring and mitigating environmental impacts	Holistic assessment of positive and negative environmental impacts of wind, wave and tidal energy generation on ecosystem	noise, turbulence etc.
	Identifying solutions to negative environmental impacts	
	Identifying environmental 'win-win' or 'lose-lose' scenarios	
	Understanding how environmental impacts change with scale of deployment	

Table 9: Research challenges in the area of resource characterisation and assessment

Sub-Topic	Challenge	Notes
Resource characterisation and assessment	Wind, wave and tidal energy resource characterisation and environmental condition monitoring via sensing to inform array/device design and location	
	Conditions that determine availability of wind, wave and tidal energy resource	climate, geography, device-device interaction
	Inter-relationships between energy resources	wind, wave and tidal etc.
	Assessing availability of future wind, wave and tidal energy resources	impact of climate change

Table 4: Research challenges in the area of economic, social and governance factors

Sub-Topic	Challenge	Notes
Economic, social and governance factors	Life Cycle Analysis (LCA) of impacts of wind, wave and tidal energy generation at multiple scales	environmental, cultural, societal, economic
	Understanding impacts of wind, wave and tidal energy on other sectors	fishing, leisure, transport
	Developing multi-constraint planning tools sensitive to these factors	
	Assessing the effectiveness of UK wind, wave and tidal energy policy	
	Assessing public attitudes towards wind, wave and tidal energy	
	Identifying public engagement approaches to foster support	

6 Research conduct

6.1 Ways of working

Interdisciplinarity. Inputs from a broad range of different research communities (e.g. engineering, geography, meteorology, and economics) will be required to address research challenges in this area. At present these communities do not collaborate sufficiently. Large-scale interdisciplinary research projects, designed via collaboration between the relevant Research Councils, e.g. EPSRC, NERC, and the Economic and Social Research Council (ESRC), could help to address this issue. Sharing of best practice in interdisciplinary research across the wind, wave and tidal energy research community could also prove valuable.

Level of research funding. The current level of RCUK research funding appears low given the potential role that wind, wave and tidal could play in the UK's energy future. This is especially true for wind energy research. However, the value of research into wave and tidal energy is closely aligned with prospects for commercial deployment and these should be kept under review.

Funding processes. Assessments of the quality of outputs from research supported by RCUK should be conducted with a view to informing future funding decisions. This would reverse the recent EPSRC decision not to require the submission of final award reports. Funding mechanisms should be set out and communicated appropriately to ensure that researchers understand how to engage. RCUK research funding should not become too applied at the expense of addressing the basic research challenges that still remain for wind, wave and tidal.

Consortium model. In general the SUPERGEN 'hub and challenge' model[47] was considered valuable by the community. However, a number of concerns were raised. The model does not provide core SUPERGEN partners with much influence over research funding. There is also concern about the time and resources spent on communication and networking within the SUPERGEN research team. More resources could be focused on communicating research impacts to potential users (e.g. policymakers). Funding could be made available within awards to support 'impact activities'. RCUK should ensure that there are opportunities for new partners to engage with SUPERGEN consortia.

Research coordination. Stronger research council integration and an improved institutional memory are essential to help avoid duplication of research funding. Whilst RCUK research coordination was welcomed, the community warned against over-managing the research agenda as this might stifle the work on more innovative, leading-edge research challenges. The establishment of a national centre for wind research could help to coordinate efforts across the wind energy research community.

6.2 Data

Central data repository. There is currently a wealth of publicly and privately funded research data that is not easily accessible to researchers. This data comes from test sites (e.g. NAREC) and operational arrays. There is a critical need to collect and curate all forms of data (e.g. device performance, reliability etc.) to facilitate research. Issues relating to the confidentiality and intellectual property (IP) of this data, for instance the anonymisation of data, will need to be addressed. Solutions will also be needed to address the practical and financial challenges associated with collating and storing so much data sourced from different parties. Lessons could be learnt from UKERC's data curation efforts. RCUK funded researchers should be required to make their data available via this

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[47] http://www.supergen-marine.org.uk/drupal/content/supergen-ukcmer#Structure

system as part of their funding requirements, an approach that is already being employed by ESRC and NERC.

Sensing technology. Collecting the necessary data to address wind, wave and tidal energy research challenges depends on the development of new *in situ* and remote sensing technology. Current technology is at or already beyond its limit in terms of resource characterisation and environmental impacts. Given the current size of the sensing technology market, it is unlikely that improved sensing technologies will emerge quickly. Regulation may be needed to help support the growth of this market. This is outside the remit of RCUK.

Methodologies. Modelling will play a key role in making sense of and manipulating wind, wave and tidal energy data (e.g. resource modelling). However, these models need to be validated using a range of experimental data (from laboratory to field trials), particularly if existing models are being restructured so that they are focused at the correct scale. Robust qualitative and quantitative methodologies are needed to process and 'make sense' of sensor data.

Stakeholder engagement. A broad range of stakeholders possess information that is particularly relevant to wind, wave and tidal energy research. For instance, the fishing industry has extensive knowledge of the resource characteristics of different marine areas. Drawing upon the experiences of such stakeholders could generate valuable data for wind, wave and tidal research.

6.3 Infrastructure and facilities

Access to large-scale test facilities such as test beds, wave tanks, wind tunnels and wind turbines is essential for future wind, wave and tidal energy research, particularly for the development of novel energy devices and device components. Existing private and public test facilities should continue to be mapped out through the UKERC landscape reports and any specific gaps in the portfolio should be highlighted. High-performance computational facilities will be essential to undertake resource modelling and integrated design of devices and arrays.

7 Training

PhD training. Interdisciplinary training is important given the cross-cutting nature of wind, wave and tidal energy research. Lessons could be learned from UKERC's interdisciplinary PhD studentship competition and PhD summer school. Interdisciplinary PhDs could be provided with more time to undertake their studies. There is a need for improved capabilities in computational fluid dynamics (CFD) and better integration with the **Metocean**[48] modelling capability.

CDT model. PhD training at the national level through CDTs provides an effective model. However, only a few universities have the critical mass of researchers and resources to house a CDT. A CDT 'hub' model could allow smaller universities to take on PhDs for specific projects.

Project studentship model. The CDT model should be complemented by PhD project studentships. However, efforts should be taken to ensure that PhDs are not employed as 'cheap' Research Assistants. Efforts could be made to attract greater financial support for training from industry. Lessons might be learned from the Edinburgh/Strathclyde/Exeter **Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE)** Engineering Doctorate (EngD) programme.

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[48] http://www.metocean.com/

8 Connections

8.1 Connections across research areas

The main connection is with the **Energy Infrastructure** topic (Prospectus Report 10) in respect of integrating wind, wave and tidal energy arrays into electricity transmission and distribution networks. There are also links to IEA energy research area **Energy Systems Analysis** (VII.1.1/VII.1.2) with respect to energy modelling and the social, economic and environmental impacts of energy.

8.2 Linkages outside RCUK

Joint-research funding. Joint-calls for research funding from both research councils and other R&D funding bodies, e.g. the Technology Strategy Board (TSB), could help to better integrate the academic and industry domains. This model has previously been employed under a joint NERC-TSB call supporting marine energy array technologies. Engaging industry will be important if industry is to take ownership of innovations generated via RCUK funded research and 'blue sky ideas' are to be translated into viable commercial propositions. This is particularly relevant for marine energy, where some large original equipment manufacturers (OEMs) are beginning to enter the market. To encourage this, industry should be made aware of the benefits of research collaboration, particularly in relation to skills, experience and expertise. Innovative energy business models that make time for their employees to engage in cutting-edge research could also help to facilitate industry engagement with research.

Innovation coordination. At present there is inadequate coordination of efforts made by the research councils and other R&D funding bodies. The effectiveness of current organisations (e.g. UKERC) in terms of coordinating should be reviewed and any weaknesses might be addressed through restructuring or establishing new bodies.

EngD CDTs. Centres such as **IDCORE** have played an important role in promoting academic-industrial research collaboration via the provision of jointly funded EngDs. This model could be replicated, particularly in the marine sector. However, care should be taken to ensure that industry fulfils its training responsibilities.

Knowledge exchange. Communicating wind, wave and tidal energy research findings via knowledge exchange mechanisms is essential to ensure that government and industry are well-informed.

8.3 International working

The UK wind, wave and tidal energy community needs to work more closely with European partners in collaborative networks, such as the European Energy Research Alliance (EERA), to ensure that research is not duplicated and that resources are shared to facilitate higher quality research. Additional incentives/resources could be made available to researchers to engage at the European level, for example by supporting travel to EERA meetings. The European Academy of Wind Energy has helped to coordinate international wind energy research and a similar organisation for marine energy could prove valuable. Opportunities also exist to promote international working through the SUPERGEN hubs which could act as an interface with researchers in other countries. UKCMER has already taken some such steps, engaging with marine research initiatives in the US, Canada, Chile, Taiwan, China and India.

8.4 Other issues

The offshore wind and marine energy sectors face some common challenges, as set out in Sections 4 and 5. However, researchers marine and wind energy differ in a number of respects. They should be considered jointly in a research context only where there is genuine overlap.

9 Conclusions and recommendations

Wind, wave and tidal accounts for a small percentage of the UK's electricity generation. Wind is the most mature of the technologies, contributing over 5% of the UK's electricity generation in 2012, the majority of it generated onshore. Marine renewables meet a negligible proportion of the UK's electricity generation needs.

Investment in offshore wind is proceeding rapidly and it is likely to account for a larger share of generation than onshore wind in the near future. There has been little commercial investment so far in wave and tidal energy technologies which are much less mature. However, some major companies have recently invested in tidal current technology, suggesting that it holds commercial promise.

There is a large degree of uncertainty as to the role of wind, wave and tidal technologies in the future generation mix. Whilst wind energy, particularly offshore, is expected to play the most important role over the coming years, this will largely be driven by public policy. The future for marine energy is less certain. The TINA on marine energy sees a very wide range of potential deployment by 2050, with near zero deployment being possible. Past projections of marine energy deployment, especially for wave technology, have proved to be over-optimistic. The value of research into wave and tidal energy is closely aligned with its prospects for commercial deployment and it is important to keep these under review.

The priority research areas fall into eight categories: **device and array design; foundations and support structures; grid integration; system reliability; asset management; monitoring and mitigating environmental impacts; resource characterisation and assessment;** and **economic, social and governance factors.** The first four categories have a strong technology and engineering focus, concerned with improving the performance of technologies at multiple scales, e.g. device components, devices, device 'fixings', arrays and grid integration. **Asset management** focuses on maximising performance via appropriate management. **Monitoring and environmental impacts** examines how the deployment of technologies will impact ecosystem, either positively or negatively, and how any negative impacts maybe avoided. **Resource assessment** is concerned with assessing the extent and distribution of wind, wave and tidal resources in the UK at various spatial and temporal scales. Finally, the last category underlines the importance of research into the governance and planning of wind, wave and tidal development, and the associated economic and social factors.

The offshore wind and marine energy sectors face some common research challenges. However, there are also many important differences. Therefore, they should be considered jointly in a research context only when there are genuine overlaps.

Research challenges in the wind, wave and tidal energy area are generally 'application-inspired' rather than 'science-inspired'. Consequently, close linkages between the research councils and innovation bodies such as TSB and ETI are essential and could be nurtured via joint-funding calls (e.g. NERC-TSB), knowledge exchange networks or possibly establishing a central organisation responsible for coordinating such collaboration. Wind, wave and tidal research also demands an interdisciplinary approach, which would benefit from greater coordination between the research councils, for example through joint research calls. International collaboration via collaborative networks (e.g. EERA) will also play a key role in facilitating high quality research. Making resources available to utilise these networks and using research consortia as the interface for exchange could help to support international engagement.

There is a critical need for access to large-scale test facilities such as test beds, wave tanks, wind tunnels, and wind turbines, as well as high-performance computational facilities. Data from wind, wave and tidal research should be curated centrally and disseminated to maximise research opportunities.

Attention should however being paid to confidentiality and commercial sensitivity. The development of new *in situ* and remote sensing technology would assist as current technology is at or beyond its limit in terms of resource characterisation and environmental impacts. Regulation may be needed to help support the growth of this market, however this is outside the remit of RCUK.

The report identifies the need for PhD training via both CDT and project-based funding models, some of which should be interdisciplinary in nature. Industrial PhD support could also provide PhD students with a richer learning experience, as well as helping to foster academic-industry collaboration.

Annex A: Research needs

The following section expands upon the priority research challenges identified in Section 5, as identified from the outputs of the expert workshop. These have been grouped in the same categories and where possible have been framed as specific research questions.

A.1 Device and array design

A.1.1 Device

- Facilitate step-change innovations at both the device and device component scale (e.g. power take-off) via the development of novel technologies, materials etc.
- Developing larger, cost optimised wind turbines (>6MW).
- Developing floating platform wind turbines.
- Developing low speed turbine design to harness tidal ocean current.
- Developing low head and variable head turbines for tidal barrage.

A.1.2 Array

- Whole system array design and operation using integrated control systems and multi-constraint planning tools that account for factors such as wake effects, power output forecasts for different technologies etc.
- Validated software tools that model performance and behaviour of arrays of tidal and wave devices, similar to those for wind.
- Developing array control strategies to manage system faults.

A.2 Foundations and support structures

- Developing validated, integrated design tools for reaction sub-systems (e.g. foundations and support structures) that account for dynamic loading from the wind, wave and tidal device.
- Developing foundations for larger offshore wind turbines (>6 MW).
- Developing floating foundations for water depths greater than 50m.
- Developing cost effective moorings and foundations for wave and tidal technologies, especially in deep water.

A.3 Grid integration

- Integrating offshore wind, wave and tidal arrays with the national grid, factoring in cables, transmission system, storage facilities, HVDC etc.
- Resource assessment to establish where and how arrays and connectors will need to be deployed.
- Manage intermittency of wind, wave and tidal energy to maintain electricity network balancing via a combination of DSM, storage technologies, network planning, grid reinforcement and utilisation of conventional generation technologies.
- Assess potential for offshore connectors to be utilised as interconnectors with other countries.
- Technological innovation to make grid connection easier, such as increasing the power output of cables, improving direct current (DC) circuit breakers and siting transformers in extreme offshore conditions.

A.4 System reliability

- Whole-system reliability analysis, accounting for component, device and array scales.
- Produce verified 'resource to wire' device models that capture everything from the wind/marine resource to electricity generation and transmission.
- Improve our understanding of the duty cycles for testing turbines under standard operation as well as extreme loads.
- Economic analysis of current and projected offshore reliability levels to understand how reliable a device/array must be to be commercially viable, i.e. the economic implications of reliability.
- Assessing the future reliability of devices via 'accelerated life' testing procedures.
- Improving reliability of devices via the light-weighting of materials or use of new materials.
- Developing models that reduce dependence on component/device field trials to assess reliability.
- Exploring innovative control systems to improve reliability.

A.5 Asset management

- Collecting sufficiently high quality data from offshore sites (wind/marine) and transferring this quickly enough to operate them as efficiently as possible.
- Short term forecasting of the power output from wind, wave and tidal arrays.
- Automatic data collection and interpretation to assess condition of array.
- Developing O&M management strategies at both the micro (device) and macro (array) scales.
- To what extent can you ascertain the performance of individual devices via the modelling of groups/arrays of devices?
- Anticipating failures for components/groups of components within devices via data analysis.
- Verification of condition monitoring systems via quantification of condition monitoring performance.
- Identifying key ancillary services for wind, wave and tidal energy and the best way to provide these. For example, taking advantage of weather windows for device repair or recovery.

A.6 Monitoring and mitigating environmental impacts

- Monitoring and modelling single and cumulative environmental impacts of offshore wind, wave and tidal technologies, such as noise and turbulence impacts on fauna.
- Identifying solutions to mitigate negative environmental impacts.
- Do positive feedback mechanisms exist that have either negative or positive implications for ecosystem services? Are there any environmental win-wins?
- Building a more holistic understanding of the environmental impacts of wind, wave and tidal energy generation.
- Exploring the impacts of wind, wave and tidal energy on all species, not just iconic/priority species.
- How do the environmental impacts of wind, wave and tidal energy devices/arrays change with the scale of their deployment?

A.7 Resource characterisation and assessment

- Characterising resources and environmental conditions pre- and post-energy extraction to help inform the device/array design (e.g. turbulence).
- Automated and integrated sensing, across different spatial and temporal scales, to facilitate wind, wave and tidal resource characterisation.
- Assessing how climatic and geographical factors, as well as device-device or array-array interactions, affect the availability of wind, wave and tidal energy resources.

- How will climate change influence wind, wave and tidal energy resources in the UK?
- How do different meteorological patterns influence the level of tidal energy resources and what are the implications for tidal energy system performance?
- How do wind, wave and tidal resources impact one another and how might this be managed as part of an energy system portfolio to maximize efficiency?

A.8 Economic, social and governance factors

- Whole life-cycle assessment of environmental, cultural, societal and economic impacts of wind, wave and tidal energy generation at multiple scales? What are the trade-offs?
- How does wind, wave and tidal energy generation impact upon other marine sectors, e.g. fishing and transport?
- What are the trade-offs associated with the intermittency of wind, wave and tidal energy, for example in terms of market price of electricity?
- Developing multi-constraint planning tools that are sensitive to environmental, economic and social implications of wind, wave and tidal energy generation.
- Assessing whether government interventions support or hinder wind, wave and tidal energy innovation. For example, market signals, land-use planning and energy pricing?
- What market and regulatory conditions will help facilitate wind, wave and tidal grid connection?
- What is the public's attitude towards wind, wave and tidal energy? How acceptable is it to the public?
- Which methods for public engagement might improve public attitudes towards wind, wave and tidal?

Annex B: Process for developing the prospectus

This Energy Research and Training Prospectus Report has been developed under the auspices of the RCUK Energy Strategy Fellowship which was established in April 2013. Fellowship activities leading the production of the Prospectus have gone through three phases.

Phase I (Spring – Summer 2012), **the scoping phase,** involved a comprehensive review of relevant energy roadmaps, pathways and scenario exercises in order to provide a framework for possible UK energy futures. Extensive consultation with stakeholders across the energy landscape was carried out in order to encourage buy-in and establish clearly the boundaries and links between the RCUK Prospectus and other products related more to deployment. One conclusion arising from the consultations was that linkage should be sought across the energy research domain and that consequently related topics linked by underlying research skills should be covered in single workshops during Phase II.

Phase II (Autumn 2012 – Summer 2013), **the evidence-gathering phase,** relied heavily on workshops bringing the research community and stakeholders together round specific topics. Three 'strategic' workshops on **Energy Strategies and Energy Research Needs, The Role of Social Science, Environmental Science and Economics**, and **The Research Councils and the Energy Innovation Landscape** were held October 2012 – February 2013. Six expert residential workshops on **Fossil Fuels and CCS, Energy in the Home and Workplace, Energy Infrastructure, Bioenergy, Transport Energy** and **Electrochemical Energy Technologies** were held January - June 2013. In addition, 'light-touch' activities were conducted in respect of: **Industrial Energy; Wind, Wave and Tide**; and **Nuclear Fission**. A final strategic level 'synthesis' workshop was held in July 2013. During Phase II, reports on each of these workshops were prepared and web-published following comments from participants.

During Phase III (Summer- Autumn 2013), **the synthesis stage,** the workshops reports were 'mined' and combined with contextual information to produce the Prospects Reports which were put out for peer review. The Prospectus, including a hard-copy Synthesis Report, was launched in November 2013.

Annex C: List of prospectus reports

No 1	Investing in a brighter energy future: energy research and training prospectus
No 2	Industrial energy demand
No 3	Energy in the home and workplace
No 4	Transport energy
No 5	Fossil fuels and carbon capture and storage
No 6	Electrochemical energy technologies and storage
No 7	Wind, wave and tidal energy
No 8	Bioenergy
No 9	Nuclear fission
No 10	Energy infrastructure