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TOPICAL REVIEW

UK perspective research landscape for offshore renewable energy and its role in delivering Net Zero

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Abstract

This paper sets out the role of offshore renewable energy (ORE) in UK targets for Net Zero greenhouse gas emissions by 2050 and provides a review of the research challenges that face the sector as it grows to meet these targets. The research challenges are set out in a Research Landscape that was established by the ORE Supergen Hub following extensive consultation with the ORE community. The challenges are divided into eight themes, each challenge is described, and current progress is summarised. The progress of the ORE sector in recent years has seen huge cost reductions, which have encouraged the great ambition for the sector seen in UK Government targets. However, in order to meet these critical targets and achieve Net Zero, further innovations and novel technologies will be needed and at pace, driven forward by new research and innovation. The strategy of the Supergen ORE Hub in framing the research and innovation activities within a community-developed research landscape and working together across disciplines and with close collaboration between academia and industry is a necessary component in achieving the ambition of sustainable energy generation.

1. Introduction

In the year of and following the UK's presidency of the UN Climate Change Conference, COP26, momentum is growing towards delivery of Net Zero greenhouse gas emissions in the UK and globally. The UK Climate Change Committee's Sixth Carbon Budget (CCC 2020) identifies a pathway for completely decarbonising electricity by 2035, despite electrification of the energy system as a whole requiring greater volumes of electricity supply. Decarbonisation of the electricity supply is to be achieved by phasing out unabated fossil fuel generation and significantly increasing renewable generation.

In 1990, renewables generated just 1% of the UK's electricity supply. Twenty years later in 2010, this had risen to over 6% (Johnstone *et al* 2020) and in 2020 accounted for 43.1% of the electricity generated in the UK (BEIS 2021). This transition has mostly been driven by an increase in offshore wind generation and a significant decrease in coal use (Allan *et al* 2020). As the UK's favoured renewable electricity generation technology, offshore wind is supported by policies for the coming decade as part of the Offshore Wind Sector Deal (Allan *et al* 2020). This set a target of 30 GW of offshore wind capacity by 2030. This target has since been superseded by the UK Government's Energy White Paper (HM Government 2022), which increases the target to 40 GW, representing a fourfold increase compared to the 10 GW of installed capacity in 2021. The White Paper also commits the Government to running further Contracts for Difference (CfD) auctions that are open to a range of renewable generation technologies including offshore wind, wave and tidal energy, onshore wind and solar photovoltaics, etc. In the British Energy Security Strategy (HM Government 2022) published in April 2022, the offshore wind target is increased again to 50 GW by 2030, including up to 5 GW of innovative floating wind.

The scenarios envisaged for Net Zero in 2050 are even more ambitious, with projections in the Sixth Carbon Budget ranging from 75 GW to 140 GW of offshore wind (or offshore renewables) (CCC 2020). Even greater installed capacities exceeding 200 GW are predicted in other scenarios, linked to the growth of the hydrogen economy with offshore generation (OWIC/ORE Catapult 2020). To meet this tenfold increase in offshore renewable energy (ORE) capacity in less than 40 years will require significant innovation to be achieved to reduce costs, speed up project development and better understand environmental constraints. The UK's waters host a growing ORE industry, alongside other industry sectors, a range of valuable ecosystems essential to biodiversity and fisheries as well as major international trade and transport routes. Economic and environmental success are intertwined, as shown in the 2021 Dasgupta review of the economics of biodiversity (HM Treasury 2021).

In this paper, we give a short introduction to the role of ORE in achieving the UK's Net Zero targets and the need for research and innovation in the sector. The Supergen ORE Hub is introduced and its function as a key structure to help connect, coordinate, support and inspire the UK ORE research community. The remainder of the paper gives a description of the research landscape of ORE and a review of the research challenges within each theme. A list of active research projects organised by research theme is given in the appendix.

2. The role of ORE in the UK's Net Zero plans

The Sixth Carbon Budget set out a Balanced Pathway to Net Zero recommended by the Committee for Climate Change (CCC 2020) that will achieve full decarbonisation of the power sector, full switchover to electric vehicle sales and installation of low-carbon heating by 2037. Electricity demand is expected to double from current levels by 2050, reflecting electrification of sectors across the economy (HM Government 2022). With over 60% of the necessary reduction to Net Zero to be achieved in the coming 15 years and the fastest rate of decarbonisation occurring in the early 2030s, the key challenge in the next decade is to scale up investment, markets and supply chains to enable all new energy generation to be zero-carbon by the early 2030s.

Under the Balanced Pathway, variable renewables reach 60% of generation by 2030, 70% by 2035, and 80% by 2050. This generation allows new electricity demands to be met with minimal emissions and at low cost. Offshore wind is the backbone of the system, providing 265 TWh of generation in 2035 and 430 TWh in 2050. To reach this target requires deploying 3 GW of new offshore wind capacity each year, plus repowering of older sites as they reach the end of their (25–30 year) operating lives. Based on recent wind turbine generator (WTG) sizes, 3 GW yr^{-1} corresponds to a new wind turbine installed every weekday, nearly double the new capacity of 1.8 GW installed in 2019; thus, rapid acceleration of the industry is needed (The Crown Estate 2019). It should be noted that turbine sizes continue to increase, with new projects under development in 2022 using WTGs of 12–14 MW and greater. This expansion will cover new geographical regions, reducing the dependence on local wind conditions and helping to provide a more stable supply. However, it will rely on sites that are further from shore in deeper waters and off new coastal regions where ports and grid connections require development.

A more flexible electricity system is needed to balance out the variability in renewable generation, both from demand (e.g. demand-side responsiveness, and use of surplus renewable generation to produce hydrogen) and supply (e.g. use of electricity storage). In addition, tidal and wave technologies have an important role to play in providing predictable power into a variable renewables-driven system, adding resilience into the overall renewable energy generation system, and both have scope for upscaling (Coles *et al* 2021, Jin and Greaves 2021).

3. Current status of ORE

The UK previously led the world in terms of installed capacity of offshore wind and reached 12.3 GW of installed capacity by the end of 2021. However, China overtook the UK during 2021, and installed 12.7 GW of capacity in that year alone. China now has 19.7 GW of installed capacity. This represents 41% of the global total of 48.2 GW, with the UK's capacity representing 26% (WFO 2022).

Already, offshore wind powers the equivalent of 4.5 million UK homes annually, generating over 10% of UK electricity in 2020, when 10 GW of capacity was in operation. The Crown Estate for England and Wales has already leased seabed rights for 45 GW of offshore wind (Round 4—June 2021), and Crown Estate Scotland (ScotWind) leased an additional 25 GW in January 2022.

This existing leasing is sufficient to meet the Government target of reaching 40 GW of offshore wind by 2030, which is expected to be met by installation of approximately 3000 new turbines of 10 MW and greater capacity added to the current fleet of 2400 smaller capacity turbines. In deeper waters, particularly across the SoctWind leases, floating offshore wind turbines will be deployed. This technology, and the greater water depth and distance from shore, reduces the constraints associated with other marine users but will introduce new technologies and supply chain requirements. The cost of new fixed offshore wind has fallen by over 50% since 2015 and it is now one of the lowest cost options for new power in the UK—cheaper than new gas and nuclear power. However, floating wind remains more costly than fixed.

Wave and tidal development is less advanced than offshore wind, but there is huge potential and considerable activity in the UK, with approximately 50 wave and tidal stream developers being based in the UK. There are over 1 GW of leased tidal stream sites in the UK, with over 800 MW of sites in development in English, Welsh, and Scottish waters, and over 40 GWh of marine energy generation have been recorded. The UK holds 35% of Europe's wave resource and 50% of its tidal resource and it is estimated that up to 20% of UK energy demand could be met by marine energy (Coles *et al* 2021, Jin and Greaves 2021). The UK marine energy sector has a high level of UK content (80%–95%), generating economic and social benefits (Cochrane *et al* 2021) and leading innovation.

4. Challenges to ORE deployment

A major challenge facing the ORE sector is the speed and extent of deployment needed to meet Net Zero targets, which require deploying 40 GW of installed offshore wind capacity by 2030 and up to 140 GW by 2050. This ambitious development trajectory needs to take into account supply chain considerations, project development timescales and the need to increase the pace of deployment. Offshore wind project development is subject to a range of constraints, including seabed availability, wildlife impacts and radar interference, and increased deployment requires the use of less ideal sites with deeper water further from shore.

Securing of new seabed leases requires several years as projects need to undergo pre-development planning, consenting applications, and construction. Accordingly, the UK will need to accelerate the rate of leasing to foreshadow the acceleration of construction and provide clarity to developers. Deploying offshore wind at very high levels could result in changes of ecosystems and hence the cumulative environmental impacts need to be considered. Increased use of autonomous technologies for environmental monitoring could help close critical knowledge gaps of these impacts. Furthermore, governance of energy networks for offshore renewables will need to be increasingly coordinated as deployment levels increase, due to the growth in the proportion of variable generation. Tidal and wave technologies could provide predictable power to a variable renewables-driven system, but costs need to reduce substantially for widespread deployment.

5. The Supergen ORE Hub Research Landscape

The £9 million Supergen ORE Hub funded by UKRI was set up in 2018 to provide research leadership and to help accelerate the development of the ORE sector, and full activities of the Supergen ORE Hub can be found on its website: https://supergen-ore.net/.

The strategy and priorities for the Supergen ORE Hub were established through extensive sector consultation. In a series of three workshops in 2017, over 200 ORE specialists representing academic, industrial practitioners, non government organisation (NGOs) and policy makers stakeholder groups provided their input. This process initially investigated the needs of Marine Energy (wave and tidal) and Offshore Wind separately, recognising their different stages of development and maturity. After analysis of the findings from each of these, the third workshop brought together the two previously separate communities, investigating where the common research challenges for both could be found. The process produced an agreed set of research challenges and innovation priorities that make up the Research Landscape for the Supergen ORE Hub.

The Supergen ORE Hub research is also informed by and contributes to international research agendas in ORE through collaborative activities. In the EU, technology development and research activities, including research funding schemes are mainly guided by the Strategic Research and Innovation Agenda (SRIA) for Ocean Energy (ETIP Ocean 2020) and the ETIP Wind Roadmap (ETIP Wind 2019). The main challenges identified in SRIA for ocean energy are (a) Design and validation of ocean energy devices (b) Foundations, connections and mooring (c) Logistics and marine operations (d) Integration in the energy system (e) Data collection & analysis and modelling tools (f) Cross-cutting challenges. For the wind sector, the five research and innovation priorities are (a) Grid & System Integration (b) Operations and maintenance (c) Next generation technologies (d) Offshore Balance of Plant (e) Floating Wind, with crosscutting areas of digitalisation, electrification, industrialisation, and human resources.

In 2020, ocean energy received a total of €28.7 m public funding from EU member states, where out of a total of 141 projects, 110 projects are focused in wave and tidal. There were 82 wave projects (58% of total projects) and 28 tidal projects (20% of total projects), providing support to Ocean Energy implementation in line with the SET Plan (Ocean SET 2022). For offshore wind, there is a target of €1090 million to be invested in research and innovation for the offshore sector to 2030 (SETWind 2022).

In the US, support for research and innovation in ORE is organised through the US Department of Energy's Wind Energy Technologies Office (WETO) for wind technology and the US Department of Energy's Water Power Technologies Office (WPTO) for marine energy technology, including wave and tidal. WETO funds research nationwide to enable the development and deployment of offshore wind technologies with a focus on key barriers to offshore wind development, including the relatively high cost of energy, the mitigation of environmental impacts, the technical challenges of project installation, and grid interconnection. The national offshore wind R&D consortium has been established to address near-term needs for the development of the U.S. offshore wind industry through wind plant technology advancement, wind resource and physical site characterization, and installation, operations and maintenance, and supply chain technology solutions (US Department of Energy 2022a).

WPTO's focus encompasses enabling research, development, and testing of emerging technologies to advance marine energy as well as next generation hydropower and pumped storage systems for a flexible, reliable grid. A programme of transformative research and development and demonstration efforts are supported to advance the development of reliable, cost-effective marine energy technologies and reduce barriers to testing these devices. The program comprises four core R&D activity areas that follow a strategic approach to addressing the challenges facing US marine energy stakeholders: high costs and lengthy permitting processes associated with in-water testing (US Department of Energy 2022b).

The Supergen ORE Hub Research Landscape, as illustrated in figure 1, summarises the research needs in ORE and is accessible through the interactive web-based landscape tool (https://landscape.supergen-ore.net/), which assembles and disseminates the full range of UK-based offshore wind, wave, and tidal energy research. The Research Landscape enables industry, government, and researchers to share opportunities and challenges across eight research themes (A)–(H). This landscape is a living resource, updated in response to new submissions and further review by the Supergen ORE Hub.

The Supergen ORE Hub, through its core research programme and flexible funding calls, is taking a strategic approach to tackling these challenges. Also, the challenges are used to advise UKRI on research direction. The following sections describe the research challenges within each theme.

5.1. Theme A: resource and environment characterisation

5.1.1. A1. Better measurement techniques for forecasting and resource characterisation

The measured metocean data includes wind, wave and current data, and measurements such as velocity, wave elevation and turbulence. It is essential to have access to high quality data to assess the offshore energy resource, plan the ORE farm, optimise ORE device performance and reduce the levelised cost of energy (LCoE). The generally applied methods for resource measurement include wave gauges, laser altimeters, pressure sensors, wave rider buoys, acoustic Doppler current profilers (ADCP), radar system (such as high frequency (HF) radar and X-band radar) and satellite-borne remote sensors (such as radar altimeter and synthetic aperture radar, SAR) for wave measurement; ADCPs, HF radar (Lopez *et al* 2015) and SAR for tidal measurement (Palodichuk *et al* 2013) with ADCPs also having a dual use in monitoring fish activity (Dunn and Zedel 2022); wind vanes, wind-cup anemometers, sonic detection and ranging and light detection and ranging (LIDAR) for wind measurements; and autonomous drones for bathymetry measurements (Widén *et al* 2015).

However, existing methods for measuring waves and currents are expensive and it can be difficult to achieve a continuous measurement record from offshore deployments of measurement instruments (Smith *et al* 2013). Also, the measurements are limited by a single point, or sparse locations in the open sea (Glenn *et al* 2000). This causes uncertainty in the potential energy resource estimation, the loading on devices and the weather windows for offshore operations. Remote measurement methods (like satellites and HF radars) show potential as be good alternatives to offer continuous and dense data if the cost can be reduced and methods made more reliable, and autonomous systems also offer new possibilities for resource measurement.

New methods for measurement of combinations of wind, wave, water level and current and for analysis of extreme combinations are needed to allow better prediction of the available ORE, better design and operation of ORE systems, and lower human risk associated with offshore operations. Therefore, within this research challenge it is recommended that better, more reliable and lower cost measurement techniques are needed to measure all forms of physical offshore environment data, to consider the influence of land and accessibility, and to extrapolate extreme events, resource variations in time and space, bathymetry and other factors. Ongoing and recent projects related to Theme A1 are given in table A1 of the appendix.

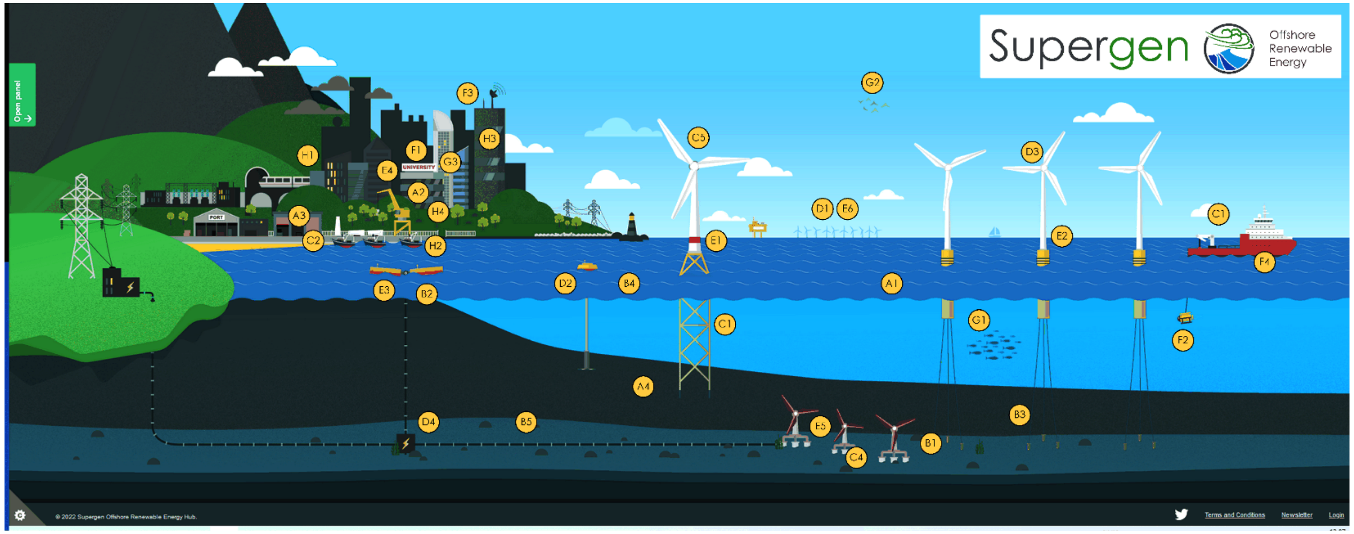

Figure 1. Supergen ORE Hub Research Landscape for ORE, which shares opportunities and challenges across eight research themes (A)–(H). The interactive web-based landscape tool is available at https://landscape.supergen-ore.net/. Reproduced from Supergen ORE Hub. © 2022 Supergen Offshore Renewable Energy Hub.

5.1.2. A2. Improved modelling tools for resource and loading assessment

Numerical modelling tools such as ROMS, OpenFast, SWAN, WAMIT, SPH, RANS CFD etc, are generally used to model waves, currents, wind and their interactions with ORE structures (Venugopal *et al* 2014). However, the existing models tend to have very simplistic representation of the turbine or wave energy device, lack the full wind-wave-current coupled environment interaction with the ORE structures and the effect of ORE development on the environment (Otter *et al* 2021). Also, conventional representations for responses of ORE single devices and of wind, wave and tidal farms are generally linear, which ignore the non-linearities that may be indispensable under extreme conditions or array interactions. Thus, existing models for predicting ORE resources and extreme loading on ORE facilities can be unreliable, particularly when extrapolating to extreme conditions, new regions, or when modelling new types of device or system.

Therefore, it is recommended that improved or further developed models are needed for designing ORE systems under the full range of conditions, particularly frontier farm developments and new device design. The main suggestions are that: (a) new models are needed that include multi-scale farm-resource interaction and allow the effect of the environment on the ORE structures to be modelled as well as the effect of the ORE farm on the environment; (b) existing models for wind resource modelling need to be adapted to include the motion responses of floating offshore wind structures and the presence of future very large farms (Christiansen *et al* 2022); (c) existing models for wave resource modelling need to be expanded to consider extreme load conditions; (d) better representation of ordinary and extreme onsite conditions and wakes are needed in wind and tidal turbine modelling, and better understanding of the interaction and coupling between device, array and farm scales of models (Zhang and Zhao 2021); (e) better ways to represent wind, wave and tidal farms will help to raise the survivability and reliability of ORE systems; (f) integration with ecological modelling and with sediment dynamics models is needed to understand the environmental impact; (Dorrell *et al* 2022); (g) fully-integrated and high-fidelity models considering ORE performance, survivability, reliability, environmental effect and LCoE will be needed, leading to efficient predictions of the ORE structures. Table A1 in the appendix summarises the ongoing and recent projects related to Theme A2.

Recent research using machine learning (ML) methods to predict how energy is transferred from the wind, dissipated, and transferred spatially across the ocean with significantly reduced data input and computational power has developed a surrogate model for wave resource estimation (Chen *et al* 2021). By incorporating *in-situ* buoy observations, outputs were found to match observations more closely than the corresponding Simulating WAves Nearshore (SWAN) numerical model and considerable reduced computational cost. This new technique could provide an important enhancement of existing physics-based wave model approaches.

5.1.3. A3. Resource and environmental characterisation in physical modelling facilities

Designing for offshore conditions requires detailed analysis of the impact of wind, waves, currents and turbulence on the loads and performance of ORE devices. Numerical modelling can inform certain design aspects, but this needs to be supported and validated by controlled and repeatable laboratory testing. This testing provides data that represents regular and extreme loading, device performance and survivability. Testing in wave basins and wind tunnels is particularly useful where complex or coupled effects are present, such as turbulence or wind and waves. However, this testing is always performed at reduced geometric scale and there can be challenges with reproducing and then characterising the field conditions in the laboratory facility (Davey *et al* 2021).

Therefore, this research challenge recommends that (a) laboratory facilities increase the realism of their simulations and provide tools for device developers to allow accurate assessments of blade and component life for a range of deployment locations and improve both design and operation and maintenance strategies to advance the industry under model scale; (b) new techniques are needed allowing complex aspects of the ocean environment to be modelled in the laboratory, such as combined wave—current characteristics, turbulence parameters, and combinations of wind, wave and current (Togneri *et al* 2021); and (c) techniques to demonstrate hostile and extreme conditions at significant laboratory scale with high quality are needed. Projects relating to theme are summarised in table A1 of the appendix.

5.1.4. A4. Long-term sediment transport measurement and modelling

The mobility of the seabed through sediment transport can affect ORE facilities. Scour management is often required around seabed structures and sediment transport can also affect cable integrity (Zou and Hu 2021). In shallow estuaries, the change in flow from tidal energy facilities can create sediment morphological change. These sediment transport phenomena can affect the function of ORE systems and can also impact on habitat and ecosystems (Auguste *et al* 2021). However, if the changes to water flow, sediment and habitat can be predicted, confidence in design and social acceptability will be raised.

To advance this research challenge, it is recommended that (a) better understanding of these sediment transport phenomena, through accurate models validated by field observations is needed to help to ensure that sediment transport processes associated with ORE systems do not cause adverse effects to those systems or the environment; (b) reliable multiscale methods—which work at region and farm scale, as well as local to structures—are needed to predict changes in bathymetry, sediments and habitat, validated by field surveys; (c) morphological change in tidal races, tidal estuaries and the open ocean needs to be well understood. Table A1 in the appendix summarises the ongoing and recent projects related to Theme A4.

5.2. Theme B: fluid-structure-seabed interaction

5.2.1. B1. Realistic fluid-structure-seabed design tools that work together, not in isolation

Design tools are used to predict how structures interact with the sea and the seabed, to test and improve designs (Day *et al* 2015, Villate *et al* 2020). The current generation of simulation tools generally focus on one aspect—aerodynamics, hydrodynamics, structural dynamics or geotechnics—with simplified exchanges of data between them, meaning conservative simplifications must be made. Additionally, there is a need to reduce the time required for the design process, and eliminate unnecessary conservatism where it exists, so that ORE systems can be optimised and made more efficient. Improving and coupling existing models will eliminate simplifications and lead to more efficient ORE designs, lower LCoE and more investments (Kwa *et al* 2021, Dehtyriov *et al* 2021).

Therefore, in order to tackle this research challenge, more accurate and efficient whole-systems design models are needed. This requires multi-disciplinary approaches, and careful attention to the interfaces between each engineering system and discipline. Research effort is often focused on improving the fidelity of simulations and adding additional phenomena. However, equal value may emerge from streamlining analyses to focus only on critical elements, and therefore allow analysis elements to be coupled—allowing a so-called wind-to-wire or wave-to-wire analysis (e.g. Penalba and Ringwood 2016). For example, Supergen ORE Hub research has developed analyses that couple the whole operating life of environmental action on wave energy devices through to the multi-year loading history experienced at the anchoring system. The resulting simulation allows long-term physical phenomena to be captured—such as slow consolidation processes in the seabed—which allows the resulting gradual improvement in system resilience to be quantified (Kwa and White 2022).

This type of modelling approach provides a basis for comprehensive information across the full performance and impact of ORE systems contributing towards improved operation and maintenance strategies, better end-of-life decisions, and stronger social and environmental acceptance and allow faster and cheaper design at an early stage.

5.2.2. B2. Novel device concepts—rethinking the mechanism of energy extraction

A step change in cost reduction may only come from the development of novel technologies and new ideas for renewable energy generation (Jin *et al* 2022c). This can apply to all ORE devices, where larger novel turbines may displace the conventional three-bladed horizontal axis turbine (whether in wind or tidal) (Gonzalez and Diaz-Casas 2016). In wind, wave and tidal there is considerable scope for new disruptive concepts, if they can be conceived (Pourmahdavi *et al* 2019) and then mass produced, and the areas for deployment would be expanded considerably by driving down the lower limits of the resource.

To date, extreme conditions have been researched but not necessarily the lower limits which has a very different challenge. The impact potential could be very significant. In order to displace existing technology, there would need to be substantial CAPEX and OPEX advantages, perhaps through economies of scale at device level. Therefore, it is suggested that the impact should be balanced against the difficulty in conceiving a ‘novel’ concept.

5.2.3. B3. Moorings, anchors and foundations

For all ORE systems, multiple devices and the connecting electrical infrastructure require support or station keeping. Station keeping requires systems of mooring lines and anchor for floating or foundation types for fixed ORE devices for a range of seabed conditions. Fixed devices require foundations that provide adequate strength and stiffness. Design methods have been developed for a range of water depths, aided by knowledge transfer from other offshore engineering sectors.

Mooring and foundation systems comprise a significant fraction of the total system costs, particularly in deeper water (Weller *et al* 2015), and reducing these infrastructure costs is important for overall cost reduction. Deployment of wave and tidal systems is contingent on a suitable anchoring or foundation systems and new developments in self-installing systems or novel ideas may be needed to reduce costs. There has been significant research completed worldwide on mooring and foundation systems for fixed and floating oil and gas structures (Randolph *et al* 2011, Ma *et al* 2019), which may be leveraged for fixed and floating ORE. However, ORE brings particular challenges beyond previous oil and gas developments linked to (a) the requirement to characterise a much greater footprint of seafloor, and mass produce the installed infrastructure, (b) for wave energy, the reliance, in some cases, on the foundation for reaction force to generate energy, leading to extremely onerous loading and (c) the deployment in new regions that have challenging seabed conditions with limited previous experience—such as the thin sediment and shallow rock found across the Celtic Sea.

Therefore, this research challenge recommends that (a) new concepts and materials for mooring, anchor and foundation are needed with lower cost and easier installation; (b) new modelling approaches are required to better capture the integrated behaviour of the mooring system with the floating structure and the coupled behaviour of the mooring and foundation systems; (c) new foundation types need to be designed particularly for high-energy environments or unusual seabeds; (d) mooring systems for ORE arrays including shared moorings and systems with multiple devices sharing a single foundation will be needed.

Emergent contributions to improved foundation design include (a) recent new models to better capture the stiffness and capacity response of monopiles, including in challenging soil types (the PISA and ALPACA projects: Jardine *et al* 2019, Byrne 2020); (b) new capacity analyses that recognise the contribution of soil inertia to foundation capacity (Kwa *et al* 2021); (c) new design approaches that recognise and leverage progressive changes in ground conditions during facility life ('whole life' design: Gourvenec *et al* 2020, Kwa *et al* 2022, 'set-up' of pile capacity, Jardine *et al* 2006); (d) new types of foundation system with higher efficiency, installability or suitability for use as shared anchor points (e.g. the embedded ring foundation (Lee and Aubeny 2020) or screw piles (Cerfontaine *et al* 2020)). Meanwhile, the urgent requirement to rapidly characterise large regions of seafloor is leading to innovations in the coupling of geophysics and geotechnics to more efficiently assess ground conditions (Vanneste *et al* 2021).

Technologies to improve mooring systems include the use of shared anchors (Fontana *et al* 2019), extensible elements for snatch load mitigation (Pillai *et al* 2018, Festa *et al* 2022) and fibre ropes in place of chain.

5.2.4. B4. Multi-purpose hybrid systems for ORE and ocean resources

For all ORE technologies, there are significant costs and design challenges that are associated with the site location and metocean conditions rather than directly with power generation. This includes power export from an offshore location, access to offshore infrastructure with acceptably low risk and provision of a floating or fixed supporting structure. Co-location of devices for generating power by combining multiple ORE devices on the same sub-structure, or at the same site, offers the potential for improved economics of power generation from a given site (Pérez-Collazo *et al* 2015, Elginoz and Bas 2017).

Therefore, it is suggested to develop hybrid ORE systems that exploit more than one ORE or ocean resource and thus raise the utilisation rate of ocean infrastructure, including floating platforms and export cables, integration of ORE systems with oil and gas structures or aquaculture, capitalising on the sharing of sea space and infrastructures. There are several aspects to this research challenge, including: (a) techniques to combine ORE technologies that are at differing stages of development (Michele *et al* 2019); (b) techniques to combine ORE technologies with other ocean resources, such as desalination, aquaculture, energy storage, engineering habitat; (c) design methods for infrastructure accounting for multiple loading types and dynamic response modes occurring due to integration of multiple ORE device types. Table A1 in the appendix summarises the ongoing and recent projects related to each research theme and the challenges within each theme.

5.2.5. B5. Design of reliable cabling systems

Cabling contributes a significant proportion of the total cost of the ORE system and can be a single point of failure. Therefore, a more cost-effective and reliable cabling design will improve confidence in project financial projections. Existing cabling designs are generally inherited from the onshore/offshore wind farms or the offshore oil and gas sectors, which may not be effective for floating ORE farms. More reliable cabling designs are needed for ORE systems by considering (a) cable damage hazards such as the exposure or suspensions caused by seabed variations, (b) failures under extreme environmental loads or accumulated effects such as fatigue and abrasion and (c) better characterisation of burial conditions and the associated substrate controls of thermal performance (Dix *et al* 2017, Dinmohammadi *et al* 2019, Griffiths *et al* 2018). Sensor systems are emerging that can monitor both the electrical performance and the physical and environmental condition of the cabling to reduce the operations and maintenance (O&M) cost. Cabling designs must also consider the potential environmental impacts associated with thermal radiation and electromagnetic fields.

In order to advance this research challenge, (a) better understanding of cable failure mechanisms, and cable hydrodynamics including fluid-cable interaction, cable-seabed interaction, thermal and electrical effects are needed to unlock more cost-effective designs; (b) strategies and techniques of detecting sensors for cables are needed.

5.3. Theme C: materials and manufacturing

5.3.1. C1. Structural integrity in the marine environment (corrosion, fatigue, coatings etc)

ORE structures are often located in harsh environments that are difficult to access. Corrosion fatigue is a significant progressive damage mechanism that adversely affects structural integrity and hence safety and LCoE of the system (Moghaddam *et al* 2020). It is suggested that corrosion and fatigue degradation of structural integrity need to be better understood, and that this may be achieved by improving the associated experimental, numerical and analytical damage models. Also, effective coating techniques and advanced materials for ORE technologies need to be developed, for example for cable protection as well as for structural elements.

5.3.2. C2. Serial (volume) manufacturing of complex structural systems

As part of the Offshore Wind Sector Deal, the UK Government is seeking 'a target of achieving total lifetime UK content of 60% for projects commissioning from 2030 onwards'. This presents a challenge for the current UK heavy manufacturing industry capability. For fixed offshore wind the UK does not have an established monopile industry, it is noted that recent developments in the North East will begin to rectify this in part. Although, jacket type structures for fixed offshore wind are in line with more traditional UK offshore manufacturing the ever-growing sector will demand high levels of production. Therefore, increasing the local structural content for fixed offshore wind is problematic. Although, a number of these structures have achieved higher technology readiness levels, the current status of UK floating wind array development comes from Hywind Scotland and Kincardine projects in Scotland, using floating foundation technology with little UK manufactured content. Jacket structures and floaters are, therefore, potentially new markets for UK fabricators and so it is important to facilitate new technology qualification and expand the supply chain for these markets. For ORE structures to be economically viable, economies of scale need to be realised. The design of next generation structural systems needs to transition from one-off laboratory scale models to volume fabrication to support wind and marine technology deployments in deep waters (Ioannou *et al* 2020).

It is recommended that (a) it is now time to study how prevailing concepts can be translated into commercial systems; (b) ORE structural design needs to integrate with advanced and emerging volume manufacture technologies; (c) generic standards for manufacturing of ORE structures are needed. Ongoing and recent projects in this research challenge are summarised in the appendix.

Recent research into very large floating structures (VLFS) is investigating their use in offshore floating wind, where most demonstrated concepts are based on a simple one turbine–one platform system. Use of VLFS would allow for operation of multiple turbines and may prove beneficial in improving efficiency and reducing costs in manufacturing, transportation, and onsite installation. One design challenge for VLFS foundations is the large bending moment caused by wave loads, and Zhang *et al* (2021) investigate the use of hinges added into the structure to help alleviate the bending moment using a discrete-module-beam-bending hydroelasticity method and show positive benefits in reduction of the wave-induced bending moment.

5.3.3. C3. Design for safe and cost-effective installation methods

Marine renewables and deep-water offshore wind require reduction of installation costs through innovative methods while maintaining, and improving, safety levels. Currently, installation approaches, for these developing sectors, are still reliant on predominately a human-led process in hazardous working environments. This is coupled with a general lack of actual installation experience considering the current development status of the industry. Opportunities exist to make step changes in how installation of these devices can be de-risked, while improving efficiency, throughout the design and installation stages (Jiang 2021).

The research challenge, therefore, is to develop designs of ORE facilities that require less offshore human activity during the installation process.

5.3.4. C4. New materials and coatings

Corrosion and fatigue degrade structural integrity and new materials need to be developed and applied for ORE applications. New materials, such as fatigue/corrosion/abrasion resistant innovative materials with special properties can result in life time extension (beyond nominal 25 years), reduce inspection/ maintenance requirements and facilitate upscaling (more units, larger, in deeper waters, further offshore) at a reduced cost (Rodríguez *et al* 2016). Currently, there is no joined-up initiative for considering the transfer of materials know-how from other sectors, or the development of a new generation of corrosion-fatigue resisting materials for marine applications.

To address this research challenge, it is necessary to investigate fatigue/corrosion/abrasion resistant innovative materials (including coatings) with special properties such as life-time extension beyond nominal 25 years and reduction of inspection/maintenance requirement.

5.3.5. C5. Recycling/reuse of composites

At the time of writing, a large number of first-generation wind turbines are entering the second half of their service life, and although service life extension and repowering can reduce LCoE, in the longer term, materials used in decommissioned blades need to be reused or recycled. However, glass fibre composites are currently not easily recycled (Chen *et al* 2019), and the sheer volume of composite turbine blades that will come out of service pose an environmentally unacceptable situation. Current practice is to landfill decommissioned blades, but this practice is not sustainable and there is a critical need for industry to tackle this major and growing un-recyclability issue.

Therefore, this research challenge is to develop new methods to repurpose and/or recycle composites for offshore wind and marine renewables.

5.4. Theme D: sensing, control and electromechanics

5.4.1. D1. Control of ORE farms

The control of individual wind turbines has been well developed (Hur and Leithead 2016) but techniques for tidal and wave devices are lagging (Ringwood *et al* 2014). In addition, load reduction and robust control technology for the next generation of wind turbines e.g. up to 20 MW, faces new and greater challenges, especially as blades become much larger and more flexible (Wang *et al* 2022, Xie *et al* 2022). Furthermore, the control technology of ORE farms (as complicated distributed systems with individual devices influencing one another within an array, and whole farms affecting neighbouring farms) needs further investigation. This is needed not only to maximize the overall yields and optimise asset operational lifecycle, but to balance these two factors to achieve the operator's performance goals, while also minimising environmental impacts.

This research challenge highlights the need for developing and validating advanced control strategies for ORE farms to balance competing requirements, such as, increase of energy yield, integration of hybrid wind-wave-tidal farms, minimisation of environment impact and decrease of maintenance cost. The ongoing and recent projects related to control of ORE farms are summarised in the appendix.

The control system is at the core of wind farm operations and has key influence on the power capture efficiency, economic profitability, and maintenance cost of wind farms. However, the wind farms' inherent system complexities, the aerodynamic couplings among turbines, and the stochastic environmental conditions bring significant barriers to control system design. Due to these challenges, existing wind farm control methods have encountered big challenges, leading to degraded performance and poor feasibility in complex tasks. With the rapid expansion of offshore wind farms, it is recognised that disruptive technologies are urgently needed to handle wind farm operational tasks, especially for large offshore wind farms.

Recent research has pioneered the development of a series of deep reinforcement learning (DRL)-based wind farm control methods (Dong *et al* 2022, Xie *et al* 2022). DRL is a growing area artificial intelligence (AI) that has been recognised as the most promising way towards general human-level intelligence. The new application-oriented DRL algorithms developed within the Supergen ORE Hub programme are designed to achieve many wind farm operational tasks (Dong *et al* 2022, Xie *et al* 2022). The algorithms are data-driven and model-free and employ various novel deep-neural-network structures to process key system information, maximise long-term rewards, and learn optimal control strategies. Validated by a large set of case studies with different wind farm specifications, the resulting intelligent wind farm control methods are shown to be able to address bottleneck issues of current wind farm control methods, including lack of adaptability to modelling errors, weak robustness to environmental uncertainties, reliance on steady-style data, and insufficiency in data mining.

5.4.2. D2. Smart sensor system use

Although ORE devices, particularly wind turbines, have a large number of sensors measuring individual device performance, the measurements are typically not treated in an integrated manner to allow rich understanding to be extracted (Rinaldi *et al* 2021). In addition, device measurements are typically not linked to comprehensive environmental measurements. As ORE devices become larger and more complex, additional sensing modalities will be required to support improved control and structural health monitoring. Improved understanding of ORE device behaviour, along with the environmental drivers (wind, waves and tides) can help reduce LCoE through improved energy yield, improved prediction of remaining lifetime, improved planning of maintenance operations and reduction of damage from extreme events. With better planning of O&M, the need for high-risk offshore operations may be reduced. Furthermore, more reliable measurement of environmental impacts may help reduce unwanted impacts and improve societal acceptance of ORE.

Therefore, this research challenge highlights the importance of identifying, evaluating and validating sensor technologies, data transmission, integration and interpretation systems to support improved control and management. This includes sensing applied to individual ORE devices, arrays of devices and the environments in which they operate.

5.4.3. D3. Drive train design

Drive trains and generators are required to meet two crucial requirements in ORE: to operate efficiently over a wide range of input conditions and to have sufficient resilience (thus low maintenance requirements) including sustaining occasional extreme loads. They typically consume a significant proportion of CAPEX and OPEX and impose constraints on the rest of the systems due, for instance, to their weight (Wang *et al* 2019). To reduce LCoE, particularly for wave and tidal energy, lower cost drive trains and generators which combine efficiency and robustness are required. Scaling up requires drive trains and generators with lower weight, lower maintenance requirement, and with reduced reliance on rare earth materials.

In this research challenge the necessity of proposing conception, design and validation of novel drive trains for ORE devices including hydraulic drives, direct drive generators and devices to couple multiple prime movers into single generators is addressed.

5.4.4. D4. Power electronic conversion

Power electronics converters are the key enabling technology for renewable energy utilisation (Ran *et al* 2010). They play an increasingly important role in power system stability and reliability, in particularly with the growth of ORE farms (mainly wind farms at present). A major challenge is performance and reliability, and effective control of the power electronic converter can enhance performance of the drivetrain and grid interface.

Therefore, it is necessary to investigate improved control systems and analysis of the power electronic converter in order to improve reliability and performance of the drivetrain and grid interface.

5.5. Theme E: survivability, reliability and design

5.5.1. E1. Higher and more consistent reliability through risk-based design

ORE systems have technologies, skills, and supply chains in common with the traditional offshore sectors such as the oil and gas industry and existing design methods for ORE systems are inherited mostly from the traditional offshore sectors (Villate *et al* 2020). The operation principles, CAPEX, OPEX and innovation requirements of ORE systems, however, are often very different from the traditional offshore structures. As a result, employing these methods can constrain design of ORE systems to relatively high-cost solutions, limit design to conservative solutions and can result in low survivability of trial systems that integrate novel components or concepts.

Thus, tailored designs for ORE systems are required. This research challenge recommends: (a) establishing risk-based and/or probabilistic design approaches that couple resource, device, control strategy, power cable, foundation, and array arrangement to allow consistent target reliability; (b) modifying existing practices from oil and gas, to remove conservatism, and counter current issues of low survivability of some trial ORE systems. Table A1 in the appendix summarises the ongoing and recent projects related to research challenges in Theme E.

Progress has been made in investigating ways of improving the efficiency of the design process through probabilistic approaches and their applicability in wave and floating offshore wind cases. A constrained wave approach for predicting characteristic loads has been developed whereby a procedure for quickly calibrating constrained focused waves combined with scaling to a high percentile target response using the response spectrum has been tested for point absorber and hinged raft type WECs (Tosdevin *et al* 2021, Jin *et al* 2022a) and for a semi-submersible floating wind turbine (Tosdevin *et al* 2022). The procedure is shown to produce characteristic load estimates in line with traditional irregular wave methods in a shorter time. However, for some device and response types where nonlinearities complicate the analysis, the approach may not be appropriate, for example when snatch loading of a mooring line occurs (Tosdevin *et al* 2021).

In order to conduct the large number of simulations necessary for the probabilistic design process, fast, accurate numerical tools are required. The potential flow based numerical model WEC-Sim is such a tool that was designed to model WECs under operational conditions. However, its validity for modelling extreme conditions and responses as needed here is an open question. Work has been conducted to provide further understanding of situations and conditions for which the model is suitable for simulating extremes (Tosdevin *et al* 2020) and to propose additions required to improve its validity (Jin *et al* 2022b). Coupling of

WEC-Sim outputs to anchor system models has also been explored to allow whole life modelling of system degradation effects (Kwa *et al* 2022)—in this example soil consolidation around the anchor was the progressive effect (Laham *et al* 2021), but in principle the same approach could be applied to other limit states associated with progressive degradation, such as fatigue.

5.5.2. E2. Extending limits to operation or performance by mitigating extreme actions

A key cost reduction mechanism is increase of the size of the power generating element of the ORE system, e.g. the turbine size or rated power of a wave device (Jin and Greaves 2021). As these parameters increase, stresses (actions) on the system and component level due to dynamic response can become prohibitive. Thus, development of methods to mitigate and control system dynamics but increase performance are required to improve the reliability of the ORE systems. This mitigation can be through the use of new technological solutions, such as compliant mooring elements (Festa *et al* 2022), or through unlocking hidden components of system capacity that apply during high strain rate loading (e.g. soil inertia: Kwa *et al* 2021).

This research challenge recommends: (a) improving the understanding of the interaction of the environment with both the fundamental structural dynamics and control of the system; (b) enabling the modelling and prediction of peak (extreme) loads or actions accounting for environmental conditions interacting with the underlying system dynamics and control applied; (c) establishing designs in which load mitigation by continuous control of dynamic response can be achieved with lower cost and/or at larger scale than traditional design approaches.

5.5.3. E3. Innovative sub-systems to provide higher and more consistent reliability and better performance

ORE systems involve complex equipment operating in a harsh and inaccessible environment. Offshore wind turbines require frequent visits for scheduled and unscheduled maintenance, tidal turbines and wave energy devices also require maintenance, and the reliability of some trial devices has been lower than planned (e.g. Pelamis and Oyster wave energy converters). This research challenge could be tackled through fundamental improvements in designs, materials, control, manufacturing, monitoring, and making sub-systems more reliable and perform better. New sub-systems that have higher performance and better reliability will reduce the maintenance costs of all types of ORE system. This will contribute to continued cost reduction in offshore wind and help to bring tidal and wave energy into commercial use.

Therefore, it is recommended to develop new component solutions with innovative materials, designs, operating principles, and control strategies to plug gaps in ORE system reliability and to extend or expand device performance with cost reduction.

5.5.4. E4. Sustainable whole-life design methods

ORE systems have a limited operating life, consume significant raw materials, and involve placing significant infrastructure in the oceans. Currently, designs are not influenced by considerations beyond the operating life, and few ORE facilities are reaching end of life, so the issue of decommissioning has not yet been faced. The oil and gas industry is however facing major decommissioning costs, borne partly by the taxpayer, which arguably could have been reduced or avoided if decommissioning, reuse or recycling was considered earlier in design. Novel approaches to decommissioning that allow structures to remain in place potentially offer ecological, sustainability and safety benefits, but the evidence basis and legal framework must first be established (Chandler *et al* 2017, Gourvenec 2018).

Also, there is the opportunity to better utilise ORE infrastructure if the working life can be extended. One route to allow life extensions is to continually re-assess the remaining useful life, by progressively replacing the design loading assumptions with the actual loading experienced—for example, using a digital twin. This approach allows the time-varying probability of failure to be assessed, as well as the utilised fatigue life (Bai and Jin 2016). For some limit states, such as the geotechnical capacity, the reliability can improve through the operating life, rather than decay, as gains in capacity accumulate (e.g. 'set-up' of pile capacity or consolidation hardening in soft clays, Jardine and Chow 2006, Gourvenec 2020, Laham *et al* 2021, Kwa *et al* 2022).

There is a need to address strategies of life extensions and decommissioning earlier in the ORE sector to learn from the lessons of the oil and gas industry. This will improve the long-term cost profile of ORE developments and will increase the social and environmental acceptability of ORE. Thus, within this research challenge it is suggested to develop new concepts, components, materials, designs, and processes with the consideration of sustainability of ORE and unlocking whole-life designs which extend new and existing facilities into recycling, reuse, repair, decommissioning and/or repowering.

5.5.5. E5. Design tools for arrays

Developing single ORE structures into efficient arrays is necessary to improve the energy yield, to improve confidence in project financial projections and minimise the cost of electricity. Numerical models are needed to predict the optimal arrangement of arrays. Existing models for wind or wave farms need to be integrated to include floating motion responses to optimise ORE farm design, and better models are needed to adapt the existing onshore/nearshore farms to offshore farms. Improved and more efficient design tools are needed, considering optimisations for array layout, control of individual or blocking devices, mooring/power take off (PTO) sharing, foundations, electrical network, and the lifecycle logistics. Integration with ecological models and with sediment dynamics models is also important to understand the impacts of ORE farms on the environment. Turbines and devices need to be designed for operation within clusters and arrays, taking account of the modification of design conditions due to the presence of other devices and arrays. Furthermore, array configurations and operating strategies must be developed to maximise fatigue life and performance whilst minimising operating risks and costs.

Thus, this research challenge recommends: (a) understanding better the hydrodynamics of array interaction, layout performance and design with moorings and anchors included through physical wave tank tests and numerical modelling; (b) developing efficient numerical models for array optimisation of ORE systems with the consideration of optimal control, device conditions, hydrodynamic interaction (e.g. flow-modification by other devices and arrays in near-field and far-field), uncertainty quantification, yield optimisation, blocking and efficient arrays in real channels, mooring and PTO sharing.

5.5.6. E6. Whole systems approaches to operation of large-scale ORE

As ORE forms a larger fraction of the grid and is being supplied by larger and larger devices (up to 50 MW is contemplated), managing the ORE system at farm level and between farms is becoming more important. Without optimum integration of supply, storage and grid, the supply will be vulnerable to the availability of the natural ORE resources (i.e. wind, wave and tidal, etc). A whole system integrated approach to operation of large-scale ORE will be a complete game changer, requiring much more flexible and intelligent operation of offshore assets. The criterion for optimisation of operation will need to change completely to create an integrated approach to operation of ORE farms, development of O&M strategy, provision of ancillary services, postproduction, and grid integration.

Tackling this research challenge will require: (a) developing a systems level approach between ORE farms and integration with storage to maintain grid supply and improve grid resilience; (b) understanding better the impact of the ORE resources variabilities on grid resilience by driving down the lower limits of the resources instead of the adequate and/or extreme resources which have been studied.

5.6. Theme F: operations, management, maintenance and safety

5.6.1. F1. Analysis of remote sensing and condition monitoring data

To minimise offshore operations and inform O&M strategies, remote sensing and remote condition monitoring through digital twin technology are important developments that have the potential to enable remote resets and repairs and significantly reduce the cost of O&M offshore (Rinaldi *et al* 2021). Improved analysis tools and treatment of big data generated by remote sensing, proven by smarter benchmarking will be needed to unlock the potential for use of AI and ML and present opportunities for advanced asset monitoring and management, potentially lowering OPEX cost, whilst increasing availabilities. Effective and efficient prognostic condition monitoring techniques are needed in order to utilise the state-of-the-art computational capability in its full breadth for the ORE sector. The size and quantity of data from ORE assets steadily increases. In order to make best and efficient use of this information, tools and standardised processes are needed to handle and interpret these important data sets. The increasing quantity and value of ORE assets allows for improved understanding and estimation of O&M activities, costs and scheduling. Risk-based approaches can help to estimate the likelihood and consequence of failure and downtime.

Currently, digital twins are used in various industries; AI/ML is established in computational science and is emerging and growing in offshore applications. Several studies have investigated isolated initiatives to collect and generate benchmark data (Rinaldi *et al* 2021), and a number of O&M models are in use, although many are deterministic or empirical and would benefit from probabilistic methods. Table A1 in the appendix summarises the ongoing and recent projects related to operations, management, maintenance and safety.

Pioneering research in developing digital twins for the wind turbine flow system, (Zhang and Zhao 2021), simulates the three-dimensional (3D) flow in front of a wind turbine based on the latest development of physics-informed deep learning. This digital twin system is shown to predict accurately the 3D spatiotemporal flow field in front of a wind turbine by the fusion of the sparse measurements by commercially available LIDAR device and the flow physics (described by Navier–Stokes equations), via physics-informed neural networks. The developed digital twin has been extensively validated using high-fidelity numerical experiments on high-performance computing clusters. The results show that by fusing LIDAR data and physics, the wind field experienced by the wind turbine is accurately reconstructed and forecasted, demonstrating that digital mirroring of the wind flow is successfully achieved. As the wind flow is directly responsible for the turbine fatigue and power generation, the developed digital twin provides valuable new opportunities for digital twin-based control for load mitigation and power maximization.

5.6.2. F2. Use of autonomous systems for inspection

The use of autonomous systems (vessels/robotics) for remote sensing of turbine and ORE structures, and condition monitoring, together with AI and ML with remote resets and repairs present opportunities for advanced asset monitoring and management for ORE. Autonomous technologies have been demonstrated for (a) aerial inspection of turbine blades (e.g. Stokkeland *et al* 2015), (b) underwater inspection of structures (e.g. Papadopoulos *et al* 2014) and (c) observation and quantification of seabed biota (Thornton *et al* 2022).

These technologies, if rolled out widely, could potentially lower OPEX cost, whilst increasing availabilities of ORE farms and individual energy converters. However, regulations and legislation of unmanned aerial vehicle (UAV) systems are not in place, but are needed as autonomous systems are expected to be increasingly used for inspection and maintenance. Currently, some guidelines are available (Maritime UK 2018), but a more detailed and specific set of guidelines and regulations applicable to the ORE sector needs to be in place.

Therefore, this research challenge addresses the need of developing both the technology and also the regulation and legislative framework for UAV operations within ORE assets, in order to form common ground for operators, asset owners, marine agencies and insurers.

Gorma *et al* (2021) investigated a vertebral column structure of a fish-like AUV able to mimic propulsion techniques observed in nature, exploiting these advantages to facilitate autonomous inspection of offshore infrastructure. They built the RoboFish AUV using cost-effective 3D printed modules joined together with innovative magnetic coupling joints and a modular software framework. It was also shown that similar kinematics and propulsive capability of the real fish may be replicated via purely passive structural deformations when using a bionic body stiffness profile (Luo *et al* 2020). The RoboFish device was demonstrated in lake trails and shown to be functional in terms of water-tightness, propulsion, body control and communication using acoustics, with visual localisation and mapping capability (Gorma *et al* 2021).

5.6.3. F3. Data and digital cyber security

ORE assets provide an increasing amount of data with heightened sensitivity, causing challenges regarding data security. ORE farms are critical assets that if compromised would disrupt the energy supply. Thus, there is a need for improving the awareness, protocols and tools for ORE digital cyber security. Better understanding of data risks and mitigation in the ORE environment and transfer of cybersecurity expertise from other sectors into the ORE sector is necessary.

It is, therefore, suggested to fully investigate the risks and mitigation measures leading to establishing best practice and procedures for data management and cyber security in ORE assets.

5.6.4. F4. Increased use of automation to reduce risk in installation and operation (O&M)

The increased number and maintenance needs of offshore assets makes human interventions one of the main hazards in the ORE sector and should be avoided wherever feasible. In order to reduce the risk to human life in servicing O&M requirements of ORE structures, systems to reduce time for maintenance and human intervention may be considered. This may be achieved through increasing system reliabilities by increasing component redundancies, however this is a design trade-off with cost. Evaluating and specifying the ideal trade-off point between system reliability and lifecycle cost is needed, as well as better understanding of O&M uncertainties and the adoption of risk-based approaches to minimise risk in ORE O&M. This will require dedicated testing and implementation efforts of automation solutions.

Therefore, the research challenge recommends the need for increased use of automation to reduce human risk exposure in ORE installation and in operation and maintenance (O&M) and advanced approaches to identify optimal trade-off between component redundancies and human intervention.

5.7. Theme G: environmental and ecosystem aspects

5.7.1. G1. Fit-for-purpose approaches to environmental monitoring

Environmental monitoring is a high-cost aspect of ORE project development and is needed during both environmental impact assessment (EIA) and post consent. Linking ecological and physical environmental data collection (as mentioned in Theme A (6.1.1.) would represent a step change. The new 'PREDICT: Predicting seasonal movement of marine top predators using fish migration routes and autonomous platforms' project with Ørsted (www.abdn.acuk/sbs/research/predict-938.php) that emerged as a direct result of the push for integrated approaches in Supergen ORE, will address knowledge gaps in offshore wind environmental characterisation, providing a vision for next-generation monitoring techniques. Proof of links between the physical environment (e.g. velocity) and fish and seabirds is beginning to emerge (Couto *et al* 2022) showing that environmental effects can be captured at the same time with same instruments that are used for engineering purposes.

However, there is generally low confidence in the predictions at the level of cumulative and population level environmental impacts. ORE industries have recognised that current EIA, Habitats Regulations Appraisal or post-consent guidelines for environmental monitoring are not fit for purpose in terms of providing informative and accurate Cumulative Impact Assessments (Willsteed *et al* 2018). Better understanding of how the environmental impacts are felt, up through the whole ecosystem, will help to define the types of models and temporal and spatial data needed. There is also a clear need to enable the development of an agreed framework for monitoring data collection and repository characteristics with EIA and post consent guidelines for all ORE sectors (MMO 2014). Thus, the research challenge suggests that an agreed standard framework is needed for collection of data and an assessment approach for environmental impacts, in particular, cumulative effects on ecosystems of all offshore industries. However, an agreed data sharing portal across offshore industries and regulators would be a necessary part of this framework such as the use of MEDIN: Marine Environmental Data and Information Network (MEDIN 2022). There has been a rapid increase in funding since 2021 from UKRI, Defra, The Crown Estate and devolved governments towards the goals of understanding ecosystem effects. Table A1 in the appendix summarises the ongoing and recent projects related to Theme G1.

5.7.2. G2. Development of population level environmental impact models

ORE projects may be prevented or held back by the lack of confidence of their effect on the marine environment. There are currently no standard analytical methods to predict population level environmental impacts and deal with the combined priority issues such as marine mammal and seabird collision risk, displacement, disturbance and changes to the environment by ORE and/or climate change. The approaches so far for marine mammals have focused mainly on the cumulative effects of noise. There are two contrasting approaches, one for a range of marine mammals called interim Population Consequence of Disturbance (King *et al* 2015) which is a non-spatial explicit model, with population parameters being estimated by expert elicitation rather than empirical data and one specific to harbour porpoise, Disturbance Effects of Noise on the Harbour Porpoise Population in the North Sea (Stalder *et al* 2020) a spatially explicit, agent-based model, where the behaviour of the individuals is modelled, and the population consequences are estimated as emergent properties of the model. But both models only assess the effects of noise and assume that the habitat stays static and do not consider the environmental effects of changes due to the introduction of ORE or climate change (Mortensen and Thomsen 2019). For seabirds, an approach that quantifies the fate of displaced seabirds encountering ORE developments is called seabORD (Searle *et al* 2018), developed by CEH. The tool estimates the survival and reproductive success for individuals from breeding colonies affected by ORE using an individual-based stochastic simulation model describing the foraging, energetics and reproductive success of seabirds during the breeding season. However, as with the models developed for mammals, the habitat and in particular the locations of prey available to seabirds are modelled as static with no effect of ORE or climate change. Approaches that forecast both climate change and the possible effects of ORE on predictions of habitat changes and prey distributions have shown that large changes are possible even by 2050 (De Dominicis *et al* 2018, Sadykova *et al* 2020).

There has been a lot of development of population level models in the last few years at least for marine mammals and seabird species (Marine Scotland 2022). However, these new modelling approaches have highlighted that the level of uncertainty in the model outputs is highly dependent on the level and type of data collection preformed for EIAs and agreement across statutory agencies and industries is needed for the standardization of analysis methodologies assessing collision risk, displacement and disturbance from individual to population levels. A step change in standardization of methods would enable the impact of ORE projects to be better understood and potentially lead to cost reduction in environmental monitoring and faster project consenting. There is an ongoing need to develop data collection, analysis and modelling techniques that include uncertainty estimates especially for highly mobile marine animals from individuals to population level. One direction that core Supergen ORE work has produced is a dynamic Bayesian network model (Trifonova *et al* 2021) that describes the ecosystem state within four contrasting regions (different ORE developments preferences) in UK waters using information only from physical (e.g. bottom temperature) and biological (e.g. net primary production) indicators. This approach allows predictions for population trends for species and functional groups at all levels of the ecosystem which can be used to predict plankton, fish, seabird and marine mammal population trends in large spatial regions such as the northern North Sea (Trifonova *et al* 2022a). Table A1 in the appendix summarises the ongoing and recent projects related to Theme G2.

5.7.3. G3. Ecosystem modelling

Prediction of cumulative and interaction of multiple effects will allow better future prediction of a range of environmental impacts from physical changes up through to food chain, far-field and cumulative effects (ecological limits/carrying capacity) and put those changes into the context of climate change. As mentioned in G2, work within core Supergen ORE has seen the application of pragmatic Bayesian ecosystem modelling that has allowed a novel, whole system perspective to translate dynamic evidence-based ecosystem effects into natural, social, and economic metrics. The approach provides a common 'currency' to communicate and generalise modelling outputs that works across different disciplines and user groups (Trifonova *et al* 2022b). The Bayesian network approach enables a more accurate spatial overlap analysis which includes the outcomes of interactions between a variety of existing marine uses (renewables, fisheries), the results from which will be able to support marine spatial planners to balance the need for profitability with the need to minimise conflicts and tensions amongst existing and any future planned marine uses of natural resources. The outcomes delivered include natural (e.g. fish biomass), social (e.g. ecosystem services) via natural capital/ ecosystem services estimates and can be fed into gross value added (GVA) models (Trifonova *et al* 2022b) ensuring that policies can be developed in a coherent manner for the maximal benefit of society as a whole and will ideally enable the integration of fisheries activities in order to better assess issues, such as potential fisheries displacement and encourage involvement of the industry at the beginning of the planning processes. Table A1 in the appendix summarises other ongoing and recent projects related to Theme G3.

5.8. Theme H: marine planning governance

5.8.1. H1. Communication: ocean literacy and public perception of ORE

There is a clear need for greater understanding of ORE, what is meant by offshore wind, wave and tidal energy, and of the whole systems approach. Better understanding of ORE across primary, secondary, tertiary education, industry, policy/ governance agencies and general public is needed so that the potential benefits of ORE is understood. However, the wider public is not well informed about offshore energy or the concept of whole-systems approaches. This can be solved through engagement events targeted at different stakeholder groups and through production of a range of material for wider public use. The Supergen ORE Hub's leadership role includes connecting those active in the sector and communicating ORE issues to a range of user groups, including politicians and public, provide education and to improve understanding via use of public engagement. Better public understanding of ORE and whole-systems approaches, ocean literacy and ecological interactions, will impact on public perception and the granting of Social License. Table A1 in the appendix summarises the ongoing and recent projects related to Theme H1.

5.8.2. H2. Interaction with other marine users

This research challenge identifies the need for a marine spatial planning framework that includes large scale ORE within policies to enable working together across ORE and other marine sectors as ORE operates in the marine environment alongside other users and there is potentially a conflict for resource, marine space and infrastructure. Offshore wind structures have only been installed in volume for around a decade but already outnumber oil and gas structures (Gourvenec *et al* 2022). With further expansion towards Net Zero targets, better understanding of the requirements, and of complementary and competing users will be necessary for rational spatial planning, throughout the beyond the operating life of the installations. There is a need to reduce potential for conflict with other marine sectors. Exploring potential synergies in technology, experience and skills across all renewables sectors and engaging with the oil & gas industries will be beneficial and will enable common learning from experience of conflict resolution, marine spatial planning, insurance and co-location (with MPAs, fishing industry, aquaculture/mariculture, Schupp *et al* 2021). Table A1 in the appendix summarises the ongoing and recent projects related to Theme H2.

5.8.3. H3. Development of market mechanisms for ORE

Fit-for-purpose market mechanisms are needed for the UK domestic ORE market, with appropriate measures reflecting requirements for technology sectors at different stages of development, particularly for marine renewable energy. Development and analysis of potential policy frameworks to support ORE technology commercialisation will allow rational mechanisms to be established (Cochrane *et al* 2021).

Thus, research is needed to inform policy on appropriate support mechanisms for emerging technologies in order to develop a fit-for-purpose, economically-viable market mechanism. This will then stimulate investment and accelerate development of the ORE sector. A market mechanism would facilitate deployment, which would enable learning-by-doing, which would in turn reduce CAPEX from economies of scale and OPEX from operational experience. While substantial work has gone into LCoE modelling, until now there has been limited investment into quantifying the return on investment of market mechanisms.

5.8.4. H4: Reducing uncertainty of both technology and social costs of ORE

There has been no agreed process to evaluate the whole-system benefits of ORE, including technology and social costs and benefits. Nor is it established how to identify and qualify/quantify the well-being from employment, identity and cultural aspects of future ORE industries. This is holding back the development of the ORE sector and establishing such an approach is necessary to allow policymakers and investors to make informed decisions on the funding of the ORE sector. Hence, there is a need to understand and qualify/quantify the benefits of ORE beyond low carbon electricity by analysing salient factors and valuation of a range of social benefits information on social capital/well-being. This need could be met through the development of methods to assess and communicate the range of social benefits and well-being from future large-scale ORE developments. The new core Supergen ORE ecosystem-based Bayesian approach (Trifonova *et al* 2021, 2022a, 2022b) can measure ecosystem change, change in ecosystem goods and services and change in socio-economic value in response to ORE deployment scenarios as well as climate change and fishing and therefore provides objective information for decision processes seeking to integrate new uses into our marine ecosystems. A coming together of currencies is being used to communicate modelling outcomes with different groups for a more coherent and comprehensive understanding of environmental perturbations.

The newly proposed approach holds the potential to provide the likely outcomes from alternative management and climate scenarios, allowing the user to make judgements and decisions about the ecological and socio-economic benefits and trade-offs within spatial scales, among sectors, and between users. By placing a monetary valuation on the environmental impacts, decision makers will be able to examine ecosystem service issues and their impact on economic activity and social welfare. The monetary valuation of environmental impacts can be used to investigate the economic, social, and technological trade-offs between long-term divergent marine uses and their alternative management scenarios, including climate change, which will lead to a greater ability to launch interdisciplinary studies. Specifically, by promoting such collaboration, decision makers will be able to identify areas where investment may not just enhance human well-being but also nature.

However, more interdisciplinary funds are needed to encourage experts in the social sciences to work directly with engineers and ecologists in the design of ORE solutions. There has recently been a watershed publication (HM Treasury 2021) and a reactionary step-change in funding rounds from UKRI across research areas with current calls targeting this type of inter-disciplinary research. Table A1 in the appendix summarises the ongoing and recent projects related to Theme H4.

6. Conclusions

As a result of both global supply chain developments and domestic policy implementation, electricity decarbonisation has been so successful in the UK that the Sixth Carbon Budget identifies a pathway for completely decarbonising electricity by 2035. As the UK's favoured renewable electricity generation technology, offshore wind has policies in place for the coming decade as part of the Offshore Wind Sector Deal (Allan *et al* 2020), UK Government's Energy White Paper (HM Government 2022) and British Energy Security Strategy (HM Government 2022). The White Paper also commits the Government to running further CfD auctions that are open to a range of ORE generation technologies including fixed and floating offshore wind, wave and tidal energy.

A key challenge for the ORE sector is the accelerated pace of renewable energy development needed in order to meet the Net Zero targets. This will require better understanding of cumulative impacts and sustainable use of marine space for established technologies, as well as the need to drive down costs for emerging and less established ORE technologies. There is a need for innovation and cost reduction in the development of new technology solutions in ORE and in the development of novel techniques and systems for rapid consenting and operation and management of ORE farms.

In this paper, we provide a review of the current research themes and research challenges that have been prioritised by the Supergen ORE Hub and summarised in the research landscape webtool. Each of the eight research themes identified have a number of research challenges within them and these are described to indicate their importance for the development of ORE, their current status and the focus of the research challenges to be addressed. The research landscape provides a framework for the activities of the Supergen ORE Hub and research community, including research projects funded through the ORE Hub's Flexible Fund. The appendix includes a table summarising ongoing and recent research projects within each of the themes.

The Supergen ORE Hub's research landscape has been developed through extensive consultation with the sector and is a live resource that is updated regularly. It provides a focus for research intended to accelerate the development of ORE for the maximum benefit to society, and the range of research challenges identified emphasises the importance of working collaboratively across disciplines and of taking a whole systems approach.

Data availability statement

No new data were created or analysed in this study.

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Appendix

Table A1. Ongoing and recent research projects related to the either research themes and the research challenges within them.

Theme A: resource and environment characterisation	
A1. Better measurement techniques for forecasting and resource characterisation	
Project	Funding body
Offshore wind energy cost reduction by an innovative floating met mast platform [https://cordis.europa.eu/project/id/784040]	EU
Radar-model-fusion approach for high-resolution marine resource mapping http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FR014779%2F1&cookieConsent=A	NERC
Offshore wind innovation hub – O&M and Windfarm Lifecycle https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Flow measurement for accurate tidal turbine design https://supergen-ore.net/projects/flow-measurement-for-accurate-tidal-turbine-design	Supergen ORE Hub
WTIMTS—Wave-Turbulence Interaction and Measurement for Tidal Stream https://supergen-ore.net/projects/wtimts-wave-turbulence-interaction-and-measurement-for-tidal-stream	Supergen ORE Hub
V-SCORES (Validating Surface Currents at Offshore Renewable Energy Sites) https://supergen-ore.net/projects/v-scores-validating-surface-currents-at-offshore-renewable-energy-sites	Supergen ORE Hub
Accounting for Current in Wave Buoy Measurements https://supergen-ore.net/projects/accounting-for-current-in-wave-buoy-measurements	Supergen ORE Hub
A2. Improved modelling tools for resource and loading assessment	
Project	Funding body
Wave energy transition to future by evolution of engineering and technology https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/ocean/wetfeet	EU
Modelling, Optimisation and Design of Conversion for Offshore Renewable Energy (UK-China MOD-CORE) https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007756/1	EPSRC
Resilient Integrated-Coupled FOW platform design methodology (ResIn) https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007519/1	EPSRC
A Collaborative Computational Project in Wave Structure Interaction (CCP-WSI) www.ccp-wsi.ac.uk/	EPSRC
MAXFARM (MAXimizing wind Farm Aerodynamic Resource via advanced Modelling) https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N006224/1	EPSRC
FloWTurb: Response of Tidal Energy Converters to Combined Tidal Flow, Waves, and Turbulence https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N021487/1	EPSRC
Offshore Wind Innovation Hub—O&M and Windfarm Lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	
Accounting for Current in Wave Buoy Measurements https://supergen-ore.net/projects/accounting-for-current-in-wave-buoy-measurements	Supergen ORE Hub
Veers' Extension to Non-neutral Incoming Winds (VENTI) https://supergen-ore.net/projects/veers-extension-to-non-neutral-incoming-winds-venti	Supergen ORE Hub
Improved Models for Multivariate Metocean Extremes (IMEX) https://supergen-ore.net/projects/improved-models-for-multivariate-metocean-extremes-imex	Supergen ORE Hub
Demonstrating a machine learning system to integrate metocean data, sensor networks, and model output for improved coverage and accuracy https://supergen-ore.net/projects/demonstrating-a-machine-learning-system-to-integrate-metocean-data-sensor-networks-and-model-output-for-improved-coverage-and-accuracy	Supergen ORE Hub
FASTWATER: Freely-Available mesoScale simulation Tool for Wave, Tides and Eddy Replication https://supergen-ore.net/projects/fastwater	Supergen ORE Hub

(Continued.)

Table A1. (Continued.)

A3. Resource and environmental characterisation in physical modelling facilities	
Project	Funding body
FloWTurb: Response of Tidal Energy Converters to Combined Tidal Flow, Waves, and Turbulence https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N021487/1	EPSRC
Marine Renewable Infrastructure Network for Enhancing Technologies 2 (MaRINET2) http://marinet2.eu/	EU
LoadTide https://supergen-ore.net/projects/loadtide#entry:5367@3:url	Supergen ORE Hub
Satellite Climate Observation for Offshore Renewable Energy Cost Reduction (SCORE) https://supergen-ore.net/projects/satellite-climate-observation-for-offshore-renewable-energy-cost-reduction-score	Supergen ORE Hub
Novel Approaches for Physical Model Testing of Floating Wind Turbine Platforms https://supergen-ore.net/projects/novel-approaches-for-physical-model-testing-of-floating-wind-turbine-platforms	Supergen ORE Hub
A4. Long-term sediment transport measurement and modelling	
Project	Funding body
SEACAMS2 Sustainable expansion of the applied coastal and marine sectors http://seacams.ac.uk/	ERDF
Natural versus anthropogenically driven behaviour of hydrodynamics and sediment dynamics in Yangtze Estuarian Delta https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R02491X/1	EPSRC
Applying nature-based coastal defence to the world's largest urban area—from science to practice https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R024553/1	EPSRC
Offshore wind innovation hub – substructures https://offshorewindinnovationhub.com/category/substructures/	BEIS
Cable scour from fluid-seabed interactions in regions of mobile sedimentary bedforms https://supergen-ore.net/projects/cable-scour-from-fluid-seabed-interactions-in-regions-of-mobile-sedimentary-bedforms	Supergen ORE Hub
Theme B: fluid-structure-seabed interaction	
B1. Realistic fluid-structure-seabed design tools that work together, not in isolation	
Project	Funding body
Collaborative computational project on wave structure interaction (CCP-WSI) and CCP-WSI+, www.ccp-wsi.ac.uk	EPSRC
Modelling, optimisation and design of conversion for offshore renewable energy (UK-China MOD-CORE) https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007756/1	EPSRC
Extreme wind and wave loads on the next generation of offshore wind turbines https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007632/1	EPSRC
Pile Soil Analysis (PISA) project https://eng.ox.ac.uk/geotech/research/offshore-foundations/pisa-project/	Carbon Trust
Tidal Stream Energy—Designing for Performance https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007322/1	EPSRC
Offshore Wind Innovation Hub—Substructures innovation priorities https://offshorewindinnovationhub.com/category/substructures/	BEIS
Offshore Wind Innovation Hub—roadmap data seabed structure interaction and fluid structure interaction https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Seabed-structure-interaction-and-fluid-structure-interaction_191014_150143.pdf	BEIS
Cable scour from fluid-seabed interactions in regions of mobile sedimentary bedforms https://supergen-ore.net/projects/cable-scour-from-fluid-seabed-interactions-in-regions-of-mobile-sedimentary-bedforms	Supergen ORE Hub
Impact of in-service oscillatory movement on insulation reliability of AC and DC cables serving offshore platforms https://supergen-ore.net/projects/impact-of-in-service-oscillatory-movement-on-insulation-reliability-of-ac-and-dc-cables-serving-offshore-platforms	Supergen ORE Hub

(Continued.)

Table A1. (Continued.)

B2. Novel device concepts—rethinking the mechanism of energy extraction	
Project	Funding body
Impact of in-service oscillatory movement on insulation reliability of AC and DC cables serving offshore platforms https://supergen-ore.net/projects/impact-of-in-service-oscillatory-movement-on-insulation-reliability-of-ac-and-dc-cables-serving-offshore-platforms	Supergen ORE Hub
Submerged bi-axial fatigue analysis for flexible membrane Wave Energy Converters https://supergen-ore.net/projects/submerged-bi-axial-fatigue-analysis-flexible-membrane-wecs	Supergen ORE Hub
B3. Moorings, anchors and foundations	
Project	Funding body
FLOTANT https://flotantproject.eu/	EU
Development of screw anchors for floating Marine Renewable Energy system arrays incorporating anchor sharing https://cordis.europa.eu/project/id/753156	EU
SharEd Anchor Multidirectional Load Envelopes with Strength Synthesis (SEAMLESS) https://supergen-ore.net/projects/seamless	Supergen ORE Hub
Cost Effective Methods of Installing Offshore Wind Infrastructure https://supergen-ore.net/projects/cost-effective-installing-offshore-wind	Supergen ORE Hub
ALPHA: Numerical Analysis of Laterally Loaded Piles Divided in Chalk https://supergen-ore.net/projects/alpha-numerical-analysis-of-laterally-loaded-piles-divided-in-chalk	Supergen ORE Hub
B4. Multi-purpose hybrid systems for ORE and ocean resources	
Project	Funding body
Offshore Wind Innovation Hub—substructures innovation priorities https://offshorewindinnovationhub.com/category/substructures/	BEIS
Offshore Wind Innovation Hub roadmap data—design for marine life and aquaculture https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Design-for-marine-life-and-aquaculture.pdf	BEIS
Offshore Wind Innovation Hub roadmap data—combined WEC and WTG floating foundations https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Combined-WEC-and-WTG-floating-foundations.pdf	BEIS
B5. Design of reliable cabling systems	
Project	Funding body
Offshore renewable energy cable health using integrated distributed sensor systems https://ore.catapult.org.uk/press-releases/dynamic-cable-test-rig/	ORE Catapult
HOME-Offshore: holistic operation and maintenance for energy from offshore wind farms https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P009743/1	EPSRC
Offshore Wind Innovation Hub Roadmap—Electrical Infrastructure innovation priorities https://offshorewindinnovationhub.com/category/electrical-infrastructure/	BEIS
FLOTANT http://flotantproject.eu/	EU
Offshore Wind Innovation Hub roadmap data—understanding of root cause of cable failures https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Understanding-of-root-cause-of-cable-failures.pdf	BEIS
Offshore Wind Innovation Hub roadmap data—improved standards of cables https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Improved-standards-of-cables.pdf	BEIS
Cable scour from fluid-seabed interactions in regions of mobile sedimentary bedforms https://supergen-ore.net/projects/cable-scour-from-fluid-seabed-interactions-in-regions-of-mobile-sedimentary-bedforms	Supergen ORE Hub
Impact of in-service oscillatory movement on insulation reliability of AC and DC cables serving offshore platforms https://supergen-ore.net/projects/impact-of-in-service-oscillatory-movement-on-insulation-reliability-of-ac-and-dc-cables-serving-offshore-platforms	Supergen ORE Hub

(Continued.)

Table A1. (Continued.)

Theme C: materials and manufacturing	
C1. Structural Integrity in the Marine Environment (corrosion, fatigue, coatings etc)	
Project	Funding body
Centre for advanced materials for renewable energy generation (CAMREG) http://camreg.chem.ed.ac.uk	EPSRC
Major Delft corrosion projects [no link]	EU
Offshore wind structural lifecycle industry collaboration (SLIC): joint industry project http://ewea.org/offshore2015/conference/allposters/PO081.pdf	Wind industry
LoadTide https://supergen-ore.net/projects/loadtide	Supergen ORE Hub
COrrosion and fatigue protection of offshore wind Turbine structures using additive manufacturing technology (COATing) (Lead Institution: Cranfield University) https://supergen-ore.net/projects/corrosion-and-fatigue-protection-of-offshore-wind-turbine-structures-using-additive-manufacturing-technology-coating	Supergen ORE Hub
Physics-informed machine learning for rapid fatigue assessments in offshore wind farms https://supergen-ore.net/projects/machine-learning-for-fatigue-assessments-offshore-wind-farms	Supergen ORE Hub
Development of thermoplastic composite tidal blades for enhanced end of life recycling and lower cost manufacturing (ThermoTide) supergen-ore.net/projects/thermotide	Supergen ORE Hub
Offshore Wind Innovation Hub roadmap data—self healing materials https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Self-healing-materials.pdf	BEIS
Offshore Wind Innovation Hub roadmap data—corrosion protection https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Corrosion-protection.pdf	BEIS
Advanced, Modular Power Take-Off Design for Marine Energy Converters https://supergen-ore.net/projects/advanced-modular-power-take-off-design-for-marine-energy-converters	Supergen ORE Hub
C2. Serial (volume) manufacturing of complex structural systems	
Project	Funding body
Offshore Wind Innovation Hub roadmap data—increased welding automation https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Increased-welding-automation.pdf	BEIS
Offshore Wind Innovation Hub roadmap data—industry wide standardisation of nodes https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Industry-wide-standardisation-of-nodes.pdf	BEIS
ThermoTide https://supergen-ore.net/projects/thermotide	Supergen ORE Hub
C3. Design for safe and cost-effective installation methods	
Project	Funding body
Offshore Wind Innovation Hub Roadmap—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Offshore Wind Innovation Hub Roadmap Data Disruptive installation techniques https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Disruptive-installation-techniques.pdf	BEIS
FLOTANT http://flotantproject.eu/	EU
Cost effective methods of installing offshore wind infrastructure https://supergen-ore.net/projects/cost-effective-installing-offshore-wind	Supergen ORE Hub

(Continued.)

Table A1. (Continued.)

C4. New materials and coatings	
Project	Funding body
CAMREG http://camreg.chem.ed.ac.uk/	EPSRC
Offshore Wind Innovation Hub—substructures innovation priorities https://offshorewindinnovationhub.com/category/substructures/	BEIS
Offshore Wind Innovation Hub roadmap data - self healing materials https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Self-healing-materials_191015_122510.pdf	BEIS
Offshore Wind Innovation Hub roadmap data—corrosion protection https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Corrosion-protection_191015_122524.pdf	BEIS
COATing https://supergen-ore.net/projects/corrosion-and-fatigue-protection-of-offshore-wind-turbine-structures-using-additive-manufacturing-technology-coating	Supergen ORE Hub
Submerged bi-axial fatigue analysis for flexible membrane Wave Energy Converters https://supergen-ore.net/projects/submerged-bi-axial-fatigue-analysis-flexible-membrane-wecs	Supergen ORE Hub
ThermoTide https://supergen-ore.net/projects/thermotide	Supergen ORE Hub
C5. Recycling/reuse of composites	
Project	Funding body
Offshore Wind Innovation Hub—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Offshore Wind Innovation Hub roadmap data—resource recovery reuse and remanufacturing https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Resource-recovery-reuse-and-remanufacturing.pdf	BEIS
Recycling Composite Wind Turbine Blade for High-Performance Composite Manufacturing https://supergen-ore.net/projects/recycling-composite-wind-turbine-blade-for-high-performance-composite-manufacturing	Supergen ORE Hub
Development of Thermoplastic Composite Tidal Blades for Enhanced End of Life Recycling and Lower Cost Manufacturing https://supergen-ore.net/projects/thermotide	Supergen ORE Hub
Theme D: sensing, control and electromechanics	
D1. Control of ORE farms	
Project	Funding body
UK-China—FENGBO-WIND—Farming the Environment into the Grid: Big data in Offshore Wind https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007470/1	EPSRC
A new partnership in offshore wind https://npow.group.shef.ac.uk/	EPSRC
Offshore Wind Innovation Hub—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Enhancing control capability of ORE systems for stress management and grid https://supergen-ore.net/projects/enhancing-control-capability-of-ore-systems-for-stress-management-and-grid-support	Supergen ORE Hub
Passive Control of Wave Induced Platform Motions for Semi-submersible FOWTs https://supergen-ore.net/projects/passive-control-of-wave-induced-platform-motions-for-semi-submersible-fowts	Supergen ORE Hub
Offshore wind innovation hub roadmap data—optimising control for atmospheric conditions https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Optimising-control-for-atmospheric-conditions.pdf	BEIS

(Continued.)

Table A1. (Continued.)

D2. Smart sensor system use	
Project	Funding body
New partnership in offshore wind https://npow.group.shef.ac.uk/	EPSRC
Structural health monitoring of systems of systems: populations, networks and communities https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R003645/1	EPSRC
HOME-offshore: holistic operation and maintenance for energy from offshore wind farms https://gtr.ukri.org/projects?ref=EP/P009743/1	EPSRC
Condition monitoring of wind turbine drive-trains via non-contact acoustic sensors https://cordis.europa.eu/project/rcn/200428/factsheet/en	EU
FLOTANT http://flotantproject.eu/	EU
A hybrid and scalable digital twin for intelligent direct drive powertrain condition monitoring https://supergen-ore.net/projects/a-hybrid-and-scalable-digital-twin-for-intelligent-direct-drive-powertrain-condition-monitoring	Supergen ORE Hub
Smart piezoelectric metamaterials for partial discharge monitoring https://supergen-ore.net/projects/smart-piezoelectric-metamaterials-for-partial-discharge-monitoring	Supergen ORE Hub
Validating surface currents at offshore renewable energy sites (V-SCORES) https://supergen-ore.net/projects/v-scores-validating-surface-currents-at-offshore-renewable-energy-sites	Supergen ORE Hub
D3. Drive train design	
Project	Funding body
Novel direct drive generators included within new partnership in offshore wind https://npow.group.shef.ac.uk/	EPSRC
Hydrostatic transmission wind turbines are studied in passive vibration control of a floating hydrostatic transmission wind turbine and theoretical extensions https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R015120/1	EPSRC
Offshore wind innovation hub—turbines innovation priorities https://offshorewindinnovationhub.com/category/turbines/	BEIS
Offshore wind innovation hub roadmap data—disruptive powertrain design https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Disruptive-powertrain-design.pdf	BEIS
A hybrid and scalable digital twin for intelligent direct drive powertrain condition monitoring https://supergen-ore.net/projects/a-hybrid-and-scalable-digital-twin-for-intelligent-direct-drive-powertrain-condition-monitoring	Supergen ORE Hub
Investigation into the coupling of a wave energy converter with a reverse osmosis desalination plant https://supergen-ore.net/projects/investigation-into-the-coupling-of-a-wave-energy-converter-with-a-reverse-osmosis-desalination-plant	Supergen ORE Hub
D4. Power Electronic Conversion	
Project	Funding body
Offshore wind innovation hub—turbines innovation priorities https://offshorewindinnovationhub.com/category/turbines/	BEIS
Advanced, modular power take-off design for marine energy converters https://supergen-ore.net/projects/advanced-modular-power-take-off-design-for-marine-energy-converters	Supergen ORE Hub
All electric drivetrain for marine energy converters (EDRIVE-MEC) https://edrive.eng.ed.ac.uk/	EPSRC

(Continued.)

Table A1. (Continued.)

Theme E: survivability, reliability and design	
E1. Higher and more consistent reliability through risk-based design	
Project	Funding body
Innovative floating offshore wind energy: Lifes50plus https://lifes50plus.eu/	EU
Supergen ORE Hub—work package 4 www.supergen-ore.net	EPSRC
WEC Design Response Toolbox (WDRT) https://wec-sim.github.io/WDRT/	NREL
Wave Energy Scotland—Knowledge Capture https://library.waveenergyscotland.co.uk/	Scottish Government
Improved Models for Multivariate Metocean Extremes (IMEX) https://supergen-ore.net/projects/improved-models-for-multivariate-metocean-extremes-imex	Supergen ORE Hub
LoadTide https://supergen-ore.net/projects/loadtide	Supergen ORE Hub
Physics-informed machine learning for rapid fatigue assessments in offshore wind farms https://supergen-ore.net/projects/machine-learning-for-fatigue-assessments-offshore-wind-farms	Supergen ORE Hub
iDRIVE: Intelligent Driveability Forecasting for Offshore Wind Turbine Monopile Foundations https://supergen-ore.net/projects/idrive	Supergen ORE Hub
E2. Extending limits to operation or performance by mitigating extreme actions	
Project	Funding body
Innovative, low cost, low weight and safe floating wind technology optimized for deep water wind sites. (FLOTANT) https://flotantproject.eu/	EU
Autonomous Robotic Intervention System For Extreme Maritime Environments (ARISE) Stage 2 https://gtr.ukri.org/projects?ref=104085	Innovate UK
Extreme Loading on Floating Offshore Wind Turbines (FOWTs) under Complex Environmental Conditions https://mmu.ac.uk/research/research-centres/cfacs/projects/offshore-turbines	EPSRC
SURFTEC: SUrvivability and Reliability of Floating Tidal Energy Converters https://gtr.ukri.org/projects?ref=EP%2FN02057X%2F1	EPSRC
SharEd Anchor Multidirectional Load Envelopes with Strength Synthesis (SEAMLESS) https://supergen-ore.net/projects/seamless	Supergen ORE Hub
Cost Effective Methods of Installing Offshore Wind Infrastructure https://supergen-ore.net/projects/cost-effective-installing-offshore-wind	Supergen ORE Hub
LoadTide https://supergen-ore.net/projects/loadtide	Supergen ORE Hub
iDRIVE: Intelligent Driveability Forecasting for Offshore Wind Turbine Monopile Foundations https://supergen-ore.net/projects/idrive	Supergen ORE Hub
E3. Innovative sub-systems to provide higher and more consistent reliability and better performance	
Project	Funding body
Innovative, low cost, low weight and safe floating wind technology optimized for deep water wind sites. (FLOTANT) http://flotantproject.eu/	EU
Wave Energy Scotland https://waveenergyscotland.co.uk/	Scottish Government
e-Drive: All Electrical Drive Train for Marine Energy Converters https://edrive.eng.ed.ac.uk/	EPSRC
Offshore Wind Innovation Hub https://offshorewindinnovationhub.com/	BEIS
Advanced, Modular Power Take-Off Design for Marine Energy Converters https://supergen-ore.net/projects/advanced-modular-power-take-off-design-for-marine-energy-converters	Supergen ORE Hub
Smart piezoelectric metamaterials for partial discharge monitoring https://supergen-ore.net/projects/smart-piezoelectric-metamaterials-for-partial-discharge-monitoring	Supergen ORE Hub
A hybrid and scalable digital twin for intelligent direct drive powertrain condition monitoring https://supergen-ore.net/projects/a-hybrid-and-scalable-digital-twin-for-intelligent-direct-drive-powertrain-condition-monitoring	Supergen ORE Hub
Submerged bi-axial fatigue analysis for flexible membrane Wave Energy Converters https://supergen-ore.net/projects/submerged-bi-axial-fatigue-analysis-flexible-membrane-wecs	Supergen ORE Hub

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Table A1. (Continued.)

E4. Sustainable whole-life design methods	
Project	Funding body
Physics-informed machine learning for rapid fatigue assessments in offshore wind farms https://supergen-ore.net/projects/machine-learning-for-fatigue-assessments-offshore-wind-farms	Supergen ORE Hub
Offshore Wind Innovation Hub-Turbines-Enabling Research-Design https://offshorewindinnovationhub.com/category/turbines/	BEIS
Resource Recovery from Waste https://rrfw.org.uk/	NERC
Development and demonstration of durable biobased composites for a marine environment (SeaBioComp) https://interreg2seas.eu/nl/seabiocomp	EU
E5. Design tools for arrays	
Project	Funding body
Dynamic Loadings on Turbines in a Tidal Array (DyLoTTA) https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N020782/1	EPSRC
FloWTurb: Response of Tidal Energy Converters to Combined Tidal Flow, Waves, and Turbulence https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N021487/1	EPSRC
EcoWatt2050 https://supergen-marine.org.uk/sites/supergen-marine.org.uk/files/attachments/Side_Ecowatt2050_2017.pdf	EPSRC
Offshore Wind Innovation Hub-O&M and Windfarm Lifecycle https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project https://research.ed.ac.uk/en/projects/perawat-performance-assessment-of-wave-tidal-array-systems	Energy Technologies Institute
Enabling Future Arrays in Tidal (EnFAIT) https://enfait.eu/	EU
Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment (DTOcean+) https://dtoceanplus.eu/	EU
Wave Energy Transition to Future by Evolution of Engineering and Technology (WETFEET) https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/ocean/wetfeet	EU
Development of screw anchors for floating Marine Renewable Energy system arrays incorporating anchor sharing https://cordis.europa.eu/project/rcn/209673/factsheet/en	EU
Modelling, Optimisation and Design of Conversion for Offshore Renewable Energy (UK-China MOD-CORE) https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007756/1	EPSRC
SharEd Anchor Multidirectional Load Envelopes with Strength Synthesis (SEAMLESS) https://supergen-ore.net/projects/seamless	Supergen ORE Hub
FASTWATER: Freely-Available mesoScale simulation Tool for Wave, Tides and Eddy Replication https://supergen-ore.net/projects/fastwater	Supergen ORE Hub
E6. Whole systems approaches to operation of large-scale ORE	
Project	Funding body
FENGBO-WIND—Farming the ENvironment into the Grid: Big data in Offshore Wind https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R007470/1	EPSRC
IRPWIND http://irpwind.eu/	EU

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Table A1. (Continued.)

Theme F: operations, management, maintenance and safety	
F1. Analysis of remote sensing and condition monitoring data	
Project	Funding body
HOME-Offshore: holistic operation and maintenance for energy from offshore wind farms https://www.homeoffshore.org	EPSRC
A hybrid and scalable digital twin for intelligent direct drive powertrain condition monitoring https://supergen-ore.net/projects/a-hybrid-and-scalable-digital-twin-for-intelligent-direct-drive-powertrain-condition-monitoring	Supergen ORE Hub
Demonstrating a machine learning system to integrate metocean data, sensor networks, and model output for improved coverage and accuracy https://supergen-ore.net/projects/demonstrating-a-machine-learning-system-to-integrate-metocean-data-sensor-networks-and-model-output-for-improved-coverage-and-accuracy	Supergen ORE Hub
V-SCORES https://supergen-ore.net/projects/v-scores-validating-surface-currents-at-offshore-renewable-energy-sites	Supergen ORE Hub
Offshore wind innovation hub—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Offshore wind innovation hub roadmap data—machine learning deep learning from big data https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Machine-learning-deep-learning-from-big-data.pdf	BEIS
F2. Use of autonomous systems for inspection	
Project	Funding body
HOME-Offshore www.homeoffshore.org	EPSRC
Offshore Wind Innovation Hub—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Offshore Wind Innovation Hub roadmap data—beyond visual line of sight BVLOS autonomous systems https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Beyond-Visual-Line-of-Sight-BVLOS-autonomous-systems.pdf	BEIS
Offshore Wind Innovation Hub roadmap data—subsurface inspection techniques https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Subsurface-inspection-techniques.pdf	BEIS
Offshore Wind Innovation Hub roadmap data—robotics autonomous systems to total replacement of human working development https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Robotics-autonomous-systems-to-total-replacement-of-human-working-development.pdf	BEIS
Autonomous Biomimetic Robot-fish for Offshore Wind Farm Inspection https://supergen-ore.net/projects/autonomous-biomimetic-robot-fish-for-offshore-wind-farm-inspection	Supergen ORE Hub
F3. Data and digital cyber security	
Project	Funding body
Offshore Wind Innovation Hub—O&M and Windfarm Lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Offshore Wind Innovation Hub Roadmap Data Cybersecurity https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Cybersecurity.pdf	BEIS
F4. Increased use of automation to reduce risk in installation and operation (O&M)	
Project	Funding body
HOME-Offshore http://homeoffshore.org	EPSRC
FLOTANT http://flotantproject.eu/	EU
A hybrid and scalable digital twin for intelligent direct drive powertrain condition monitoring https://supergen-ore.net/projects/a-hybrid-and-scalable-digital-twin-for-intelligent-direct-drive-powertrain-condition-monitoring	Supergen ORE Hub
Demonstrating a machine learning system to integrate metocean data, sensor networks, and model output for improved coverage and accuracy https://supergen-ore.net/projects/demonstrating-a-machine-learning-system-to-integrate-metocean-data-sensor-networks-and-model-output-for-improved-coverage-and-accuracy	Supergen ORE Hub

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Table A1. (Continued.)

Theme G: environmental and ecosystem aspects

G1. Fit-for-purpose approaches to environmental monitoring

Project	Funding body
INSITE Programme https://insitenorthsea.org/	NERC
MEDIN: Marine Environmental Data and Information Network (https://medin.org.uk/)	Joint funded
FORTUNE: Floating Offshore Wind Turbine Noise https://supergen-ore.net/projects/fortune	Supergen ORE Hub Supergen ORE Hub
Satellite Climate Observation for Offshore Renewable Energy Cost Reduction (SCORE) https://supergen-ore.net/projects/satellite-climate-observation-for-offshore-renewable-energy-cost-reduction-score	Supergen ORE Hub Supergen ORE Hub Supergen ORE Hub
Autonomous Biomimetic Robot-fish for Offshore Wind Farm Inspection https://supergen-ore.net/projects/autonomous-biomimetic-robot-fish-for-offshore-wind-farm-inspection	Supergen ORE Hub
Proving a robust approach to assess bio-physical interactions with floating tidal turbines https://supergen-ore.net/projects/robust-approach-to-assess-bio-physical-interactions-tidal	
V-SCORES (Validating Surface Currents at Offshore Renewable Energy Sites) https://supergen-ore.net/projects/v-scores-validating-surface-currents-at-offshore-renewable-energy-sites	
Going where modern technology cannot: novel adaptions of conventional approaches to record seabird behaviour and fish communities in tidal stream environments https://supergen-ore.net/projects/going-where-modern-technology-cannot-novel-adaptions-of-conventional-approaches-to-record-seabird-behaviour-and-fish-communities-in-tidal-stream-environments	
Offshore Wind Innovation Hub—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	BEIS
Offshore Wind Innovation Hub roadmap data—coordinated environmental monitoring https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Coordinated-environmental-monitoring.pdf	BEIS TCE
OWEC: Offshore Wind Evidence and Change Programme https://thecrownestate.co.uk/en-gb/what-we-do/on-the-seabed/offshore-wind-evidence-and-change-programme/	

G2. Development of population level environmental impact models

Project	Funding body
Offshore Renewables Joint Industry Programme (ORJIP) http://orjip.org.uk/	The Carbon Trust
Cumulative Effects Framework Key Ecological Receptors (CEH) (https://ceh.ac.uk/our-science/projects/cumulative-effects-framework-key-ecological-receptors)	Marine Scotland
Offshore Wind Strategic Monitoring and Research Forum (OWSMRF) https://jncc.gov.uk/our-work/owsmrf/	JNCC
MS ScotMER https://www2.gov.scot/Topics/marine/marineenergy/mre/research/maps	Marine Scotland
MMO Strategic Report (https://gov.uk/government/publications/evidence-strategy-for-the-marine-management-organisation-mmo-2021-2025)	MMO
Renewable energy deep dive: recommendations https://gov.wales/renewable-energy-deep-dive-recommendations-html	Welsh Government
Offshore Wind Innovation Hub (O&M and windfarm lifecycle innovation priorities and roadmap data marine life and ornithology monitoring) https://offshorewindinnovationhub.com/category/operations-maintenance/	OWIH
Offshore Wind Environmental Evidence Register (OWEER) https://marinedataexchange.co.uk/details/3480/2021-jncc-offshore-wind-evidence-and-change-programme-offshore-wind-environmental-evidence-register-/summary	Marine Data Exchange (TCE / JNCC)

G3. Ecosystem Modelling

Project	Funding body
Marine Ecosystems Research Programme (MERP) http://marine-ecosystems.org.uk/Home	NERC
EcoWatt2050 https://masts.ac.uk/media/36374/ecowatt2050-booklet.pdf	EPSRC
Valuing Nature Programme http://valuing-nature.net/	CEH/NERC
UK National Ecosystem Assessment http://uknea.unep-wcmc.org/	CEH/NERC
INSITE Programme http://insitenorthsea.org/	NERC

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Table A1. (Continued.)

Theme H: marine planning governance	
H1. Communication: Ocean literacy and public perception of ORE	
Project	Funding body
Gaia's Energy Adventure https://supergen-ore.net/news-and-events/childrens-book	Supergen ORE Hub
Frontiers for Young Minds https://kids.frontiersin.org/	Frontiers
Policy Network http://britishecologicalsociety.org/	British Ecological Society
UK energy research centre (UKERC) http://ukerc.ac.uk/	EPSRC, NERC, ESRC
People Ocean Planet (POP) https://peopleoceanplanet.com/	MASTS
POST—Parliamentary Office of Science and Technology https://parliament.uk/post	UK Government
Offshore Wind Innovation Hub—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	OWIH
Offshore Wind Innovation Hub roadmap data—generating and standardising social and economic impact methodology https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Generating-and-standardising-social-and-economic-impact-methodology_191015_133650.pdf	OWIH
H2. Interaction with other marine users	
Project	Funding body
INSITE Programme http://insitenorthsea.org/	NERC
Maritime Alliance for fostering the European Blue Economy through a Marine Technology Skilling Strategy (MATES) https://projectmates.eu/	EU
Multi-use platforms at sea (MUPS): an innovative way to manage offshore space and reduce coastal anthropic pressure https://supergen-ore.net/projects/multi-use-platforms-at-sea-mups-an-innovative-way-to-manage-offshore-space-and-reduce-coastal-anthropic-pressure	Supergen ORE Hub
Offshore Wind Innovation Hub—O&M and windfarm lifecycle innovation priorities https://offshorewindinnovationhub.com/category/operations-maintenance/	OWIH
Offshore Wind Innovation Hub roadmap data—mitigating an impact on shipping navigation and commercial fisheries https://landscape.supergen-ore.net/uploads/Offshore-Wind-Innovation-Hub-Roadmap-Data-Mitigating-an-impact-on-shipping-navigation-and-commercial-fisheries.pdf	OWIH
H3. Development of market mechanisms for ORE	
Project	Funding body
INSITE Programme http://insitenorthsea.org/	NERC
Maritime Alliance for fostering the European Blue Economy through a Marine Technology Skilling Strategy (MATES) https://projectmates.eu/	EU
Marine spatial planning is now operational at governance level via the Marine Plan and Marine (Scotland) Plan, https://gov.scot/Topics/marine/science/MSInteractive/Themes/msp	Marine Scotland
H4: Reducing uncertainty of both technology and social costs of ORE	
Project	Funding body
Improve understanding of the economics of biodiversity Programme www.ukri.org/opportunity/improve-understanding-of-the-economics-of-biodiversity/	NERC AND ESRC
The Sustainable Management of UK Marine Resources (SMMR) programme UKERC Flexi funds https://ukerc.ac.uk/news/flexible-fund-call-3/	UKERC
LoadTide https://supergen-ore.net/projects/loadtide	Supergen ORE Hub
FASTWATER: Freely-Available mesoScale simulation Tool for Wave, Tides and Eddy Replication https://supergen-ore.net/projects/fastwater	Supergen ORE Hub

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