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Geoscience Solutions for Sustainable Offshore Wind Development

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Low carbon energy infrastructure, such as wind and solar farms, are crucial for reducing greenhouse gas emissions and limiting global temperature rise to 1.5˚C. During 2020, 5.2 GW of offshore wind capacity went into operation worldwide, taking the total operational capacity of global offshore wind to 32.5 GW from 162 offshore windfarms, and over 200 GW of new capacity is planned by 2030. To meet net-zero targets, growth of offshore wind generation is expected, which raises new challenges, including integration of offshore wind into the natural environment and the wider energy system, throughout the wind farm lifecycle. This review examines the role of geosciences in addressing these challenges; technical sustainability challenges and opportunities are reviewed, filtered according to global governance priorities, and assessed according to the role that geoscience can play in providing solutions. We find that geoscience solutions play key roles in sustainable offshore wind energy development through two broad themes: 1) windfarm and infrastructure site conditions, and 2) infrastructure for transmission, conversion and energy storage. To conclude, we recommend priorities and approaches that will support geoscience contributions to offshore wind, and ultimately enable sustainable offshore wind development. Recommendations include industry collaboration and systems for effective data sharing and archiving, as well as further research, education and skills.

Keywords: offshore wind energy, sustainability, geo-assets, climate change, whole system, life cycle, seismic stratigraphy, ground models

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INTRODUCTION

The deployment of low carbon infrastructure, such as wind and solar farms, are central to the strategy to reduce greenhouse gas emissions with the aim of limiting global temperature rise to 1.5˚C above pre-industrial levels (UN, 2015; IPCC, 2018; Jensen et al., 2020). Cost of offshore wind energy has rapidly decreased (Taylor et al., 2020), and the technology has high societal acceptability (Karakosta et al., 2013; Contestabile et al., 2017; Ahsan and Pedersen 2018; Morrissey and Heidkamp 2018). In 2020, a total of 32.5 GW offshore wind was in operation globally, with a further 10.4 GW under construction (World Forum Offshore Wind, 2021). The World Forum Offshore Wind assessed that the United Kingdom holds the largest market with close to 10 GW operational capacity, with China expected to take over the leading position during the 2020s (World Forum Offshore Wind, 2020). By 2050, offshore wind could reach 75–175 GW in the United Kingdom, 450 GW across the EU, and 1,400 GW globally (WindEurope, 2019; Global Wind Energy Council, 2020; Ocean Renewable Energy Action Coalition, 2020).

While offshore wind farms alter the physical and biological environment, with associated positive and negative impacts (Soukissian et al., 2017) [deemed comparatively minor relative to other energy technologies (Stamford and Azapagic, 2012)], the rapidly growing offshore wind market raises significant challenges for sustainable development (Velenturf, 2020). To address sustainability challenges, offshore wind experts point to the need for whole-system design, and turning offshore wind farms into multi-functional structures (e.g., Contestabile et al., 2017; Soukissian et al., 2017). For example, integrated solutions could combine different types of renewable energy infrastructure with secondary users, including nature conservation. Whole system assessments rely on the ability to measure economic, societal and environmental costs and benefits. To do this, there is a need for data to assess the effects of offshore wind on hydrodynamics and biodiversity (e.g., Van Berkel et al., 2020). In addition, the ability to investigate site-specific conditions and adapt the design, (de)construction and operations of offshore wind farms accordingly (e.g., Nielsen and Sørensen, 2011; Martin et al., 2016; Shankar Verma et al., 2021), across the lifecycle of a site, including considering decommissioning/repowering governance and solutions, is required (Jensen et al., 2020).

Accessing local wind power expertise and skills can increase regional benefits and societal acceptability, but the offshore wind sector often struggles to meet local supply chain content–and consequently local job targets (e.g., Allan et al., 2020). The sector has highlighted the potential to retrain skilled workers from the oil and gas industry (e.g., Arcelay et al., 2021), a sector that is expected to decline, but with workers who have skills and experience needed for low carbon applications (Hastings and Smith, 2020). Moreover, repurposing of oil and gas infrastructure for offshore wind could facilitate green hydrogen, another sector which could offer low carbon jobs for oil and gas workers, and which is anticipated to support offshore wind development by helping to ease key bottlenecks to deployment (Spyroudi et al., 2020; Quirk et al., 2021).

The ambitions to grow offshore wind requires tremendous steps forward in engineering capabilities in order to increase the scale of deployment. Here, we aim to make a unique contribution by joining up sustainability challenges and opportunities for offshore wind with geoscience-led solutions across the lifecycle of developments. In particular, we identify four integration challenges that require input from the geosciences, and geoscientists, to be solved (see *Prioritising Technical Offshore Wind Challenges and Opportunities* Section). Therefore, we start by reviewing the technical challenges in offshore wind and we prioritise these based on global governance targets. We assess the potential of the geosciences in addressing these challenges and recommend priorities and approaches that would support geoscience contributions to offshore wind and, ultimately, enable sustainable offshore wind development. Furthermore, we emphasise the need for education and skills development in collaboration with industry in which the development of systems for effective data archiving and sharing play a key role.

PRIORITISING TECHNICAL OFFSHORE WIND CHALLENGES AND OPPORTUNITIES

Overview of Technical Challenges and Opportunities

Offshore windfarm sites, whether evaluated, under development, or fully operational, cover large areas of many continental shelves, such as the North Sea (**Figure 1**). The sustainable growth of the offshore wind sector faces a broad range of environmental, societal, economic and technical challenges and opportunities (Velenturf, 2020). The technical challenges and opportunities can be grouped under four categories in terms of integration: 1) the natural environment, 2) other users of the marine space, 3) the energy system, and 4) the lifecycle of offshore wind farms (**Figure 2**). We consider each category in turn.

Integration into the Natural Environment

Integration of wind farms into the natural environment requires the identification of sites with amenable conditions for wind power generation to access the underexploited global wind resource, which is estimated at a potential 39 TW (Shaker and Patton, 2014; Drunsic et al., 2016; Soukissian et al., 2017). Locations for new wind farms are likely to be further away from the coastline where more wind resource is available (Brink, 2017; Ahsan and Pedersen, 2018), and generally has the advantage of less wind turbulence. An understanding of the site-specific conditions for each offshore wind farm has to be developed to optimise design, (de)construction, and low-risk and cost-effective operation and maintenance (O&M) (Nielsen and Sørensen, 2011). Developing this understanding can be challenging due to sites being dynamic and possibly environmentally sensitive (Jenner et al., 2002; Brink, 2017; Topham and McMillan, 2017, Morrissey and Heidkamp, 2018).

Integration with Other Users of the Marine Space

A recognized advantage of offshore wind is that it helps to reduce pressure on land resource, but infrastructure developments have taken on such a scale (**Figure 1**) that conflicts with other users of the marine space (such as fishing, transport, military defence systems, recreation, cultural heritage, and nature conservation) have emerged (Azzellino et al., 2013; Soukissian et al., 2017). In response, there is a growing call to move from single sector planning to integrated maritime planning approaches, known as Maritime Spatial Planning (MSP). An EU Directive defines MSP as "a process by which the relevant Member State's authorities analyse and organise human activities in marine areas to

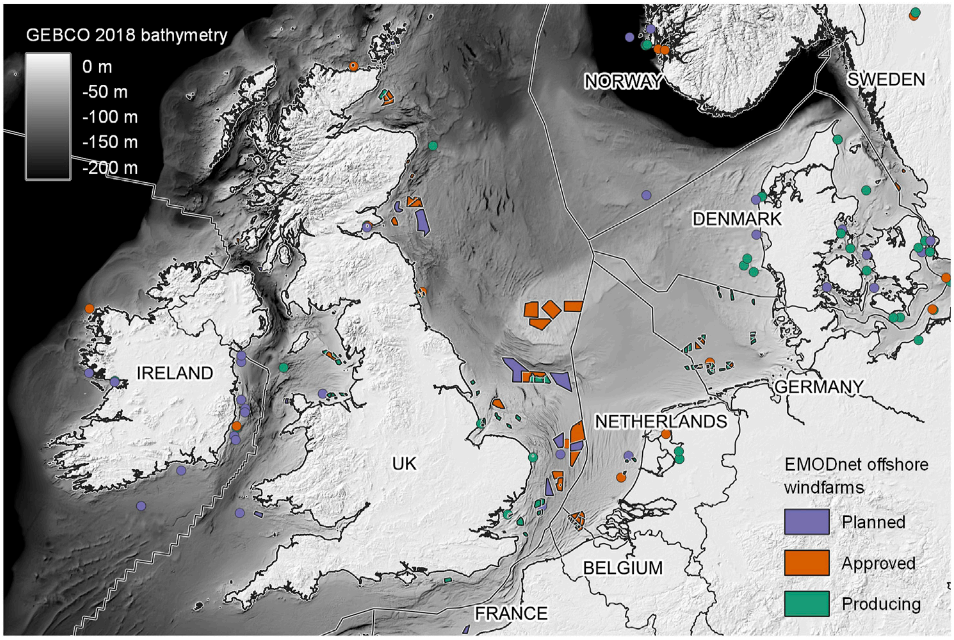

FIGURE 1 | Operational and planned offshore windfarms on the NW European continental shelf. The large areas these farms cover is driving the need for multi-functional systems and structures in which different marine uses and users are combined. Bathymetry data source: Global Wind Energy Council, 2020 bathymetry tiles (https://www.gebco.net/data_and_products/gridded_bathymetry_data/). Windfarm shapefile source: EMODnet, accessed 17/02/2021 (https://www.emodnet-humanactivities.eu/search-results.php?dataname=Wind+Farms+%28Polygons%29). Topography data source: EU-DEM (https://www.eea.europa.eu/data-and-maps/data/eu-dem). Colour map used "grayC" from Crameri (2021).

achieve ecological, economic and societal objectives". MSP aims to work as an integrative process to cope with the increasing for maritime space demand from traditional and emerging sectors while preserving the proper functioning of the marine ecosystems. These challenges open new opportunities for the development of multi-functional systems and structures in which different marine uses (and users) are combined to create synergies rather than trade-offs (e.g., Wever et al., 2015; Contestabile et al., 2017).

Integrating Offshore Wind into the Energy System

Intermittency and integration of offshore wind power into the energy system are well-known issues (e.g., Rohrig and Lange, 2008; Karakosta et al., 2013), for example, in the provision of low carbon cooling and heating solutions. In part, the intermittent electricity supply can be balanced by commissioning more energy storage capacity, possibly aided by fast-moving development in battery technology for electric vehicles (Soukissian et al., 2017) and utilization of geo-asset storage capacity. Geo-assets are defined here as legacy or new geological infrastructure with the potential to be (re) deployed for energy or carbon storage. Legacy geo-assets include abandoned mine shafts and decommissioned oil and gas fields, and new geo-assets include saline aquifers suitable for hydrogen storage or CO_2 disposal. Geo-assets suitable for energy storage could be used to introduce greater flexibility for the integration of offshore wind into the energy system. Greater flexibility will increase the efficiency of the whole energy system, which remains a concern for wind energy development (Contestabile et al., 2017).

Integrated Whole Windfarm Lifecycle Perspective

The efficiency of individual turbines and windfarm arrays can be optimised further throughout the whole offshore wind lifecycle, which can help to reduce costs from the design phase through to construction, O&M and decommissioning at end of use. The increasing scale of offshore wind infrastructure brings advantages in terms of greater economies of scale and reduced costs, but it also causes new challenges, such as the increasing complexity of construction projects (Simani, 2015; Brink, 2017). To date, the offshore wind sector has focussed more on project development and commissioning and less on decommissioning and repowering. The limited attention for end of use processes from project outset makes decommissioning operations more difficult at the end (Topham and McMillan 2017; Jensen et al., 2020).

Global Governance Priorities for Energy Systems

Global governance of energy systems is mainly led by the UN Sustainable Development Goals (SDGs) (UN, 2015) and the UN Framework Convention on Climate Change, supported and

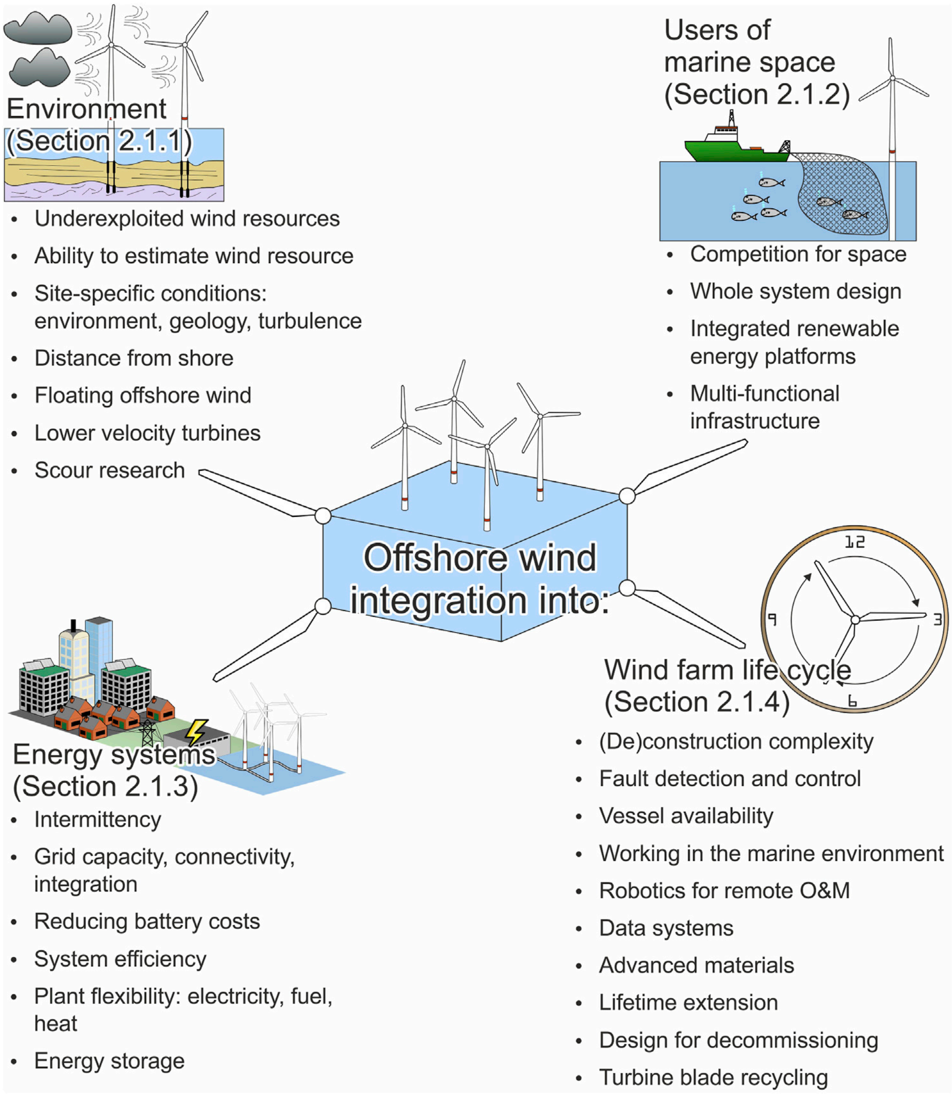

FIGURE 2 | Technical challenges and opportunities to integrate offshore wind into the environment (2.1.1), with other users of marine space (2.1.2), the wider energy system (2.1.3) and throughout the wind farm lifecycle (2.1.4).

influenced by organisations in the wider UN family and others such as the Intergovernmental Panel on Climate Change (IPCC), World Bank and World Health Organisation. The International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) translate ambitions into more detailed and action-oriented measures, which are developed further and implemented by national governments.

Taking a lifecycle approach to offshore wind farms is essential to strengthen the sustainability potential and secure long-term clean energy provision responding to several SDGs. First and foremost, geoscience solutions are critical in maximising the contribution that offshore wind can make to SDG 7, "Ensure access to affordable, reliable, sustainable and modern energy for all", while responding to SDG 13, "Take urgent action to combat climate change and its impacts", given that "Climate change is one of the greatest challenges of our time and its adverse impacts undermine the ability of all countries to achieve sustainable development". SDG 7 emphasises the importance of ensuring universal access to affordable, reliable and modern energy services, which can be provided by offshore wind.

In addition, system integration for energy storage helps to achieve SDG target 13.2, "Integrate climate change measures into national policies, strategies and planning". Trade-offs must be managed to prevent adverse unintended consequences at different scales. There is a risk in SDG 14, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", from the disturbance and pollution during construction of offshore infrastructure. This must be mitigated by avoiding any measures that limit the success of target 14.2, "By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans", and target 6.6, "By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes" which is particularly important given the freshwater (and terrestrial) ecotoxicity risks associated with the mining and processing of the materials for wind turbine manufacturing. Nevertheless, using marine space to generate low carbon energy can alleviate pressure on land and support SDG 15, "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss".

Using geo-assets for energy storage will help to unlock the full potential of offshore wind to contribute to target 7.2, "By 2030, increase substantially the share of renewable energy in the global energy mix". This offers an important building block for SDG 9 to "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation", which enable industries and residential areas alike to adopt "clean and environmentally sound technologies and industrial processes". In that regard, SDG 12 to "Ensure sustainable consumption and production patterns" is also important as integrated use of offshore wind and energy storage will reduce demand for the exploitation of materials needed for fuels and batteries (which would otherwise increase risks to SDGs 6, 14, and 15 as discussed above). There is a trade-off, nevertheless, as increasingly affordable renewable energy supply does not motivate reduced consumption as it should in most developed countries and indeed fully deliver on the intentions of target 12c, "Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption", and not simply replacing them with an alternative unsustainable practice that would get in the way of ensuring "the lasting protection of the planet and its natural resources".

There is an urgent need for appropriate attention to be placed on whole system sustainability, otherwise there is a growing risk of displacing climate impacts from fossil fuels to impacts from renewables, such as wind, which require large volumes of metals and other materials (Vidal et al., 2013). The mining and processing of these material is associated with potential destruction of aquatic and terrestrial environments. Embedding circular economy practices in the design, use, and end-of-use of wind energy infrastructure will be essential to improve the sustainability of offshore wind (Velenturf, 2021).

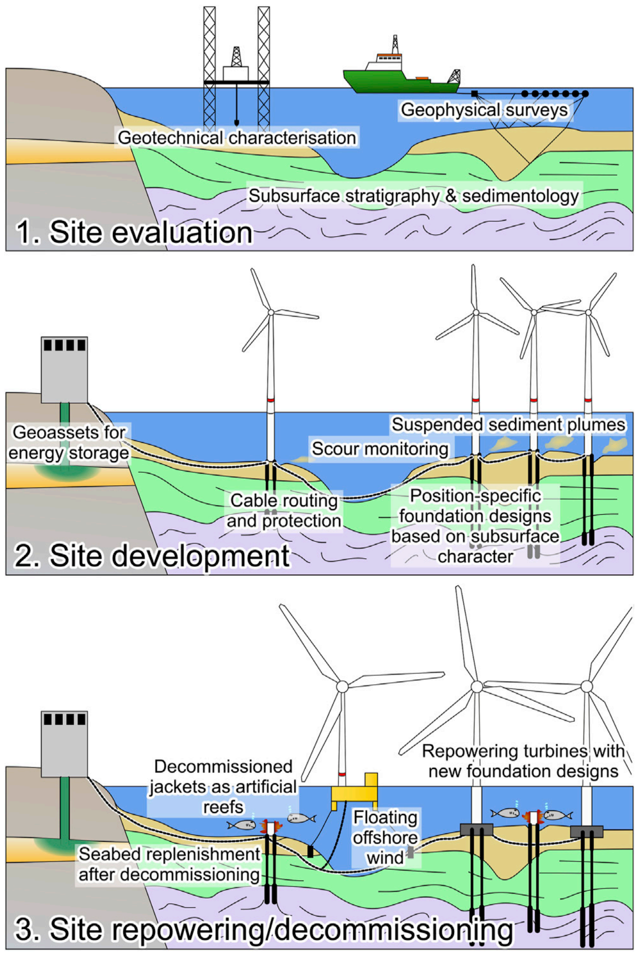

FIGURE 3 | Example of the many roles of geoscience in integrated offshore wind through the lifetime of a site, from 1) site identification and evaluation, 2) site development, and 3) site repowering and/or decommissioning.

GEOSCIENCE SOLUTIONS

To meet the UN SDGs, it is crucial that the technology-related global governance priorities are addressed by transformation of energy systems. First, to establish a diverse global energy mix by making the most of integrating energy systems and increasing energy solutions and developments that are appropriate to place and scale, thereby supporting affordability, cost effectiveness, limiting price volatility and ensuring energy access. Second, the provision of low carbon cooling and heating is an important part of this energy solution, and forms part of an integrated offshore wind energy system. Third, to continue to reduce energy usage overall through demand reduction and increased production efficiencies. The technology-related global governance priorities for energy systems present a series of challenges and opportunities, which must be addressed, and which may have multiple solutions. Here, we explore how geosciences can contribute to these issues to support growth of sustainable offshore wind (**Figure 3**; **Table 1**) including by: 1) estimating wind resource now and in the future; 2) assessing site-specific conditions; 3) constraining ground conditions for wind turbine foundations, and forecasting the provision of anti-scour measures; 4) designing whole energy systems, with greater plant

TABLE 1 | Summary of geological characteristics and properties and their consideration during site evaluation, construction, and maintenance.

Geological characteristic/process	Site appraisal consideration	Wind farm development stage
Seabed composition		
Soft muds	Low strength, potentially unable to bear large loads (e.g., jack-up rig used during construction)	IC, DR
Coarse lag (gravel to boulders) deposits	A hard, potentially heterogeneous substrate that is difficult to penetrate. Can lead to refusal of infrastructure or damage of equipment	IC, DR
Overconsolidated sediments	Difficulty in construction (e.g., driving piles) in strong sediments. Difficult to predict scour behaviour	IC, M, DR
Bedrock outcrop at seabed	Provides a hard substrate for emplacement of seabed infrastructure (e.g., drilled piles). However, may be weathered with lower strengths at the interface with Quaternary sediments	IC
Mobile sediment		
Migrating erosional and depositional bedforms changing topography at the time scale of operation	Can bury or expose infrastructure (e.g., piles, cabling) or may present a barrier to activities	M, DR
Mobile sediment can change sediment composition at seabed	Dynamic mobile sediment layer leads to variation in samples taken from the same site at different times, leading to difficulty characterising seabed for scour mitigation	M, DR
Bedform migration in different direction to prediction from morphology and tidal currents	Necessitates repeat bathymetric surveys to observe actual bedform migration	M, DR
Seabed glacial landforms misinterpreted as mobile sediment bedforms	Misinterpretation may suggest mobile sediment in an area where it is not present, potentially leading to unnecessary mitigation steps	CP, M
Changing bedform topography modifies currents and can lead to scour	Changing bedform topography alters hydrodynamics, making scour prediction and mitigation difficult	CP, M, DR
Wind farm array and cable route interaction with sediment migration	Multiple seabed installations can complicate hydrodynamics, changing sediment and bedform migration direction and rate (e.g., sediment plumes)	M, DR
Shallow gas and fluid mobility hazards		
Gas or fluid present in shallow subsurface	Can lead to blow outs when drilling for sediment sampling and infrastructure construction. Gas can cause acoustic blanking of seismic reflection data, preventing interpretation of units below	SA, IC, DR
Methane-derived authigenic carbonates (MDACs)	Forms a hard substrate that is recognised as a special habitat that must be assessed for habitat preservation. Hard substrate may lead to construction issues	SA, CP, IC, DR
Pockmarks	Can indicate the presence of shallow gas or overpressured pore fluids in sediments. Pockmarks may be unstable and should be avoided during turbine installation and cable routing	SA, IC, DR
Quaternary sediments		
Variable sediment thickness	Sediment thickness can vary abruptly in a small spatial area due to complicated palaeotopography or depositional process, complicating turbine siting and cable routing	SA, CP, DR
Variable lithology (vertical and spatial)	Past processes deposit and rework sediments that are highly variable laterally, over large areas and at many stratigraphic levels. A single foundation design may be unsuitable across a wind farm site. Landforms and onshore analogues can be used to reduce uncertainty in foundation design and cost	SA, CP, DR
Heterogeneous sediment composition	Continental shelf to slope stratigraphy is commonly heterogeneous, with abrupt changes in geotechnical properties	SA, CP, IC, DR
Sediment instability	Slope instability may be caused by sediment heterogeneity or fluid overpressures. Loading of slopes has the potential to trigger submarine landslides	SA, M, DR
Past submarine landslides	Tsunami and their causal past submarine landslides should be understood to mitigate for future possible natural submarine landslides	SA, M, DR
Overconsolidated sediments	Past processes, such as ice sheet loading or subaerial exposure and desiccation, can lead to overconsolidation of sediments and difficult testing and construction conditions	SA, IC, DR
Palaeochannels	Palaeochannels can have steep sides, with sharp variations in sediment composition either side and within channel fills, requiring a complicated foundation design	SA, IC, DR
Anthropogenic		
Mining and oil and gas extraction		SA, M, DR

(Continued on following page)

TABLE 1 | (*Continued*) Summary of geological characteristics and properties and their consideration during site evaluation, construction, and maintenance.

Geological characteristic/process	Site appraisal consideration	Wind farm development stage
	May have weakened bedrock, with potential for seismic activity if mines collapse	
Aggregate extraction	Can disturb or remove stratigraphy, leading to incorrect interpretation of geological history, and can change hydrodynamics locally	SA, IC, M, DR
Fishing activity	Some types of fishing (e.g., trawling) damage seabed and alter sediments, forming trenches and artificial bedforms	SA, IC, M, DR

Abbreviations in the "Wind farm development stage" column: SA, site assessment/feasibility; CP, uncertainty in cost prediction; IC, infrastructure construction; M, maintenance; DR, decommissioning/repowering. Adapted from Mellett et al. (2015).

flexibility and system efficiency; 5) increasing grid capacity, connectivity and integration to manage intermittency of offshore wind; and 6) improving energy storage using subsurface geo-assets (e.g., depleted oil and gas reservoirs, salt caverns, coal mines) and batteries.

Wind Farm and Infrastructure Site Conditions

Wind Resources and Climate Change Impacts

Estimating wind resource at a potential windfarm site uses empirical data, or modelling approaches, or a combination of both. Observational methods expand relatively short records to longer-term predictions by using correction methods (Barthelmie et al., 2005; Grilli et al., 2010; Lee et al., 2010), or by a measure-correlate-predict approach, where measurements are made over a period and correlated to longer-term climate observations at a reference location or atlas of low-resolution wind climate (e.g., Barthelmie et al., 2005; Standen et al., 2017). Advances in remote data observation, such as Light Detection And Ranging (LiDAR) measurements (Bodini et al., 2019), and satellite observations such as Advanced Scatterometer (ASCAT) remote sensing (Remmers et al., 2019), increase spatial and vertical resolution of observations. These approaches are sufficient for short-term wind resource estimation. However, extrapolation to longer timescales contain uncertainties in accurate projection of wind resource at an appropriate elevation. Modelling approaches, which combine long-term climate corrections to statistical techniques with high spatial and vertical resolution of topography and climate observations, such as the Met Office's Virtual Met Mast, reduce the spatial and vertical uncertainty in wind climate projection (Standen et al., 2017).

Wind resource estimation over wide areas is applied to maps by calculating the wind power density from modelled wind speeds for individual grid squares (Grilli et al., 2010; Soukissian et al., 2017; Bodini et al., 2019). This allows rapid identification of sites with suitable wind speeds in areas with lowest turbulence. Wind turbulence, which can damage wind turbines, is greatest close to coastlines, and the influence of the coastal topography on wind flow can extend for over 20 km offshore (Barthelmie et al., 2005). Sites with suitable wind resources and minimal turbulence can then be combined with areas assessed for geological and ecological suitability to assess offshore wind site feasibility and siting (Grilli et al., 2010; Peters et al., 2020).

Changing climate presents both opportunities and challenges for offshore wind, altering the global distribution of wind resource and driving inter- and intra-annual variability (Wiser et al., 2011; Collins et al., 2013). Decadal-scale ocean-atmosphere oscillations (e.g., North Atlantic Oscillation, Pacific Decadal Oscillation) can drive changes in wind speed, regionally and globally. These processes have resulted in global mean annual wind speed rising from 3.13 m/s in 2010 to 3.30 m/s in 2017, which has the potential to increase power generation from a typical 2.5 Mw turbine by 17% (Zeng et al., 2019). However, such oscillations can also result in reduced wind speeds. Long-term climate change will have similar consequences, with models underpinned by climate projections suggesting changes in local wind power of ±5–20%, with potentially even greater seasonal variability (e.g., Hueging et al., 2013; Reyers et al., 2015; Tobin et al., 2016). Climate change is set to increase the occurrence of extreme events (Seneviratne et al., 2012; IPCC, 2018), with increases in storm intensity and rising sea levels creating new challenges to the operation and maintenance of offshore wind turbines, and potentially accelerate leading edge erosion (Herring et al., 2019). Advances in computational modelling of future climate provides an opportunity to forecast areas of projected wind energy increase (e.g., Davy et al., 2018; Soares et al., 2019), alongside climate-related hazards, with the potential to prioritise sites for development where the levelized cost of energy (LCOE) may decrease as a result of climate change (Hdidouan and Staffell, 2017).

Site Identification and Investigation

The ideal site for an offshore windfarm maximises wind resources (Grilli et al., 2010; Lee et al., 2010) balanced with a range of societal, technical and environmental factors. Minimising the visual impact can reduce opposition for offshore wind projects (Ho et al., 2018). Considerations also have to be given to reducing the risks of disruption to offshore flight patterns of birds (Dirksen et al., 1998; Fox et al., 2006; Hüppop et al., 2006), and avoiding high mortality rates (Cleasby et al., 2015; Lane et al., 2019). Spatial tracking of bird foraging movements allows identification of flight density and altitude, and planning of offshore wind sites. Sites further from coastlines are optimal, as they minimise wind turbulence caused by topography and coastlines (Barthelmie et al., 1996, 2005), are out of visual range of coastal communities (Ho et al., 2018), and are in areas where foraging bird species, such as the northern gannet, generally fly lower (Cleasby et al., 2015).

For turbines with fixed foundations, maximising distance from coastlines may be limited by suitable water depth and seabed substrate. Before site surveying and new data collection, geological desk studies can provide first-pass site identification and design survey approaches (Coughlan et al., 2020). Regional marine geoscience studies and seabed mapping programmes, acquired as collaboration between government or state agencies and research institutions, lend themselves to site identification and early investigation. The INFOMAR programme in the Republic of Ireland provides, amongst other things, open access bathymetry and sub-bottom profiler data, which can be used to supplement the European Union's EMODnet products (Guinan et al., 2021). In the United Kingdom, the Marine Data Portal provides access to legacy data from the United Kingdom Continental Shelf. Other examples include mapping the Irish Sea (Mellett et al., 2015), North Sea Basin (Le Bot et al., 2005), offshore Atlantic Canada (Eamer et al., 2021), and the Taiwan Straits (Han et al., 2020), which can support appraisal of prospective areas with accumulations of sediment suitable for foundations. Shallow continental shelves were also historical targets for hydrocarbons exploration, and legacy datasets may be repurposed to enhance understanding of stratigraphic and sedimentary architecture when assessing suitability of offshore wind sites (Fitch et al., 2011; Cotterill et al., 2012; Dove et al., 2016, 2017). Such legacy datasets not only allow for refining regional stratigraphic understanding (Dove et al., 2016), but also allow reuse of knowledge gained during oil and gas infrastructure installation and operation (Sturm, 2017). While the spatial resolution of such datasets are often unsuitable for site-specifc developments, they may be invaluable in first- and second-pass evaluations reducing risk and costs (**Table 1**).

Specific site investigation survey design depends on the planned scale of turbine and foundation type. Common to all surveys is the need to characterise the seabed-geology of the subsurface for geotechnical properties to form a ground model (Clare et al., 2012; Oh et al., 2018). Geophysical surveys image the seabed and subsurface to allow for geological investigation. Current standards in subsurface geophysical investigation are to acquire a dense two dimensional grid of sub-bottom profiles and single-channel seismic reflection profiles to build a "pseudo-3D" volume (Monrigal et al., 2017). Three dimensional seismic reflection techniques could provide much more complete datasets, with multichannel systems allowing attribute analysis like standard hydrocarbon industry techniques (Vardy et al., 2017). Geological data are acquired based on sediment samples to be tested for geotechnical properties, such as density and shear strength. For example, cyclic lateral loading of monopiles is commonplace once wind farms are in operation, but tests and models of long-term effects are still under development (e.g., Nikitas et al., 2016; Ma et al., 2020). Bhattacharya (2019) provides a comprehensive summary of engineering parameters that are required for various calculations used in site development.

Identified offshore wind sites may have pre-existing construction hazards, both geological and human, which geophysical data can identify. Unexploded ordnance (UXO), shipwrecks, shallow gas and boulder submerged in sediments, need to be identified prior to turbine foundation installation. Multibeam bathymetry data are acquired to identify shipwrecks in high resolution (Majcher et al., 2020), and can be combined with magnetic gradiometer surveys to identify UXOs (Clare et al., 2012; Liingaard et al., 2012). Shallow gas hazards can be identified on sub-bottom and seismic profiles, but the extent of shallow gas can be hard to detect. However, using image analysis and reflection coefficient techniques, phase reversals in the seismic reflections can be identified, even in subtle reflectors (Blackford et al., 2014; Cevatoglu et al., 2015; Vardy et al., 2017). Complicated stratigraphic terminations may also hide or produce false shallow gas hazards through tuning (Barrett et al., 2017). Boulders and large dropstones may be identified through modern two dimensional deep tow sparker and ultra-high-resolution three dimensional seismic reflection surveys (Monrigal et al., 2017), and diffraction imaging of multichannel seismic data (Grasmueck et al., 2012; Wenau et al., 2018).

Subsurface Characterisation for Optimal Foundation Design

Foundation design and installation accounts for 20–30% of overall offshore wind construction costs (Zdravković et al., 2015). Soil (substrate) conditions and water depth are amongst the most important factors influencing overall cost (Zhang et al., 2016). Monopile foundations have been used in 75–80% of offshore wind turbine installations (Zhixin et al., 2009), because they are simple and cheap to install (Lacal-Arántegui et al., 2018). Optimising foundation design based on a detailed understanding of the subsurface geology has the potential to significantly reduce both the LCOE of offshore wind projects, and the risk of foundation failure (Kallehave et al., 2015; Oh et al., 2018). Pile diameters of 5–6 m are regularly used, but can be up to 10 m (Zdravković et al., 2015; Arany et al., 2017). Pile depths can be up to 40 m below the seabed (Augustesen et al., 2009; Kallehave et al., 2015), and are likely to be deeper than 50 m with the advent of "XXL" monopoles (Empire Engineering, 2019).

Site-specific pile designs are based on detailed subsurface conditions, varying factors such as pile diameter, length, and wall thickness (Kallehave et al., 2015). The key requirement for

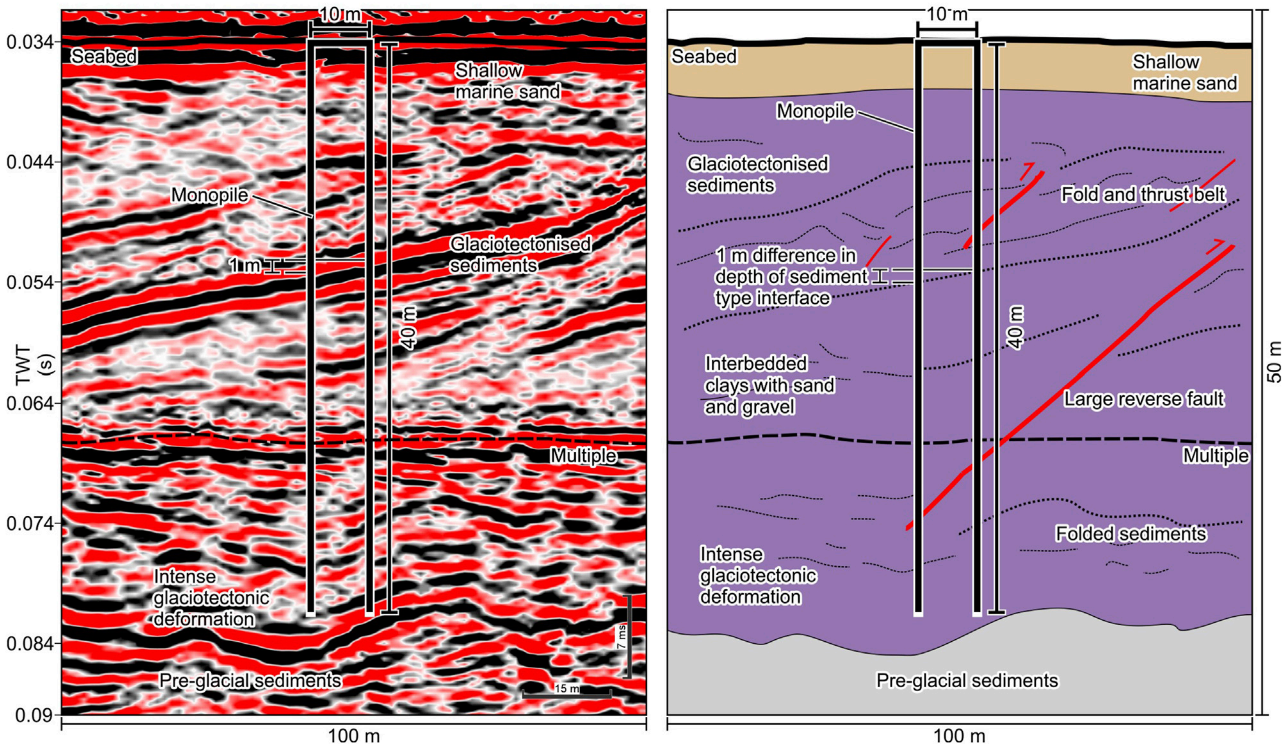

FIGURE 4 | Example of the use of high-resolution seismic reflection profiles in identifying complex subsurface conditions that may impact foundation design. The complicated stratigraphy (in this case glaciotectonised sediments) needs to be constrained through subsurface investigation to design a stable foundation that minimises material use and costs. At the scale of a monopile, here shown as 10 m diameter and 40 m deep, stratigraphic changes in sediment/soil physical properties can necessitate metre-scale variations in position-specific foundation design.

foundation design is development of a geotechnical ground model (Clare et al., 2012), involving identification of engineering parameters of the subsurface geology through a combination of geological, geophysical, and geotechnical datasets (Oh et al., 2018; Bhattacharya, 2019), normally as a desk study (Clare et al., 2012; Achmus et al., 2013). These datasets are integrated to provide a geological evolution of the subsurface (e.g., Jensen et al., 2008; Cotterill et al., 2012; Cotterill et al., 2017 C.; Cotterill et al., 2017 C. J.; Le et al., 2014; Reynolds et al., 2017a, 2017b; Vardy et al., 2017; Emery et al., 2019a, 2019b; Eaton et al., 2020; Van Landeghem and Chiverrell, 2020), which constrains the three dimensional distribution of sediment properties within the ground model. Ground conditions on continental shelves, especially where previously glaciated, comprise complex stratigraphy and different depositional environments (**Figure 4**: Example of the use of high-resolution seismic reflection profiles in identifying complex subsurface conditions that may impact foundation design). The complicated stratigraphy (in this case glaciotectonised sediments) needs to be constrained through subsurface investigation to design a stable foundation that minimises material use and costs. At the scale of a monopile, here shown as 10 m diameter and 40 m deep, stratigraphic changes in sediment/soil physical properties can necessitate metre-scale variations in position-specific foundation design.), leading to spatially variable sediment properties such as density and over-consolidation ratio. Predicted sediment and geotechnical characteristics can be supported by quantitative geophysical techniques. Analysis of attributes, such as attenuation (Q), P-wave velocity, and seismic inversion, provide powerful remote characterisation that is underused in site investigations (Pinson et al., 2008; Vardy et al., 2017, 2018; Vardy and Pinson, 2018). Geotechnical ground characterisation and examination is essential, is governed by the type of foundation and depends on the depth of the water, the geology of the area, and the environmental conditions (Bhattacharya, 2019).

There are concerns within the offshore wind industry that current design approaches, especially the commonly-used *p-y* method (suggested by most guidelines, e.g., API, 2014; DNV, 2014), are not suitable for designing large diameter stiff piles. This is because these approaches were developed for more flexible and much smaller piles, adopted from the offshore oil and gas industry (Kallehave et al., 2012; Byrne et al., 2015). The geometry and cyclic nature of the load conditions of large-

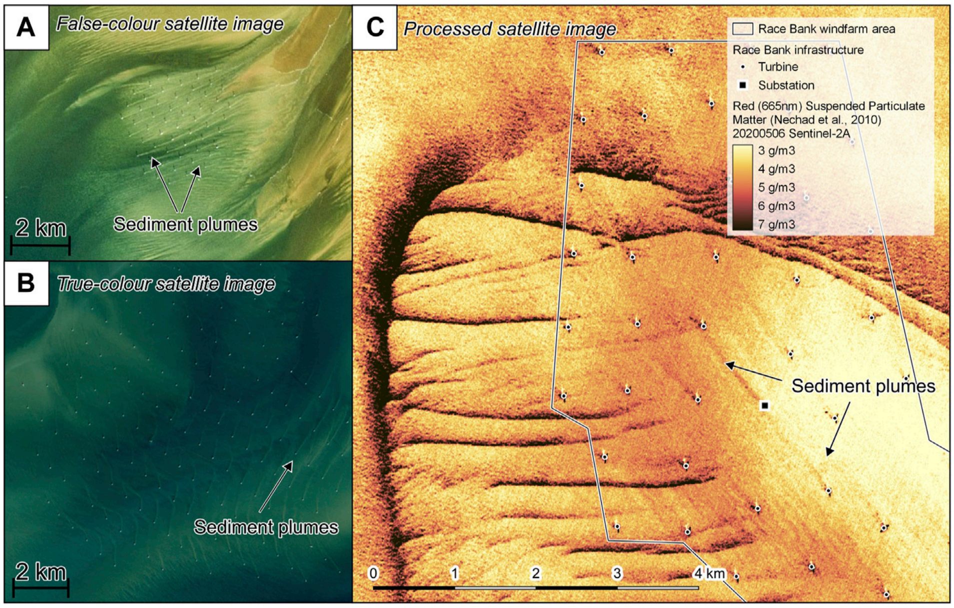

FIGURE 5 | Interaction of infrastructure and hydrodynamics generate long-lived suspended sediment plumes observed in satellite data. **(A)** Robin Rigg offshore windfarm, Solway Firth, a sandbank midway between the Galloway and Cumbrian coasts. Note sediment plumes in wake of turbines. False colour image, acquired by the Operational Land Imager on the Landsat 8 satellite on October 2nd, 2019. **(B)** London Array offshore windfarm, southern North Sea. True colour image acquired by the Operational Land Imager on the Landsat 8 satellite on June 30th, 2015. Note sediment plumes in wake of turbines. **(C)** Sentinel-2 satellite data showing suspended sediment concentrations at Race Bank offshore windfarm, generated from the red band (665 nm) using the method of Nechad et al. (2010). Colour map "lajolla" from Crameri (2021). **(A)** and **(B)** adapted from the NASA Earth Observatory, part of the EOS Project Science Office, https://earthobservatory.nasa.gov.

scale wind turbines are markedly different from load conditions of oil and gas infrastructure (Doherty and Gavin, 2012; Oh et al., 2018). Recently, new finite-element and macro-element modelling approaches have been developed which are more robust, including effects of cyclic loading and damping (Augustesen et al., 2009; Schafhirt et al., 2016; Page et al., 2017, 2018; Jostad et al., 2020). However, these rely on a well-constrained ground model of sediment properties to predict pile behaviour over decadal timescales.

Sediment Mobility and Turbine Wakes

Bed stresses induced by tidal currents, waves or a combination of both, can induce suspended and bedload sediment transport, which can lead to erosion of the seabed, or deposition, resulting in a wide range of bedforms being identified on continental shelves. Present day patterns of seabed erosion, sediment transport and bedform migration are controlled over time periods of weeks to decades by the variations in tidal currents, storm surges, and wave action (Stride, 1982; Whitehouse et al., 2011). Over decadal to millennial time periods patterns of net erosion and deposition are controlled by changes in climate and relative sea level. Repeat bathymetric surveys show that the seabed is highly dynamic (e.g., Van Landeghem et al., 2012), and sediment mobility and bedform migration are important factors to consider over the lifespan of an offshore windfarm array (Games and Gordon, 2014). When a single wind turbine foundation is installed, the hydrodynamic field will be perturbed locally (Whitehouse, 1998), with formation of a horseshoe vortex in front of a monopile structure, and lee-wake vortices behind a structure (Chen and Lam, 2014; Wu et al., 2020). The patterns of turbulence, wave reflection and diffraction, and breaking waves can cause instability and liquefaction of substrate (soil) leading to increased seabed scour, sediment suspension and transport. Therefore, seabed topography will be modified after installation of offshore windfarm infrastructure potentially compromising long-term foundation stability and cable durability. At the planning stage, projects are required to determine the physical impact on the seabed arising from installed structures (e.g., Whitehouse et al., 2011). Installation of scour protection for structural foundation stability or cable protection can cause edge scour or secondary scour in the seabed around the protection deeper than the unprotected case (Whitehouse et al., 2011).

The evolution of seabed scours has been documented through interpretation of monitoring data, highlighting variations between sites with different sediment characteristics in terms of seabed morphology and substrate type (e.g., Whitehouse et al., 2011; Matutano et al., 2013; Miles et al., 2017). For example, Whitehouse et al. (2011) noted that scours are shallow in muddy substrates, but in sandy substrates can develop up to 1.38 times deeper than the monopile diameter. In high latitude and temperate offshore locations, the subsurface contains a complicated Quaternary stratigraphic record of multiple ice sheet advance and retreat

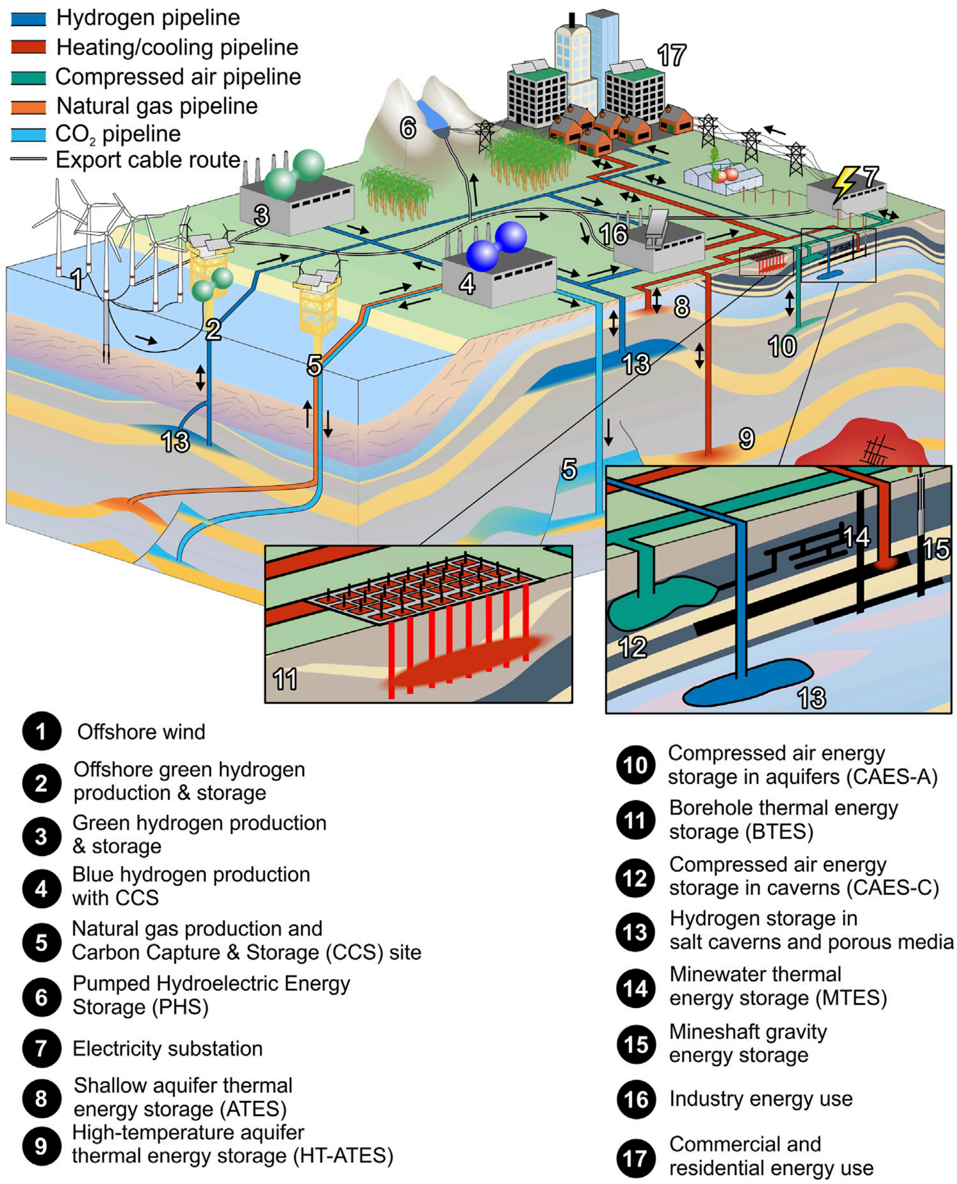

FIGURE 6 | Schematic diagram showing opportunities to integrate offshore wind into a wider energy network (see *Transmission, Conversion and Energy Storage* Section for details).

cycles, and associated RSL change, which results in a highly heterogeneous substrate (e.g., Emery et al., 2019b; Eaton et al., 2020). This stratigraphic architecture will influence erodibility, sediment availability and mobility, and therefore the type and migration rate of erosional and depositional bedforms.

A monopile will cause increased turbulence in downstream flow, which enhances the carrying capacity of the flow, leading to increased sediment transport (Butt et al., 2004; Rogan et al., 2016). However, the impact on sediment suspension and transport after installation of an entire offshore wind array is poorly understood. Satellite observations of sediment plumes and sediment transport altered by offshore wind turbines (Vanhellemont and Ruddick, 2014; **Figure 5**) can provide information about sediment mobility to inform models of scour. Satellite-derived bathymetry is being developed at a spatially and temporally higher resolution and provides a cheaper method for bathymetric mapping than traditional shipborne surveys (Traganos et al., 2018). Difference mapping from repeat bathymetric surveys remain the most accurate source for scour and bedform interactions with offshore wind installations (e.g., Whitehouse et al., 2011). Nonetheless, remote sensing of coastal zone bathymetry can benefit from satellite imagery with high spatial resolution and acquisition repeat frequency, high radiometric resolution and image quality, and suitable blue and green spectral bands. These new remote sensing techniques, combined with *in-situ* measurements of sediment mobility (Baeye and Fettweis, 2015), and measurements of bed shear stress (Stanev et al., 2009), are required to constrain long-term sediment dispersal patterns.

There is a major challenge in forecasting flow-infrastructure interactions and sediment dispersal patterns over long timescales and large spatial scales (e.g., Rivier et al., 2016; Raaijmakers et al., 2017; Nagel et al., 2018). Existing numerical models are not fit for this purpose. Current forecasting capabilities of sediment mobility remain limited because of the complexity in the interplay of hydrodynamics (waves and tides), sediment suspension (grain-size and shape), erosional and depositional bedforms (scours and sediment waves), and substrate character. Uncertainty in the efficacy of sediment mobility forecasts could undermine decision-making and increase hazard to the offshore natural environment. However, extensive integrated datasets of metocean, bathymetry, seabed sediment character, and subsurface geophysical data collected by the offshore wind industry can be employed to optimise the siting of turbines and improve their lifespan. For the first time, these datasets could enable the detailed investigation of sediment mobility and develop models designed to forecast longer-term and larger-scale process interactions arising from installation of offshore wind arrays, and the subsequent O&M requirements, and benefit other marine infrastructure projects, and habitat mapping and modelling.

Transmission, Conversion, and Energy Storage

Electricity generated by offshore wind turbines needs to be integrated into the broader energy system through the transmission, conversion and storage of energy (**Figure 6**). Arguably, offshore wind has a relative disadvantage to other energy technologies due to its limited development for tri-generation in the form of electricity, fuel and heat (Stamford and Azapagic 2012). Limited flexibility can hinder the pathways through which offshore wind power can be made available *via* the whole energy system, creating challenges around intermittency with periods of over- and under-supply (Karakosta et al., 2013; Soukissian et al., 2017). Geoscience offers solutions to the energy system through both more flexible integration of offshore wind, and through de-risking and monitoring. Energy generated by offshore wind may be converted into energy-storage systems, which can accommodate demand when supply from offshore wind production (**Figure 6**: 1) is low. In particular, energy may be converted into hydrogen (**Figure 6**: 2, 3) and stored in subsurface structures (**Figure 6**: 2, 3, 13), stored as gravitational potential energy (**Figure 6**: 6, 15), or converted to compressed air for storage (**Figure 6**: 10, 12), Furthermore, suitable wind farm location may allow a combination of direct and indirect, through aforementioned energy storage, energy use by commercial and industrial needs *via* onshore cabling and substation (**Figure 6**: 7, 16, 17). The envisaged integrated energy system can be supported onshore by thermal energy storage and supply utilizing the subsurface. Here, heat storage in naturally occurring shallow and deep aquifers (**Figure 6**: 8, 9), and in industrial heritage assets such as minewater and boreholes (**Figure 6**: 11, 14), The green hydrogen network that offshore wind enables could potentially be supported by blue hydrogen from natural gas with subsurface carbon capture and storage (**Figure 6**: 4, 5).

Such an integrated energy system (**Figure 6**) will help to alleviate challenges with grid capacity, which are widely reported as a limiting factor for offshore wind development around the world (Chen, 2011; Karakosta et al., 2013; Contestabile et al., 2017; Pal et al., 2017; Soukissian et al., 2017; Ahsan and Pedersen, 2018; Morrissey and Heidkamp 2018). Herein, we offer an outlook to where geoscience can contribute to increasing the tri-generation potential of offshore wind by converting electricity into hydrogen, storing electricity and hydrogen in geo-assets, and transferring electricity and hydrogen *via* a network of cables and pipelines to shore (**Figure 6**).

Transfer of energy to onshore facilities presently depends on a network of high-voltage subsea transmission cables. As of 2018, the UK's operational offshore wind farms were using 62 export cables, totalling 1,499 km in length, and over 1,806 km of inter-array cables (Strang-Moran and El Mountassir, 2018). Diversifying energy transfer from electrons to molecules in the form of hydrogen would require the development of a network of pipelines. Thus, future wind farm developments will require cables and hydrogen pipelines to extend up to 90 km from the coastline of the United Kingdom. Thirteen percent of cable failures are due to external and environmental factors (Strang-Moran and El Mountassir, 2018). Where feasible, cables are buried 2–3 m below the seabed to avoid tangling with fish nets (Bhattacharya, 2017). However, erosion of seabed sediments (as discussed in *Sediment Mobility and Turbine Wakes* Section) is a major issue that often require scour protection measures (Srinil, 2016). Natural gas pipelines in the North Sea have been buried to avoid scour, however, onshore hydrogen transfer might require separate pipelines and storage caverns from those established for natural gas given corrosion and contamination risks (Ozarslan, 2012).

Electricity Storage

Electricity can be stored in batteries, or by conversion to another form of energy, such as gravitational potential energy (GPE, **Figure 6**: 6, 15). Given adequate gravitational potential energy, i.e., topography, the most common electricity storage system is pumped hydroelectric storage (PHS) (Fan et al., 2020), but such opportunities are not always viable (Yang and Jackson, 2011). Alternatives include systems using fluid of higher density than water requiring lower topographic gradients, or geo-assets such as reused mineshafts and salt caverns. These different types of GPE have expected energy efficiency of 65–87% (Botha and Kamper, 2019). With deployment of chemo-electric batteries limited by high costs and/or access to critical materials, GPE linked to geo-assets can complement energy storage capacity, especially if subsurface geo-assets such as salt caverns or mineshafts are available. Such geo-asset-related PHS may provide opportunities to store energy for delayed dispatch on demand, as sustainable development demands a “place-based” evaluation of locally feasible alternatives to batteries (Evans and Karvonen, 2014). Cryogenic liquid-air storage has been advocated as an additional, surface-based alternative (Krawczyk et al., 2018).

Synergies may occur when single subsurface voids, such as abandoned mine infrastructure, are used for combine GPE and thermal energy storage (Menéndez et al., 2019). An advantage of suspended-weight gravity storage in dry mine shafts (**Figure 6**: 15) is the provision of rapidly dispatched electricity storage (Morstyn et al., 2019), such as that currently demonstrated in Leith, Edinburgh (Watson, 2020; O’Grady, 2021).

Electricity from offshore wind could be stored by conversion to compressed air energy (Lund and Salgi, 2009). Proven methods of compressed air energy storage (CAES) require natural gas fired reheating to prevent freezing during the re-expansion process (Bullough et al., 2004). CAES in caverns (CAES-C, **Figure 6**: 12) requires developing new caverns accessed within 1 km of the surface, ideally in formations at least 30 m thick, with between 69–138 MPa compressive strength (Mehta and Spencer, 1988). Subsurface CAES requires high purity halite formations, but if available is tremendously competitive with construction of voluminous pressure vessels or other surface-mounted thermo-mechanical energy storage systems (Olympios et al., 2021). CAES in offshore aquifers (CAES-A; **Figure 6**: 10), at the point of offshore wind electricity production, has also been suggested as a potential storage solution (Mouli-Castillo et al., 2019), which could complement integrated offshore wind-green hydrogen production and storage.

Hydrogen

Given its potential to decarbonise the industrial, electricity, transport, heating and building sectors, hydrogen can help achieve net-zero greenhouse gas emissions by 2050 (Committee on Climate Change, 2020). There are two types of hydrogen technologies of significant interest to policy makers and industry. The first is “blue hydrogen”, which uses the process of steam methane reforming (SMR) to convert methane to hydrogen and, unlike current practice, captures and stores the associated CO_2. The second is “green hydrogen”, which uses renewable electricity (such as OSW) to power an electrolyser that splits water into hydrogen and oxygen. While there is ongoing debate about efficiency, effectiveness and carbon intensity of blue versus green hydrogen (Friends of the Earth, 2020), it appears policy space for both technologies is emerging (e.g., Parnell, 2020). For example, the United Kingdom Climate Change Committee (CCC) is taking a pragmatic approach, backing blue hydrogen as a means of scaling up the hydrogen economy quickly, with the medium-to long-term goal of green hydrogen (Committee on Climate Change, 2020). Green hydrogen is highly relevant to the offshore wind industry, given substantial quantities of relatively cheap renewable electricity will be required to make it technically and economically feasible (**Figure 6**).

Integrated offshore wind with *in-situ* green hydrogen production has the potential to increase system efficiency and cost, by reducing the reliance on high-voltage cables, which may suffer from transmission losses (e.g., Nambiar et al., 2016). In settings where hydrogen compression is uneconomical and onshore caverns cannot provide enough storage volume (Bennion et al., 2000; Heinemann et al., 2018), hydrogen produced offshore may be more feasibly stored offshore in subsurface saline aquifers (Amid et al., 2016). The potential to store hydrogen within offshore salt formations has been explored (Caglayan et al., 2020) (**Figure 6**). Because of the relative stability of the density and viscosity of hydrogen at temperatures and pressures equivalent to 200 m depth (Heinemann et al., 2018), it could potentially be stored shallower than CO_2, reducing the competition on subsurface storage space. However, this “grey area”, between 100 and 2000 m below surface, remains under-characterised because of its relative lack of importance in the hydrocarbon industry (UKCCSRC, 2015). Reuse of depleted gas fields or former gas storage sites offshore, such as the Rough gas field, could provide a more robust storage reservoir (Amid et al., 2016). These sites have proven hydrocarbon retention capability over million-year timescales, so should be suitable for storing hydrogen for days or months, despite the lower viscosity and density of hydrogen (Heinemann et al., 2018).

There are several engineering challenges associated with a move towards a hydrogen economy integration with offshore wind (e.g., Spyroudi et al., 2020). Most importantly there is the need for major energy system and infrastructure changes to deploy blue or green hydrogen at scale. Demonstration projects are required for carbon capture and storage (CCS) and low-carbon hydrogen, to create industrial clusters and regional hubs for CCS and hydrogen production and storage (Committee on Climate Change, 2020) (**Figure 6**).

Heating and Cooling

Heating and cooling accounts for 79% of EU household energy demand (Fleiter et al., 2016), and could be to a significant part decarbonised through offshore wind electricity production. Electricity can be used directly for heaters, heat pumps and air conditioners, or converted to hydrogen for use in hydrogen boilers. Offshore wind may also meet the expected demand increase for electricity as natural gas boilers are replaced by heat pumps and heat networks. Heat pumps are used to extract thermal energy from geo-assets, such as soil, the ground from shallow (0–100 m) to deep (2000 m) levels, warm water in abandoned mine infrastructure (**Figure 6**: 4; Banks et al., 2019; Farr et al., 2021), or in groundwater in sedimentary aquifers. Subsurface heat extracted can either be used for

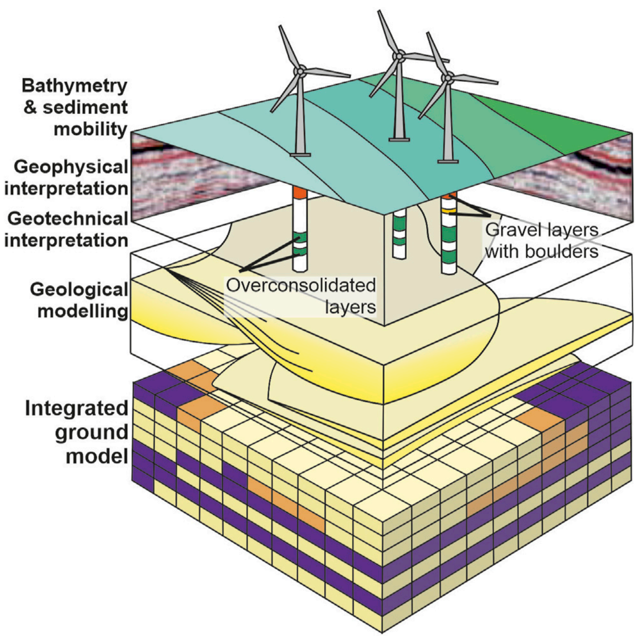

FIGURE 7 | Recommended integrated three-dimensional ground models that capture sediment mobility, and integrate geophysical, geological (including geomorphological) and geotechnical information. Adapted from Bentley and Smith (2008) and Cobain et al. (2021).

individual buildings or be fed into grids. As well as heat pumps, excess heat generated as a by-product of industry (powered by hydrogen or offshore wind), housing or building infrastructure, can be pumped underground and stored in mine-water (Minewater Thermal Energy Storage, MTES) and groundwater (High-temperature Aquifer Thermal Energy Storage, HT-ATES), or in rock or sediment masses through boreholes (Borehole Thermal Energy Storage, BTES) (**Figure 6**).

DISCUSSION AND RECOMMENDATIONS

Research and Development Priorities

Geosciences has a crucial role in contributing to sustainable growth in offshore wind energy generation, and in improving the transmission, conversion, and in de-risking onshore storage, of excess energy produced by offshore windfarms (**Figure 6**). Here, we highlight a selection of key priorities and opportunities that require harnessing geoscience-related expertise and technology to improve the sustainability and economics of windfarm sites through their lifecycle, the efficiency of energy utilization once onshore, and the integration of the two.

Integration of Geophysical and Geotechnical Data

Geophysical data and geotechnical testing interact with subsurface stratigraphy in different ways, and the relationships between the two are non-linear and complex. The reliance on one dimensional geotechnical data in the development of ground models, whether offshore site development or onshore energy storage, undervalues the role that quantitative geophysics (i.e., rock physics) can play in lowering costs. Geophysical expertise can improve ground models by incorporating understanding in energy attenuation, which is critical for first pass interpretation on stratigraphic architecture. This allows more robust stratigraphic architecture interpretations away from data coverage, more accurate constraints on time-to-depth relationships, and helps to delimit the distribution and thickness of potentially weaker (or overconsolidated) clay-rich sedimentary facies, or gravel- and boulder-rich layers (**Figure 7**). Nonetheless, geoscientists can extract more stratigraphic and palaeoenvironmental information from geotechnical data, such as Cone Penetration Test (CPT) logs, combining seismic units and CPT facies to better characterise geotechnical stratigraphy (Prins and Andresen, 2021). This includes deriving substrate bulk density/unit weight and shear velocity, and undrained shear strength, and therefore the overconsolidation ratio due to palaeoenvironmental changes (e.g., loading by ice sheets), recorded in different stratigraphic levels.

Another area of future development is joint seismic inversion and machine learning workflows that generate synthetic CPT data from geophysical inputs (Vardy et al., 2018). These predictions can be validated at blind control locations, with potential for cost saving by avoiding unnecessary drilling. An overall recommendation is to adopt approaches from the oil and gas industry, where collaborative teams of engineers and geophysicists are formed from early in a development cycle. This early stage sharing of data and ideas will reduce errors and could be cost-effective by lowering remediation and interventions, ultimately reducing the LCOE.

Advanced Three Dimensional Geological Ground Models

A crucial step in the integration of geophysical and geotechnical data is the construction of three-dimensional ground models, for onshore energy storage in geo-assets and offshore windfarm sites, which should be augmented with geological and geomorphological understanding. Three-dimensional geological characterisation of subsurface volumes is standard practice during the exploration, appraisal, and development of oil and gas fields (e.g., Bentley and Smith 2008), and carbon storage sites (e.g., Jiang et al., 2013). The models are built at different grid resolutions, and often incorporate information from analogue datasets to populate geological information below seismic resolution, such as faults and the dimensions and stacking patterns of sedimentary architectural elements. These models are then upscaled to simulate the flow of fluids through the prospective reservoir. These workflows, and expertise, are readily transferrable to the offshore wind development sites, to complement the geotechnical ground models, which is currently the dominate approach. The uptake of three dimensional geological models as a standard approach in the future is particularly important in many prospective development areas, such as the North Sea, where the subsurface stratigraphy has been demonstrated to be highly heterogeneous (e.g., Clare et al., 2012; Liingaard et al., 2012; Emery et al., 2019b; Eaton et al., 2020; Mellett et al., 2020), undermining cost-effective placement of monopiles.

We advocate the integration of geological and geotechnical approaches to develop three dimensional ground models that will permit bespoke design of turbine foundations (**Figure 7**). This is particularly important as future developments in offshore wind are focused on very large ("XXL") turbines (>8 m wide foundations). A site-specific approach is feasible because of the vertical resolution of the geophysical data. However, adoption of geophysical techniques in oil and gas industry could further reduce installation costs and decrease the risk of failure. The wider use of three-dimensional geophysical data collection, and use of high-resolution techniques such as three dimensional Ultra-High Resolution (UHR) surveys (e.g., Monrigal et al., 2017) and P-cable (e.g., Brookshire and Scott, 2015; Bellwald et al., 2019), will provide high resolution and improved spatial control. Adoption of P-cable techniques could be particularly attractive to improve site lifecycle management because geophysical data can be (re)collected during windfarm operations, and thereby support decommissioning and repowering plans. A further innovation in future ground models will be development of dynamic bathymetry, and sediment mobility layers (**Figure 7**), to integrate the substrate architecture and erodibility with seabed hydrodynamics. Improved modelling of sediment suspension and scour would assist the modelling of habitat creation and modification provided by hard surface creation to increase seabed biodiversity.

Improved Prediction of Sediment Mobility and Substrate Heterogeneity

The dynamic nature of the present-day seabed is well known, but poorly understood. The modelling and monitoring of sediment mobility over different time- and spatial-scales is an urgently needed input into the lifecycle management of offshore windfarms. Monitoring and modelling sediment mobility is essential in the management and mitigation of erosion and scour around turbine foundations and cable routes (Whitehouse et al., 2011), and to plan for and manage sediment mobility caused by interactions between monopiles and ocean-sediment dynamics (Rivier et al., 2016; Nagel et al., 2018). It is important to forecast how the seabed will evolve in the future, with changing climate and hydrodynamics, and there are likely to be complicated biological controls on susceptibility to scour through changes in sediment cohesivity. There is also an important added benefit from ground model improvements in that the documented highly heterogeneous substrate (e.g., Cotterill C. J. et al., 2017; Eaton et al., 2020) means there is additional complexity in forecasting sediment mobility over long timescales (McCarron et al., 2019). The influence of stratigraphic architecture on present day sediment mobility, including bedform spatial distribution and migration, is under-investigated (Couldrey et al., 2020). Nonetheless, the heterogeneity of substrate means that as a scour evolves at an unprotected monopile foundation, the erodibility, and therefore rate and geometry of scour development, will change in time (Whitehouse et al., 2011; Wu et al., 2020).

Integration of Weather Forecasting, Earth Observation, and Climate Change

Forecasting changes in wind resource, and quantification of the risk of extreme events, will permit appropriate site selection, and the management of ongoing maintenance, driving down the LCOE. To be effective, there is a need to integrate weather and climate models across different temporal and spatial scales, from wakes of individual turbines during weather events to regional models that incorporate climate projections and consider changing climate patterns. This is particularly important with respect to leading edge erosion, and the drive to develop materials that are more resilient to changing climates. The use of artificial intelligence in forecasting models and probabilistic forecasting could form important decision-making tools in future energy markets (Bazionis and Georgilakis, 2021).

Advances in Earth observation methods have the potential to provide satellite monitoring of array-wide sediment mobility, turbine wakes/shadows and interactions with bedforms (e.g., Vanhellemont and Ruddick, 2014), particularly through repeatable satellite-derived bathymetry over the entire lifespan of an offshore windfarm (e.g., Sentinel-2 data). However, satellite-derived bathymetry may or may not work depending on seabed albedo, water depth, the complexity of correcting for atmospheric affects and the concentration of suspended sediments and plankton (e.g., Casal et al., 2020; Goodman, et al., 2008; Knudby et al., 2016; Monteys et al., 2015). This is an important area of ongoing research that will help to support environmentally sustainable offshore windfarm developments.

Maximising Subsurface Energy Storage Potential

To maximise the benefits of offshore wind turbines, there needs to be improved integration of the electricity generated into the wider energy system. A crucial contribution from geosciences is in the storage of excess energy generated (**Figure 6**), including underground storage of excess electricity as heat. The use of geo-assets for energy storage depends entirely on place-based availability. Potential technologies include compressed air storage, converting excess electricity to compressed air, gravity potential storage in mine shafts, and subsurface storage of electricity converted to hydrogen (**Figure 6**). Subsurface thermal energy storage of excess wind power generation was proven to operate for many years on detached houses in Massachusetts and Pennsylvania (Cromack, 1978; Manwell and McGowan, 1981), which was the basis for a proposed development in Hull (Hodges, 1979).

Minewater geothermal and energy storage schemes are rapidly gaining traction in areas with abandoned mine infrastructure, such as the Carboniferous coal mines of the United Kingdom and the Netherlands (Verhoeven et al., 2014; Banks et al., 2019). For example, the United Kingdom total historical underground coal production since 1853, has left approximately 19 billion m^3 of abandoned void space (BEIS, 2020) that could be used to store thermal energy. The Permian salt mines of East Yorkshire could also be repurposed to store excess electricity production from adjacent North Sea windfarms like Hornsea and Dogger Bank as compressed air or hydrogen. Minewater geochemistry and three dimensional heat-flow modelling are important areas of geoscience research that are needed to maximise efficient use of offshore wind electricity, requiring characterisation of the abandoned subsurface infrastructure (Banks et al., 2019; Menéndez et al., 2019). Similarly, heat-flow modelling of rocks and sediments for subsurface borehole thermal energy storage (BTES) requires detailed stratigraphic understanding of the subsurface to minimise the amount of time required before a BTES project can attain efficient heat recovery rates (Catolico et al., 2016). Integrating energy storage into offshore wind therefore requires careful assessment of potential geo-assets.

Collaboration, Data Sharing, and Knowledge Transfer

Realising the research and development opportunities highlighted in 4.1 requires a collaborative culture, open access and data sharing, and knowledge transfer (Gill, 2017; Gill, 2021), especially as offshore seabed and subsurface observations are expensive and often difficult to obtain. The oil and gas industry has long collaborated with academia by co-producing research programmes, sharing data, and transferring of knowledge, with various data management and release protocols in place, albeit varying by country. The future sustainable development of offshore wind sector requires adoption of similar approaches to collaboration, data sharing, and knowledge transfer. National geoscience and mapping programmes, such as the INFOMAR programme in the Republic of Ireland, have a crucial role in the delivery of data relevant to offshore wind development. Collaboration between government or state agencies, industry, and academic institutions can feed back into an overall improvement in the quality of data provided by national mapping programmes (GDG, 2020). The resulting benefits include better integration of offshore wind into the environment, with other users of the marine space, and with the energy system throughout the lifecycle of wind farms. Data sharing is of particular importance in that regard.

Currently, however, in offshore wind a culture of limited lifecycle thinking and data sharing between supply chain actors prevails (Purnell et al., 2018; Jensen et al., 2020). Actors at each lifecycle stage generate data on factors that are important to them from a competitive, operational or legal perspective, but data are generally not passed on along the lifecycle. The development of whole lifecycle data systems requires a sector wide and coordinated approach. Some system wide data platforms are under development. For example, the National Materials Datahub and the United Kingdom Continental Shelf data system, and collaborative agreements with research institutes [e.g., the Netherlands Enterprise Agency (RVO)] can benefit data collection and sharing approaches, and co-producing solutions for shared use of marine space. The cost of data collection and sharing can be lowered with innovation in advanced sensors, robotics and blockchain technologies. Effective use of data will require development of sets of comprehensive and aligned metrics, and accessible archiving, to optimise lifecycle management.

Nonetheless, at present proprietary systems remain barriers to data sharing across the lifecycle of OSW farms (Velenturf, 2020). This creates disadvantages to the sector in the form of risks. For example, unforeseeable events or issues are likely to crop up during management of offshore windfarms, and actors will not have a full insight into the history and characteristics of components and infrastructure which creates demands for data. Such data may already be available from, or could have been collected by, actors elsewhere in the lifecycle of OSW components and infrastructure. Furthermore, decisions on lifetime extensions of windfarms require insights into component specifications from original equipment manufacturers, the conditions during operation that affect the fatigue life from operators, and insights into repairs that may have been carried out by maintenance contractors. Not sharing such data inhibits effective decision-making and could lead to more waste and higher lifecycle costs than necessary (Jensen et al., 2020).

Integrated Whole System Perspective to Move Forward

Geosciences are essential for sustainable offshore wind development at every stage of the lifecycle of a windfarm, from initial planning, siting, foundation, and layout design, installation, operations and maintenance, lifetime extension, repowering and decommissioning (**Figure 3**), and onshore energy storage (**Figure 6**). End-of-use management of offshore windfarms is an area with gaps in terms of governance, business models and technical solutions (Velenturf et al., 2021). While the growth of renewables such as offshore wind are essential for climate targets, there are trade-offs due the impacts of mining of materials that are needed to build wind infrastructure. Recovery of metals such as steel, copper and rare earth elements is critical to limit the lifecycle environmental impact and associated adverse impacts on communities. Recovering cables (containing copper) from the seabed has been flagged by industry as disruptive to flora and fauna in the sea, but mining the materials anew would cause environmental impacts elsewhere. On the other hand, recovering concrete from the foundations would hold little material value though, when left in place, could add environmental value as artificial reefs (**Figure 3**). These lifecycle considerations are particularly challenging due to the complex nature of offshore wind ownership structures and supply chains, and difficulties in balancing competition within a rapidly growing market with potential to learn, progress and integrate the sector as a whole. Collaboration is essential for proactive and inclusive MSP, bringing together stakeholders with widely differing needs, values and views, to avoid conflict, make use of local knowledge and create synergies, such as multi-functional structures and use of the marine space, which can reduce costs and strengthen environmental sustainability. Geoscientists need to play a role in communicating how geoscience is integral to providing solutions to the challenges that society faces in the energy transition, and in moving towards an integrated whole systems approach to offshore wind. Effective communication of the importance of geoscience and geoscientists requires close collaboration with social and environmental scientists in order to drive co-production of research, sustainability assessments, and engagement with all stakeholders (Gibson and Roberts, 2018).

CONCLUSION

Solving the four integration challenges, integrating offshore wind into the environment, into the energy system, with the demands of other users of the marine space, and by maximising of benefits throughout the wind farm lifecycle, require crucial input from the geosciences, and geoscientists. To integrate offshore wind into the environment in an efficient and sustainable way, geosciences are needed to provide spatial assessment of substrate heterogeneity, and to predict future changes in sediment mobility. Geoscientific understanding is a key component to the development of multi-functional systems and structures, such that marine space users, and uses, are combined to be synergistic and avoid conflict. Unlocking increased flexibility for the integration of offshore wind into the energy system, and reducing issues of intermittency can be improved by commissioning more energy storage capacity using geo-assets, such as abandoned mine shafts or decommissioned oil and gas fields, which requires significant contribution from the geosciences. Furthermore, geosciences and geoscientists, are integral to the whole lifecycle management of offshore windfarms, from initial site evaluation, foundation and layout design, through installation, and operations and maintenance, to lifetime extension, repowering and decommissioning strategies. Therefore, it is essential that the skills and training of geoscientists are focused on meeting these challenges.

Crucially, however, to make a significant contribution to the sustainable growth of offshore wind, geoscientists must work more collaboratively with other disciplines, and vice versa. Indeed, interdisciplinary working, and co-production of research and development programmes between academia, government agencies, and industry, are essential for long-term sustainable whole lifecycle management of offshore wind energy generation infrastructure, and energy storage. For offshore wind to be sustainable and effective, governance structures need to take whole system approaches, facilitate data sharing and knowledge exchange, and take into account, and actively communicate with, the diverse range of stakeholders and other marine users.

AUTHOR CONTRIBUTIONS

AV and DH are lead authors, with major contributions from AE, NB, AM, JV, EP, SP, and MT. AE designed and drafted **Figures 1**, **4**, **6**. AV designed and drafted **Figure 2**. DH designed and drafted **Figures 3**, **5**, **7**.

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CONFLICT OF INTEREST

ARE and MT were employed at the University of Leeds when their contributions to the research was completed. ARE is now employed by company Gavin & Doherty Geosolutions, and MT is now employed by company M Thorp Geo Consultants.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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