Scoping an Offshore Wind Sustained Observation Programme (OW-SOP)

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Scoping an Offshore Wind Sustained Observation Programme (OW-SOP)

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List of abbreviations

Acoustic Doppler Current Profiler	ADCP
Autosub Long Range	ALR
Autonomous Underwater Vehicle	AUV
Before-After	BA
Before-After-Control-Impact	BACI
British Energy Security Strategy	BESS
British Oceanographic Data Centre	BODC
Centre for Environment, Fisheries and Aquaculture Science	CEFAS
Chlorophyll-a	Chl-a
Computational Fluid Dynamics simulation	CFD
Conductivity, Temperature, Depth	CTD
Continuous Plankton Recorder	CPR
Contract for Difference	CfD
Co-ordinated Environmental Monitoring Programme	CEMP
Crew Transfer Vessel	CTV
Crown Estate Scotland	CES
Department for Energy Security & Net Zero	DESNZ
Dissolved Oxygen	DO
Ecosystem Structure Functions and Processes	ESFP
Environmental Impact Assessment	EIA
Essential Ocean Variable(s)	EOV(s)
Final Investment Decision	FID
Findability, Accessibility, Interoperability and Reusability	FAIR
Fixed-Point Observatories	FPO
Floating Offshore Wind	FLOW
Floating Offshore Wind Farm	FLOWF
Floating Offshore Wind Turbine	FLOWT
Future Energy Scenarios	FES
General Bathymetric Chart of the Oceans	GEBCO
Gigawatt	GW
Good Environmental Status	GES
Habitat Regulation Appraisal	HRA
Innovation and Targeted Oil and Gas	INTOG

International Council for the Exploration of the Seas	ICES
Iterative Plan Review	IPR
Joint Assessment and Monitoring Programme	JAMP
Joint Industry Project	JIP
Kilometre	km
Large Eddy Simulations	LES
Marine Autonomous Robotic Systems	MARS
Marine Autonomous Systems	MAS
Marine Biological Association	MBA
Marine Data Exchange	MDE
Marine Environmental Data and Information Network	MEDIN
Marine Strategy Framework Directive	MSFD
Megawatt	MW
Minimum Detectable Change	MDC
Mixed Layer Depth	MLD
National Oceanography Centre	NOC
Natural Environment Research Council	NERC
Non-Indigenous Species	NIS
North Atlantic Oscillation	NAO
North European Storm Study	NESS
North Sea Transition Authority	NSTA
North-West Approaches Group	NWAG
Offshore Energy Strategic Environmental Assessment	OESEA
Offshore Wind	OW
Offshore Wind Energy	OWE
Offshore Wind Environmental Improvement Package	OWEIP
Offshore Wind Evidence and Change programme	OWEC
Offshore Wind Farm	OWF
Oil and Gas	O&G
Potential Energy Anomaly	PEA
Photosynthetically Active Radiation	PAR
Regions Of Freshwater Influence	ROFI
Regional Seabed Monitoring Plan	RSMP
Remotely Operated Towed Vehicle	ROTV

Remotely Operated Vehicle	ROV
Scottish Environment Protection Agency	SEPA
Scottish Marine Animal Strandings Scheme	SMASS
Scottish Marine Energy Research Programme	ScotMER
Sea-Level Rise	SLR
Sea-Surface Temperature	SST
Sectorial Marine Plan	SMP
Social Impact Assessment	SIA
Standard Operating Procedure	SOP
Strategic Environmental Assessment	SEA
Subsurface Chlorophyll Maximum	SCM
Suspended Particulate Matter	SPM
Synthetic Aperture Radar	SAR
The Crown Estate	TCE
Technology Readiness Level	TRL
Terawatt	TW
The Crown Estate	TCE
Turbulent Kinetic Energy	TKE
United Kingdom Continental Shelf	UKCS
Unmanned Surface Vehicle	USV
Vessel Monitoring System	VMS
Weather Research and Forecasting	WRF
Wind Farm Parametrisation	WFP
Wind Turbine	WT

Glossary of terms

Baseline (conditions/parameters)	Referring to physical and biogeochemical water column parameters in absence of offshore wind infrastructures (but including climate change effects).
Far-field effect	Specifically refers to the impacts of wind farms on the surrounding marine environment and human activities beyond the 'immediate vicinity' of the turbines. These effects can include changes in oceanographic conditions, such as alterations in water currents and sediment transport, as well as potential shifts in marine biodiversity, habitat distribution, and ecosystem dynamics. Additionally, far field effects may extend to socioeconomic aspects, such as changes in maritime transportation routes, fishing grounds, and recreational activities in areas surrounding offshore wind installations.
Immediate vicinity	Typically refers to the area directly surrounding the wind turbines, encompassing the waters within a relatively close distance from the turbines themselves. This area is defined by the physical footprint of the wind farm infrastructure, including the turbines, substructures, and associated inter-array cables. The exact extent of the immediate vicinity can vary depending on factors such as the size and layout of the wind farm, the spacing between turbines, and the depth of the water. This may extend several hundred meters to a few km around the turbines (and typically excludes the region of the wake).
Marine Autonomous System	MAS includes a broad spectrum of systems that operate with varying degrees of autonomy - e.g. unmanned surface vehicles (USVs), gliders, fully autonomous underwater vehicles (AUVs) at one end, through to partially automated and remotely operated vehicles (ROVs) at the other end.
Monitoring	Is the process of collecting data and generating reports on different metrics that define system health.
Near-field effects	Specifically refers to the impacts of wind farms on the surrounding marine environment and human activities within the 'immediate vicinity' of the turbines. However, it has to be acknowledged that it may sometimes include the area over the wakes (of individual turbine structures and of the wind farm) and is, therefore, not necessarily

	limited to the immediate vicinity of the turbines. Defined on site-specific basis.
Precautionary principle	Within this report we are using the definition from (Olsen & Motarjemi, 2014) which states that “*If a product, an action or a policy has a suspected risk of causing harm to the public or to the environment, protective action should be supported before there is complete scientific proof of a risk*”.
Public bodies	A ‘public body’ is a formally established organisation that is (at least in part) publicly funded to deliver a public or government service, though not as a ministerial department. The term refers to a wide range of entities that are within the public sector (see Public bodies).
Regulatory bodies	A regulatory body is a public organization or government agency that is set up to exercise a regulatory function. This involves imposing requirements, conditions or restrictions, setting the standard for activities, and enforcing in these areas or obtaining compliance. Scotland has several regulatory and advisory bodies responsible for managing its marine environment. Some key organizations include Marine Directorate of the Scottish Government, Scottish Environment Protection Agency (SEPA), NatureScot. These bodies work together to ensure the responsible management of Scotland’s marine environment, balancing environmental protection, economic growth, and social well-being (Scottish Government, 2010).
Sustained observations	Investigative approach looking closely at distributed system component interactions and data collected by monitoring to find the root cause of issues.

Executive summary

The Scottish Government, through the Offshore Wind Directorate, commissioned the National Oceanography Centre (NOC) to undertake a project to provide recommendations for designing a programme of sustained observations of physical and biogeochemical water column processes. This project's objective is to improve the evidence base and support the sustainable development of the offshore wind (OW) industry within, but not limited to, the Scottish sector of the North Sea. The project included a review of the current state of knowledge about the North Sea water column structure, previous and ongoing observational programmes, and current efforts in understanding the interaction between fast-growing, large-scale infrastructures and the ocean environment. This review highlighted existing data, knowledge gaps, and the role that models could play. These ultimately feed into recommendations for the appropriate methodology necessary to assess the potential impact of offshore wind farms (OWFs) (and especially floating offshore wind farms, FLOW) being developed in deeper seasonally stratified shelf sea waters. These impacts could include changes to the physical and biogeochemical properties of the water column, which could impact the wider ecosystem.

Recommendations on the use of modelling approaches, on the 'best-practice' for sustained observation programmes and a roadmap towards their implementation have been proposed both through review of academic literature and a stakeholder engagement workshop.

This final report provides an overview of the development landscape in the Scottish North Sea and a review of the current state of knowledge, before a series of recommendations, which can be summarised as follows:

i. Existing and new data from observational/monitoring programmes should be used in conjunction with models to predict impact, provide guidance on future observational/monitoring efforts, and validate model predictions at shelf-wide (regional) and site-specific (OWF project) scales.
ii. Existing data on water column physical and biogeochemical parameters (including data from OW, O&G, fisheries, etc.) should be accessible from data repositories ideally managed by public bodies and should follow international standards of Findability, Accessibility, Interoperability and Reusability (FAIR) for data formats.

iii. The observation of fundamental EOVs at shelf-scale (regional) and site-specific (OWF project) scales should be prioritised and parameters have been proposed.

iv. 3D models can support our understanding of the water column baseline conditions (in absence of OWFs). Existing, and new, observational data from the vicinity of OWFs should be used to parametrise, refine and validate model outputs.

v. 3D far-field hydrodynamic models, using existing data, taking a ‘precautionary approach’ to the mixing effects due to OWFs, could be used in project scoping and EIAs to assess the potential levels of mixing due to infrastructure. These models could be augmented by site-specific modelling performed by developers.

vi. Models’ recommendations should guide future observational/monitoring programmes focusing on the transition between mixed and stratified water columns (spring/autumn), as well as throughout the stratified period (summer). Transition zones where there is marginal water column stability or intermittent stratification (e.g. changes through spring-neap cycle) should also be monitored and data used to parameterise and validate models.

vii. Future programmes should use a combination of fixed (e.g. moorings), dynamic (e.g. marine autonomous systems (MAS), ship based) and/or remote (e.g. satellite data) platforms and sensors, prioritising sustained observations from fixed platforms at/near early OWFs in stratified waters. The addition of Conductivity, Temperature, Depth (CTD) sensors to other planned, or existing, moorings (e.g. marine mammal/passive acoustic detection moorings and eDNA) should be considered in order to contribute to the understanding of stratification in an efficient and cost-effective manner. Similarly, the collection of additional biological data on moorings primarily designed for physical process monitoring, could be cost efficient and generate complementary datasets. Relevant sampling duration(s) and recommended temporal and spatial resolutions are provided in this report, where possible.

viii. Monitoring plans should look beyond the project level and consider strategic sustained observations. This report considers potential funding mechanisms for such programmes.

ix. Observational and impact modelling guidelines require further definition.

These recommendations aim to support the implementation of sustained observations at regional and site-specific scales. It is important to fully understand the potential OWF-induced changes to the environment, and for this, models are key. Water column changes may also impact higher trophic levels and the wider ecosystem; however, discussions around the potential impact to seabed, pelagic and benthic communities, etc. is out of the scope of this project. This report focuses discussion on the possible interaction between OW activities and the physical and biogeochemical structure of the water column only.

The recommendations presented in this report, and the associated qualitative assessment presenting ‘best-to-worst’ case scenarios for implementation, should be integrated within existing assessments to inform project level Environmental Impact Assessments (EIA), Habitat Regulation Appraisals (HRA) and Strategic Environmental Assessments (SEA) for offshore developments to support future planning work. This guidance is intended to be used to make recommendations for best practice only.

Background and objectives

Scotland has a current reported potential pipeline of over 40 GW of OW projects, on top of the 3 GW which is currently operational (Figure 1.1 and Appendix A). ScotWind reflects a very significant market ambition for OW in Scottish waters, with around 27.6 GW across 20 projects. The INTOG leasing round could also potentially add around 5.5 GW of capacity, of which up to 449 MW for INnovation (IN) projects and 5 GW for Targeted Oil and Gas (TOG) decarbonisation (Offshore Wind Scotland, 2024).

The Scottish Government developed the Sectoral Marine Plan for Offshore Wind Energy (SMP-OWE) to inform the spatial development of ScotWind. This plan, adopted in October 2020, identified 15 sustainable options for future commercial scale OW developments. The plan is currently undergoing a review, as part of the Iterative Plan Review (IPR) process, to update the plan to reflect the ScotWind and INTOG leasing rounds and to ensure the plan remains reflective of current scientific understanding and knowledge, as well as the wider regulatory and policy context. Scotland, as part of the UK OW market, is already a key player being home to the Beatrice OWF demonstrator project in the Moray Firth, the world's first deep-water OW turbine deployment and Robin Rigg, E. ON's fully commissioned 180 MW OWF in the Solway Firth. Also, in 2017, the world's first commercial FLOW project became operational (Hywind Scotland) just off Peterhead in Grampian. The 2022 ScotWind and INTOG lease rounds will also provide a significant push to the Scottish offshore renewables industry. Very recently SSE and TotalEnergies' Seagreen Phase 1 OWF, Scotland's largest OWF, became fully operational (October 2023), as the world's deepest fixed-bottom OWF.

Such a rapid and large-scale utilisation of seabed space can create a positive socio-economic impact through the generation of green electricity, creating new jobs, and strengthening the country's economy; however, it also introduces questions and uncertainties related to any potential environmental impact of such a large-scale expansion of OWFs. Based on these considerations, this report's objectives are to:

i. Review the current knowledge and data availability around the baseline (in absence of OWFs) physical and biogeochemical parameters of the water column within, but not limited to, the Scottish North Sea waters.

ii. Inform how existing data can be used to define the water column baseline parameters, also identifying what are the data gaps that prevent a proper forecast (using modelling techniques) and understanding of the potential impact of future OWF developments.

iii. Review the importance and the limitations of modelling strategies in predicting environmental changes due to OW infrastructures.

iv. Review existing observational programmes/data which can be used for environmental impact assessments.

v. Recommend new and targeted observational programmes.

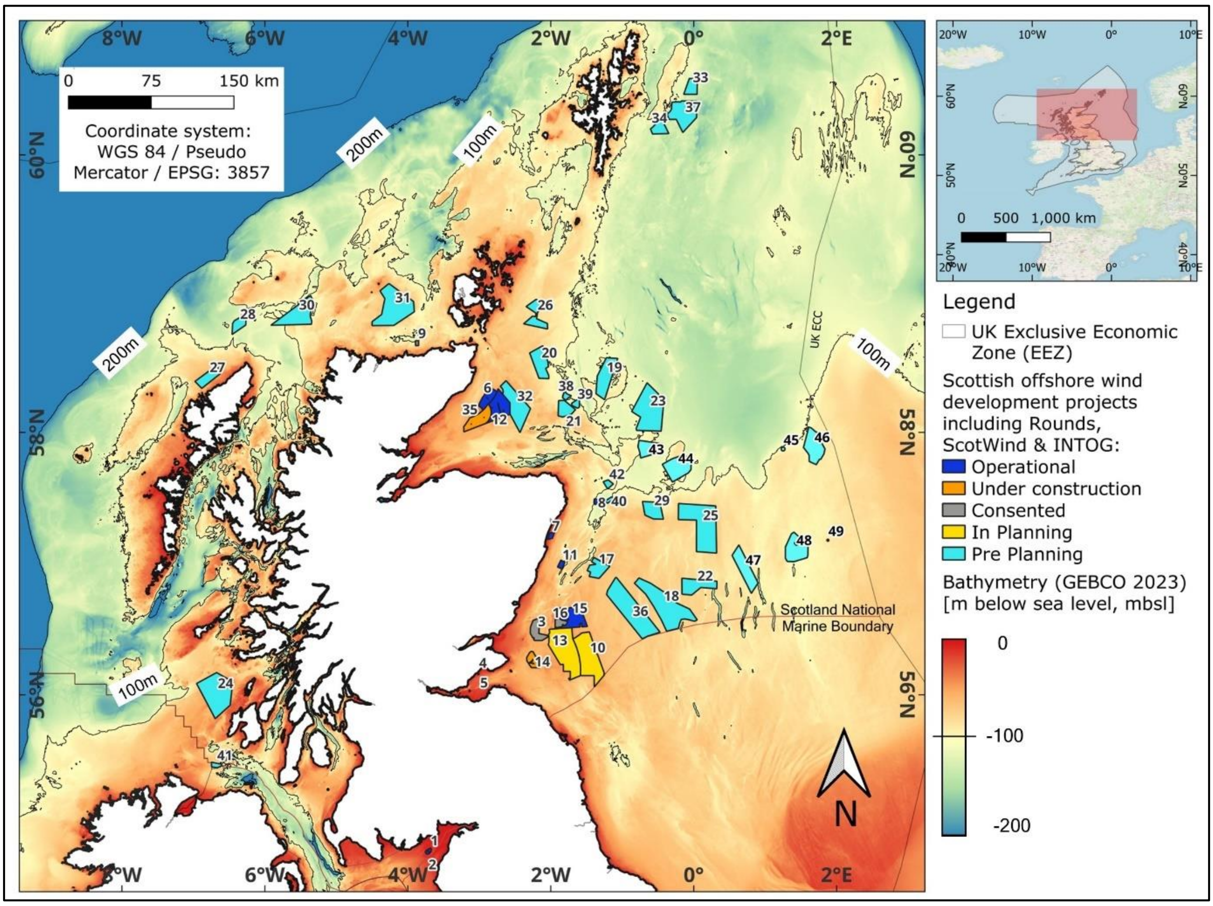


Figure 0.1. Bathymetric map showing part of the Scottish sector of UK territorial waters (GEBCO, 2023). The Scottish OWF developments (including leasing rounds, ScotWind and INTOG) are shown in overlay. Colour coding refers to the project status (refer to legend to Table A.2) (Crown Estate Scotland, 2024).

1 Introduction

The Scottish Government has set a range of targets to cut greenhouse gas emissions and to generate more energy from renewable resources. The Climate Change (Scotland) Act 2019 commits the Scottish Government to reach net zero emissions for all greenhouse gases by 2045. Offshore wind (OW) energy plays an important role within these targets, as it is widely regarded as one of the most credible sources for renewable energy production towards a resilient and decarbonised energy supply (e.g. Galparsoro et al., 2022). This energy sector has rapidly expanded within shelf seas over the past decade motivated by the high-quality and reliable wind energy resources (Esteban et al., 2011), the space availability and site accessibility for installation of large and efficient turbine systems (Sun et al., 2012), as well as the reduced visual impact compared to OW infrastructures in populated areas (Wen et al., 2018).

Government programmes have helped drive development of renewable OW energy from offshore wind farm (OWF) arrays, increasing from tens to hundreds of offshore wind turbines (OWT) supported by various fixed foundation designs. Now, new floating foundations are being designed to access deeper water sites and further expand offshore development opportunities.

However, interplay of social and economic drivers already places significant stress on shelf seas and further industrialisation of shelf seas will enhance these stresses, with the potential for significant long-term environmental impact (Kröger et al., 2018). The dynamic physical oceanographic processes in shelf seas directly control the magnitude and timing of primary production: the growth of microscopic marine plankton. However, from OWT scale to coastal scale, the impact of OW development on shelf seas has yet to be fully considered (Dorrell et al., 2022). Therefore, it is important to further our understanding of the potential impacts of OW energy developments on shelf sea dynamics. This is important in establishing potential risks to marine ecosystems due to wind energy production and infrastructure, and assessment of these risks needs to be relative to baseline(s) that include climate change. Critically, advancing our understanding of the interaction between offshore infrastructures and shelf sea environments will enable balance of key global societal goals, i.e., to ensure access to affordable, reliable and sustainable energy, and to conserve and sustainably use the oceans, seas and marine resources (United Nations, 2015). Therefore, understanding the potential physical and bio-geochemical risks to marine ecosystems from OW energy production is both timely and vital, and will support the adoption of management measures that minimise impacts and the environmental sustainability of this energy sector (Galparsoro et al., 2022).

Most research to date covers areas of the southern North Sea that are either fully mixed or only weakly/intermittently stratified during the summer season, leaving some unanswered questions, such as:

i. What changes may occur by installing OW infrastructure in stratified waters that could influence primary productivity, which could impact higher trophic levels through potential changes to biodiversity, carbon and nutrient fluxes, and the broader ecosystem functioning (e.g. Dorrell et al., 2022).
ii. What physical and biogeochemical changes could influence predator-prey interactions by changing locations where prey feed (e.g. Russell et al., 2014).

These physical effects are not considered a consenting risk at the scale of current developments, but possible resulting changes to the ecosystem have the potential to be of increasing interest as the industry expands. This is particularly relevant given the expected rapid expansion into deeper, more stratified waters made possible by the development of robust fixed foundations and the increasing utilisation of floating platform solutions which form the bulk of the ScotWind project proposals.

The challenge for this type of study lies in discriminating changes in the physical and biogeochemical parameters directly caused by the presence of OWF infrastructures from natural variability, with appropriate consideration of the influence of climate change. For this reason, the ScotMER Physical Processes Receptor Group has highlighted the need to identify the key parameters to be monitored as well as where and how to monitor them (Scottish Government, 2024).

Based on the above, a detailed review is necessary to assess:

i. How OWFs may change near-/far-field water column structure?
ii. How OWFs in seasonally stratified shelf seas may change primary production?
iii. What are the potential mechanisms (fixed vs. floating) that can have the greatest impact?

iv. Do we have sufficient baseline data to characterise and understand baseline conditions across the Scottish shelf areas and how these may alter due to climate change?
v. What relevant baseline monitoring is currently underway and what opportunities exist for a cost-effective improvement (e.g. using autonomous vehicles)?
vi. How can models be used to assess impacts and help inform monitoring programmes?
vii. What sustained observation/monitoring is required?

To answer the questions above, a review process and stakeholder engagement were carried out including government bodies, industry, academia, and research organisations involved with, but not exclusively, the Scottish marine environment. The results of this review process and of active stakeholders' engagement are summarised in this report, in which recommendations for future monitoring and observational programmes are ultimately drawn in the form of a roadmap.

To provide a clear overview of the subject, this chapter (Chapter 1) provides an overview of potential benefits and issues associated with the fast-growing OW sector (**Section 1.1)**

Further insights on the history, current status and future trends of OW energy development in the wider North Sea as well as more details on the Scottish developments are provided in Appendix A.

1.1 Challenges facing the rapidly-expanding Offshore Wind sector

The OW energy sector has rapidly expanded over the past two decades, providing a renewable energy solution for coastal nations, including Scotland. Such a rapid scale utilisation of the offshore space does not come without environmental challenges and unknowns.

1.1.1 Large-scale utilisation of the offshore environment

To date, most OWFs have been installed in the near-shore shallow water regions, up to 60 m depth, of shelf-seas. Near-shore, shallow-water installations have been preferred due to the cost reduction from ease of access for installation, grid connection and operation and maintenance (Jacobsen et al., 2019). With global sector aspirations for an additional 208 GW of operational capacity in the next decade, and targets of 1.4 TW total by 2050 (Offshore Renewable Energy Action Coalition, 2020), near-shore and shallow-water sites are rapidly becoming limited.

Advances in engineering design have allowed larger turbines to be constructed, thus increasing energy output capacity. New foundation types have allowed OW expansion into deeper waters: mainly due to the development of floating foundations which can be used in water depths > 200 m (Figure 1.2) (Soares-Ramos et al., 2020).

The transition from near-shore and shallow water environments to deeper water further from shore could mark a fundamental change in the physical and biogeochemical structure of the water column. Shallow waters are typically well-mixed; however, deeper waters may be subject to seasonal stratification where density varies vertically with depth (Dorrell et al., 2022) (see Chapter 2). Stratified waters are a vital part of shelf seas, controlling primary production and biogeochemical cycling (Simpson & Sharples, 2012). As mentioned by Dorrell et al. (2022), ‘expansion into this new environment means that OWFs could increasingly come into conflict with its environmental functioning, controlled by natural mixing of water column stratification’ (Figure 1.2). Thus, there is a need for recommendations for the appropriate methodology necessary to assess the potential impact of OWFs.

1.1.2 OWFs and their interaction with water column structure

Stratification is a term used to describe when two distinct layers occupy the vertical water column in the sea: the near-surface one is less dense than the near-bed one (see also stratification/potential energy anomaly (PEA) assessment; Chapter 2 and Appendix B). This can be due to differences in temperature (warm layer overlying a cooler layer), salinity (fresh water overlying saltier water), or both. The balance between inputs of fresh water and/or heat from the sun and mixing from tidal currents, wind, and waves determines whether the water column is stratified. The interface between the two layers is very efficient at limiting the exchange of water and its properties such as nutrients (Figure 1.2) (Marine Scotland, 2020).

In areas with significant river inputs (Clyde, Forth, Inverness, Beauly, Cromarty and Dornoch Firth), stratification due to river run-off (input of fresh water) can occur year-round. There is currently no evidence that the strength of stratification (the density difference between the two layers) in these regions is systematically changing, although it can change due to particular rainfall events.

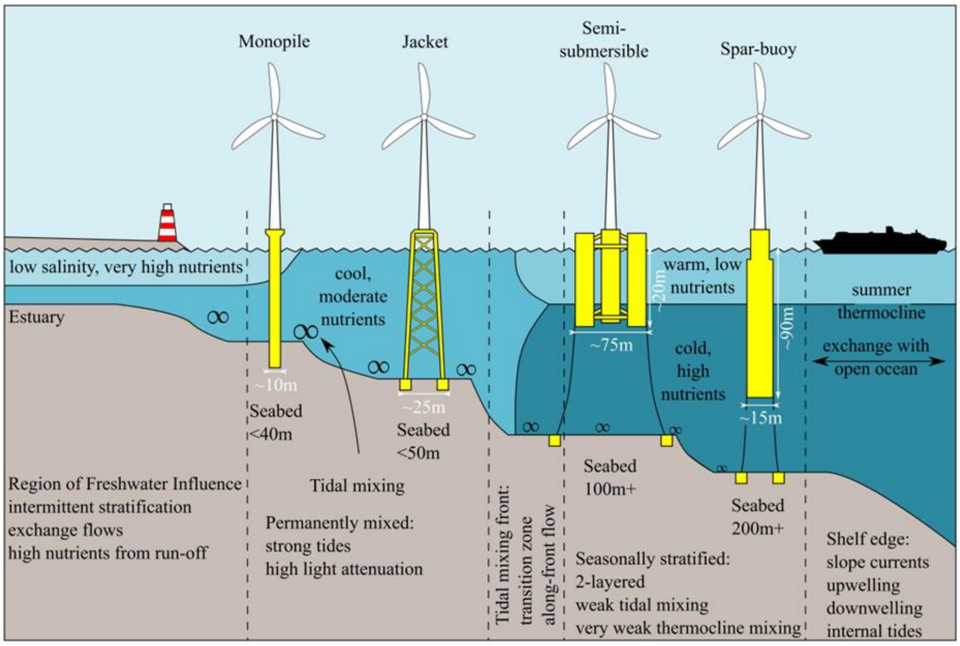


Figure 1.2 Diagram showing OW engineering solutions in comparison to shelf sea regimes from coastline to open ocean - see Dorrell et al. (2022) and references therein.

In large parts of Scottish shelf sea waters, stratification occurs on a seasonal basis: once the heat input from the sun is sufficiently strong, stratification develops in regions where the water is sufficiently deep or the tidal currents sufficiently weak (see Chapter 2). In these regions, the strength of mixing is insufficient to keep the water column vertically homogenous (Marine Scotland, 2020).

The rapid growth in OW infrastructures within stratified waters may alter the physical properties of the water and, with that, create a cascade of potential impacts. However, until now, research has primarily been focussed on assessing and proposing mitigation solutions on the direct impacts of OWF development on well-mixed shallow water marine ecosystems, such as benthic habitats (Dannheim et al., 2020), fisheries (Gray et al., 2005) and seabirds (Exo et al., 2003). Whilst this research is translatable with sector growth, the seasonally stratified regime offers a fundamentally new challenge: the introduction of infrastructure may lead to enhanced 'anthropogenic' mixing of stratified waters which may ultimately lead to profound impacts on shelf sea dynamics and thus marine ecosystem functioning. The dynamics of atmospheric wakes from OWTs are already of key interest, given their influence on available wind power from turbine to array scale (Howland et al., 2019). However, the dynamics of sub sea surface wakes from foundations within the immediate vicinity of OWFs are poorly understood, particularly in stratified waters, as are the modification of near-surface mixing due to changes of the near-surface atmospheric flow over the near-field extent of wind farm wakes (see Chapter 3). Despite this, the > 20 m minimum draft of current floating foundations is already large enough to penetrate the thermocline and directly mix seasonally stratified shelf seas (Figure 1.2) (Dorrell et al., 2022).

This document sets the scene for sector development into these new environments, reviews the potential physical and environmental impacts of large-scale industrialization of seasonally stratified shelf seas and identifies areas where research and best practice modelling strategies and observational programmes are required to quantify, manage, and mitigate environmental change. To support the above, the following chapters discuss:

- **Chapter 2 – What is changing? Baseline parameters and existing data.** This chapter focuses on the water column structure and provides a review of the prevailing physical and biogeochemical properties and how they change. It also looks at exiting data and potential data gaps.
- **Chapter 3 – How to predict change using models?** This chapter focuses on numerical modelling simulations used to predict water column natural variability, climate change effects, and also changes induced by anthropogenic activity (OWFs). The mechanisms through which an OWF can change the physical water column are outlined. This chapter

also provides a review of existing modelling capabilities, limitations and observations required to enable improvements of the methods.

- **Chapter 4 – Where and when to observe change - sustained observation programmes.** This chapter outlines existing monitoring/observational efforts, as well as discussing best practice and standards needed to support our understanding of the interaction between the natural environment and anthropogenic stressors. Furthermore, it provides considerations for planning sustained observations and monitoring programmes.
- **Chapter 5 – Roadmap towards sustained observational programmes supporting Offshore Wind**. This is the key chapter of the report, summarising the outcomes from the review and from discussion held during the workshop. It proposes recommendations and a roadmap towards a sustained observational programme which could be implemented in order to support the sustainable development of the OW industry.

2 What is changing? Baseline parameters and existing data

In order to assess what the impact may be due to the presence of new infrastructures, there are some key questions that need to be answered:

i. What are the baseline conditions (including climate change) of the system?
ii. What changes are expected?
iii. What are the Essential Ocean Variables (EOVs) needed to detect OWF-induced change and evaluate the scale of resulting impact?

This chapter introduces the prevailing physical properties of the North Sea (**Section 2.1**) and discusses available data and gaps in our understanding of the system (**Section 2.2**).

2.1 Prevailing physical properties of the North Sea waters

The North Sea is a relatively shallow shelf sea (15-200 m), generally increasing in depth from south to north, with the Dogger Bank separating the North Sea into two regions of different physical and biogeochemical properties, which are driven by regional and local water circulation, tides, etc. (Figure 2.1) (Queste et al., 2016; Otto et al., 1990). Prevailing (historic) physical properties of the North Sea waters, inclusive of climate change effects, are considered here to represent the ‘baseline’ conditions. Baselines are defined, therefore, as the water column properties (inclusive of climate change effects) in absence of OWF infrastructures. The impact of new infrastructure is to be quantified relative to this baseline.

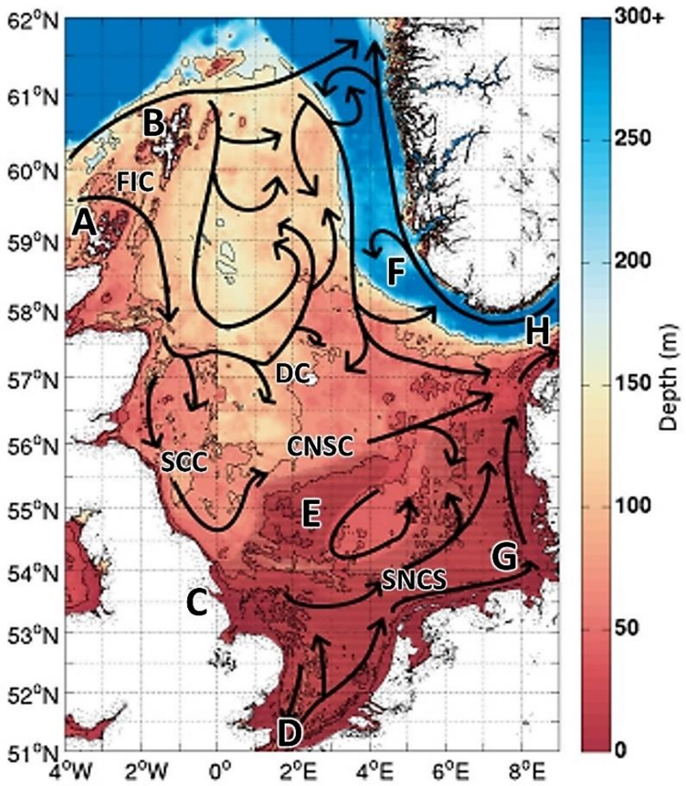


Figure 2.1. Bathymetric map of the North Sea with depth contours shown as the 20, 40, 80 and 160 m isobaths. Major landmarks are: A and B – Shetland and Orkney isles; C – Humber estuary; D – the Channel; E – Dogger Bank; F – Norwegian Trench; G – German Bight; H – Skagerrak. The general circulation of the North Sea (adapted from Turrell et al., 1992; Hill et al., 2008) is overlaid as arrows for FIC (Fair Isle Current), DC (Dooley Current), SCC (Scottish Coastal Current), CNSC (Central North Sea Current), and SNSC (Southern North Sea Current). Image from Queste et al. (2016).

More details about the ‘prevailing physical properties of the North Sea waters’, including water circulation and tidal currents, are presented in Appendix B.

2.1.1 Water column structure

Owing to its shallow depths, much of the water column in the southern half of the North Sea (south of Dogger Bank) is well-mixed throughout the year (Figure 2.1) (Otto et al., 1990). Shallower water requires less energy from the wind and tides, compared to deeper water, to become fully mixed. Van Leeuwen et al. (2015) utilised 51 years of simulation data to identify five stratification regimes in the North Sea (Figure 2.2), however, they failed to classify ~ 30% of the North Sea, especially in the southern part which exhibits interannual variations. North of Dogger Bank (excluding the Norwegian Trench which is permanently stratified) much of the North Sea undergoes seasonal stratification (green areas indicated as SS in Figure 2.2).

Thus, much of the northern North Sea undergoes seasonal thermal (temperature driven) stratification from spring (March/April), when stabilising buoyancy input from solar heating out-competes the mixing from the tides, wind and wave, and a layer of warmer water overlies a layer of cooler water separated by a vertical density gradient driven by temperature (the thermocline; Figure 1.2). In some areas, buoyancy input from freshwater sources contributes to stabilising stratification by reducing the density in the surface mixed layer. In autumn, when solar heating reduces and wind and waves increase, this temperature gradient is broken down and the water column becomes fully mixed again. The thermocline effectively acts as a barrier between surface and bottom waters, limiting the vertical exchange of heat, salt and nutrients between the two layers.

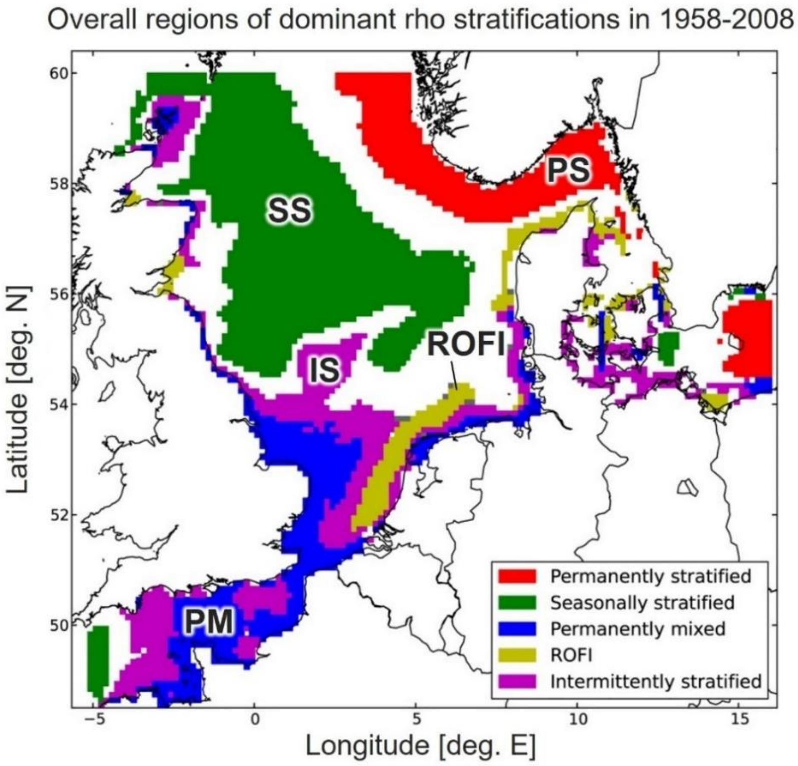


Figure 2.2. Five stratification regimes in the North Sea; PS = Permanently Stratified; SS = Seasonally Stratified; PM = Permanently Mixed; ROFI = Regions of freshwater influence; IS = Intermittently Stratified. Image modified from van Leeuwen et al. (2015).

The ‘Potential Energy Anomaly’ (PEA) is a measure of how much energy is needed to fully mix the water column, or how ‘strong’ the stratification is; a PEA value of 0 indicates a mixed water column as no energy is required to mix it. PEA can be used to 'classify' regions according to their vertical structure (PEA map represented in Figure 2.3).

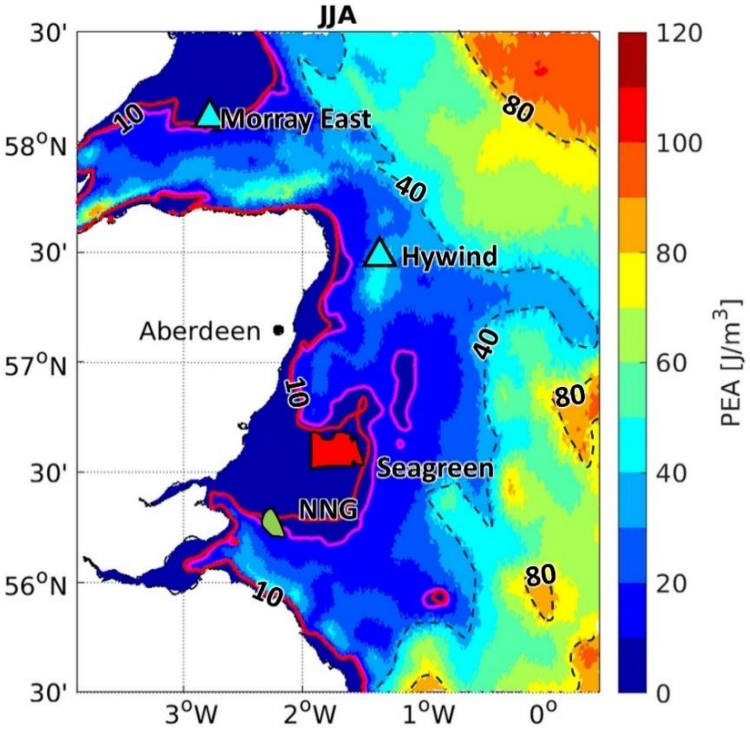


Figure 2.3. Summer (JJA: June-July-August) climatological average 'Potential energy anomaly' (PEA) map of the Scottish North Sea calculated from modelled density (derived from temperature, salinity and depth) from an FVCOM model run. Pink contour (approximately 10 PEA) defines the boundary between mixed (blue colour) and seasonally stratified (light blue to red colour) waters, the red contour shows how the boundary will change with future climate condition (2050). Image modified from De Dominicis et al. (2018).

A recent study from Holt et al. (2022) demonstrated that, under projected climate scenarios, the length and strength of seasonal stratification in the North Sea will increase. Therefore, it is also important to understand how OWF infrastructures may interact with climate-driven changes. Baseline physical properties of the water column in complex settings such as the North Sea are affected by seasonal variability (through water stratification), mixing, and changes in meteorological forcing. In order to understand the impact of anthropogenic activity (e.g. energy industry operations), these factors need to be separated from the natural variability of the system. This requires data and models at the appropriate spatial and temporal resolution, in order to provide a robust understanding of physical properties and their change in space and time.

2.2 Existing data on water column baseline and potential gaps

The North Sea is one of the most intensely investigated sea areas in the world (Sündermann & Pohlmann, 2011). Long-term routine monitoring of baseline parameters (e.g. temperature, salinity, dissolved oxygen and chlorophyll) in the North Sea is carried out by a number of European organisations. A number of European data centres such as the British Oceanographic Data Centre (BODC), International Council for the Exploration of the Sea (ICES) and the Marine Environmental Data and Information Network (MEDIN) provide more than 100 years' worth of environmental data from the North Sea collected by hundreds of organisations.

2.2.1 Parameters indicative of ecosystem pressure

Offshore platforms and marine renewable energy installations were identified in the literature as one of the main potential environmental pressure elements changing the hydrodynamic conditions, though large data sets are required to observe and detect changes in these conditions (see Galparsoro et al., 2022, and references therein). In particular, underwater structures such as foundations and piles may cause turbulent current wakes, which impact circulation, stratification, mixing, and sediment resuspension (Forster, 2018) (see Chapter 3). Consequently, stratification of the water column affects nutrient availability in the euphotic zone indicating potential impact on marine ecosystem processes; however, Daewel et al. (2022) noted that ecosystem impacts are less clear for the following reasons:

i. The changes in nutrient concentration would start a cause-effect chain that translates into changes in primary production and effectively alters the food chain.
ii. In a dynamic system like the North Sea, characterised by strong tidal and residual currents, changes in the biotic and abiotic environment are exposed to advective processes.
iii. The expected changes depend strongly on the prevailing hydrodynamic conditions, which makes it difficult to disentangle natural changes from those due to offshore wind deployments. Changes in the hydrodynamic conditions can have significant and varied effects on marine ecosystems (Shields et al., 2011).

In-situ measurements of salinity and turbidity, combined with remote sensing (Li et al., 2014; Vanhellemont & Ruddick, 2014) and modelling (Cazenave et al., 2016; Lass et al., 2008; Rennau et al., 2012) demonstrated that each turbine can generate an upwelling effect of up to 1 km. This increase in primary production (potentially leading to enhanced nutrient supply to the light, surface layer) can enhance phytoplankton biomass, which provides the base for marine food webs, and thus favour the concentration of pelagic fish.

Enhanced primary production in the surface results in more organic matter being available to be remineralised by bacteria, and some of this organic detritus sinks through the water column into the bottom mixed layer. Bacterial respiration of organic matter in bottom waters results in a net consumption of oxygen (as no oxygen is being produced by phytoplankton due to the low light levels and there is no exchange with the atmosphere) and a remineralisation of nutrients such as nitrate and phosphate. Thus, in stratified waters, bottom oxygen levels will be lower than in the surface mixed layer. In some seasonally stratified shelf seas, bottom mixed layer oxygen concentrations may reach ecologically concerning levels by the end of the stratified period (e.g. Queste et al., 2016; Diaz & Rosenberg, 2008).

Amongst the most relevant monitoring parameters indicative for pressure elements, the ones representing EOVs which allow definition of the strength and duration of stratification (when sampled at the correct location and time), are outlined below (sub-sections 2.2.2 and 2.2.3).

2.2.2 Essential Ocean Variables: temperature, conductivity and depth

Temperature, conductivity and depth are the most confidently sampled oceanographic variables. These variables are commonly measured using a CTD (conductivity, temperature, depth) sensor which is at the highest Technology Readiness Level (TRL; 9-10). The largest amount of baseline data vertically through the water column (i.e. not from remote sensing) in the North Sea is that collected from CTDs. Salinity is derived from measuring the conductivity of seawater and, when combined with measurements of temperature this can be used to calculate the density of seawater. Through vertical profiles of density one can simply derive the potential energy anomaly, which is a measure of how much energy would be required to fully mix the water column, or how stratified the water column is. From the available studies on the potential impact of OWFs on the marine environment, it is evident that the vertical stratification is considered most likely to vary due to the presence of OWFs (via OWFs driven changes to mixing). Any change to stratification resonates through the marine ecosystem, as the position of the pycnocline (the vertical gradient in density) also dictates the location and concentration of phytoplankton. The depth of the pycnocline will dictate the vertical position of the Subsurface Chlorophyll Maximum (SCM) during summer months, which occurs when nutrients have been depleted in the well-lit surface layer following the spring bloom. In summer, phytoplankton biomass becomes concentrated at the pycnocline where phytoplankton can utilise nutrient fluxes from the nutrient rich bottom waters combined with sufficient light levels. The strength, length, and the timing of the onset of stratification, as well the surface mixed layer depth/position of pycnocline are all ecologically important parameters that can be gained from measurements of temperature, salinity and depth performed at the right time and in the right location. It is important to note that there is high horizontal variability in temperature, salinity and depth across the North Sea, as well as high temporal variability in temperature and salinity. Seasonal cycles drive some of the temporal variability, however extreme weather events (e.g. heat waves, storms, rainfall) can also drive periodic changes to temperature and salinity. A monitoring strategy would need to resolve some of these high spatial and temporal variabilities in the immediate vicinity/near-field of OWFs and to increase confidence in modelling tools at measurement locations to enable models to be applied over larger spatial areas, and to underpin longer term model predictions.

2.2.3 Essential Ocean Variables: Chlorophyll biomass

Measurements of chlorophyll biomass can be used to infer the concentration of phytoplankton in the water column. In-situ fluorometers are widely used to estimate chlorophyll-a (Chl-a) biomass as they are at a reasonably high TRL (8-9), low power and easily installed on moorings, ship-based and autonomous platforms. This has resulted in the temporal and spatial resolution of Chl-a measurements in the North Sea being dramatically increased with increasing glider (small autonomous unmanned vehicle, AUV) deployments. Productivity and phytoplankton biomass observations across large spatial scales mainly rely on ocean colour measurements derived from satellites. However, satellite derived ocean colour products do not necessarily penetrate very far through the water column to where much of the production in the North Sea occurs, particularly during summer within the SCM, and thus these data are spatially limited (Weston et al., 2005). Marine Autonomous Systems (MAS) can be used for surface calibration of satellite derived Chl-a. Glider mounted fluorometers can be used to measure phytoplankton abundance throughout the entire water column. Additionally, multiple wavelengths can be used to differentiate between different pigments found within various species of phytoplankton. Furthermore, as these data are available in near real time, glider missions and sampling strategies can be continuously updated.

Despite fluorometers being widely deployed as a standard sensor to measure Chl-a, factory calibrations can differ widely from the natural environment as they are typically based on the Chl-a concentration of one phytoplankton species, when in fact there are many in the natural environment at different times throughout the year. In addition, instrument signals can fluctuate and drift due to power and temperature oscillations. Furthermore, physical damage and biofouling to the sensors can occur during long-term deployments, which has been observed in many North Sea glider deployments (Charlotte Williams, personal comm.). Best practice is typically to carry out in situ calibrations in close proximity to the fluorometer at the beginning and end of deployment, although remote sensing data from satellites can also be used to calibrate the surface fluorometry value. Thus, although easily available, Chl-a fluorometers require more expense to gain accurate data than CTD as they need to be calibrated against discrete water samples.

2.2.4 Data repositories

Although thousands of surveys have been carried out in the North Sea (Appendix B), there is no standard repository for all environmental information. There are individual databases that contain some of the information compiled from consultancy reports. A good example of this is the UK Benthos database (BGS, 2014). Although some data have been deemed commercially important, most data collected are in theory available but difficult to find and access in practice, and therefore fail to meet one or more of the Findability, Accessibility, Interoperability and Reusability (FAIR) data principles (Wilkinson et al., 2016). There have been ongoing efforts to make more commercial data and metadata available, for example through the INSITE Interactive data portal.

More information on ‘existing data on water column baseline and potential gaps’ related to ocean observations generally performed for various purposes and including water column parameters (e.g. CTD/hydrographic data including turbidity; current speeds, direction/tides) and seafloor data are presented in Appendix B. Appendix B also discusses some of the standards for ‘strategic assessment’, ‘current state of the art and adopting future technologies’, and ‘relevant data collection from past and current programmes’.

2.2.5 Data collected to-date on OWF impacts

The reviewed studies show that OWF foundations and structures generate a turbulent wake that contributes to localized vertical mixing which can move nutrients confined to the near bed layer higher up into the water column making it more readily available for primary production (Broström, 2008; Nerge & Lenhart, 2010; Ludewig, 2014) (see Chapter 3). Therefore, the development of large OWFs in areas already sensitive to seasonal low oxygen concentrations (such as Oyster Grounds) may experience further decreases in dissolved oxygen (DO) concentrations in the bottom mixed layer due to accumulation of phytoplankton biomass in the bottom mixed layer. Additionally, enhanced mixing at the seabed will resuspend organic matter within the sediments, making it available for pelagic bacterial respiration, and thus further biological oxygen consumption. Consequently, any changes to mixing and sediment resuspension at the bed resulting from the presence of OWFs may also further impact DO and remineralised nutrient concentrations in the bottom mixed layer.

Regular monitoring and in-situ analyses of the levels of dissolved oxygen (DO), total nitrogen, total phosphorus, and Chl-a concentration at OWFs provide insight into marine oxygen deficiency problems (Janßen et al., 2015; Qvarfordt et al., 2006).

To effectively protect the marine environment across Europe, the European Union put in place the Marine Strategy Framework Directive (MSFD) in 2008. EU member states are required to take actions and measures in order to achieve and maintain Good Environmental Status (GES) in the marine environment. GES is a qualitative description defined as ‘ecologically diverse and dynamic ocean and seas which are clean, healthy and productive’. The UK Marine Strategy outlines how the UK is currently performing and how GES status can be achieved in the future via a number of existing and planned marine monitoring programmes. In general terms, there are relevant GES quality descriptors, and associated variables, which can be monitored and used to assess the potential environmental impact of OWFs.

3 How to predict change using models?

Chapter 1 outlines how OWFs in quiescent, less tidally energetic, regions have the potential to cause notable changes to mixing which could impact the extent, timing and magnitude of seasonal stratification. Such changes to the mixing and stratification in shelf seas like the North Sea could thus, over-time, lead to changes in the behavior of fish, seabirds and marine mammals (via 'bottom up' trophic cascades) (Figure 3.1).

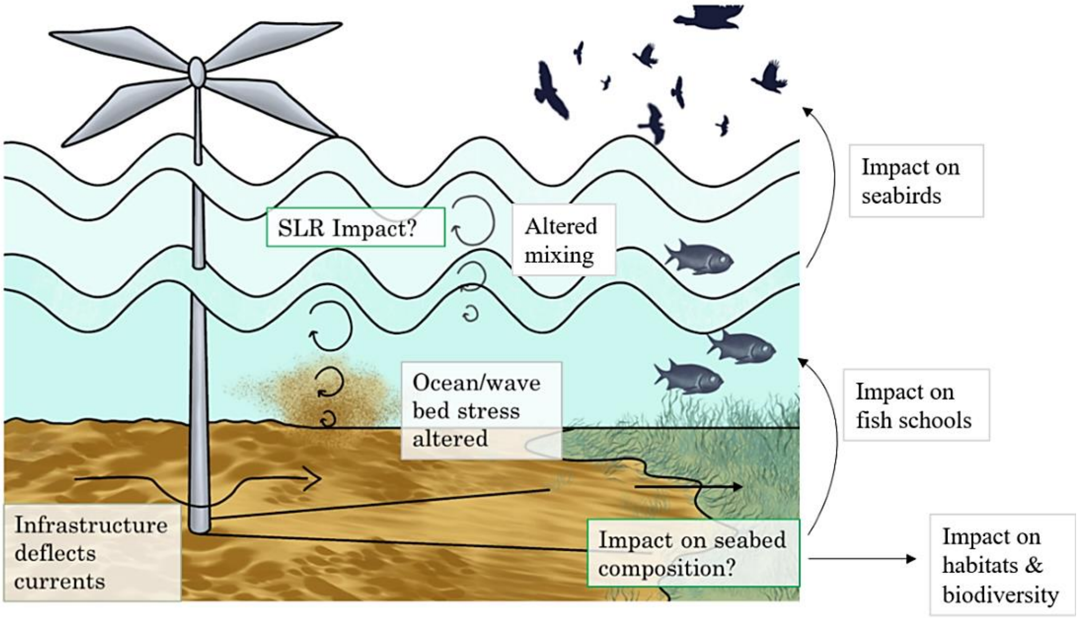


Figure 3.1. Schematic of cascading processes from single turbine to ecosystem scale. SLR = Sea-Level Rise (credit Julia Rulent).

Numerical modelling is essential for predicting changes to the marine environment and marine ecosystem due to the presence and operation of offshore infrastructures such as OWFs and due to processes such as climate change, especially in absence of direct data and in support of existing data. This chapter discusses:

- Understanding impact pathways on physical and biogeochemical water column processes, also highlighting the potential impacts at higher trophic levels (**Section 3.1**).
- Modelling the chain of impacts: how understanding and prediction of the accumulated chain of impacts can feed into the planning and impact assessment process, and modelling tools (**Section 3.2**).

3.1 Understanding impact pathways on physical and biogeochemical water column processes

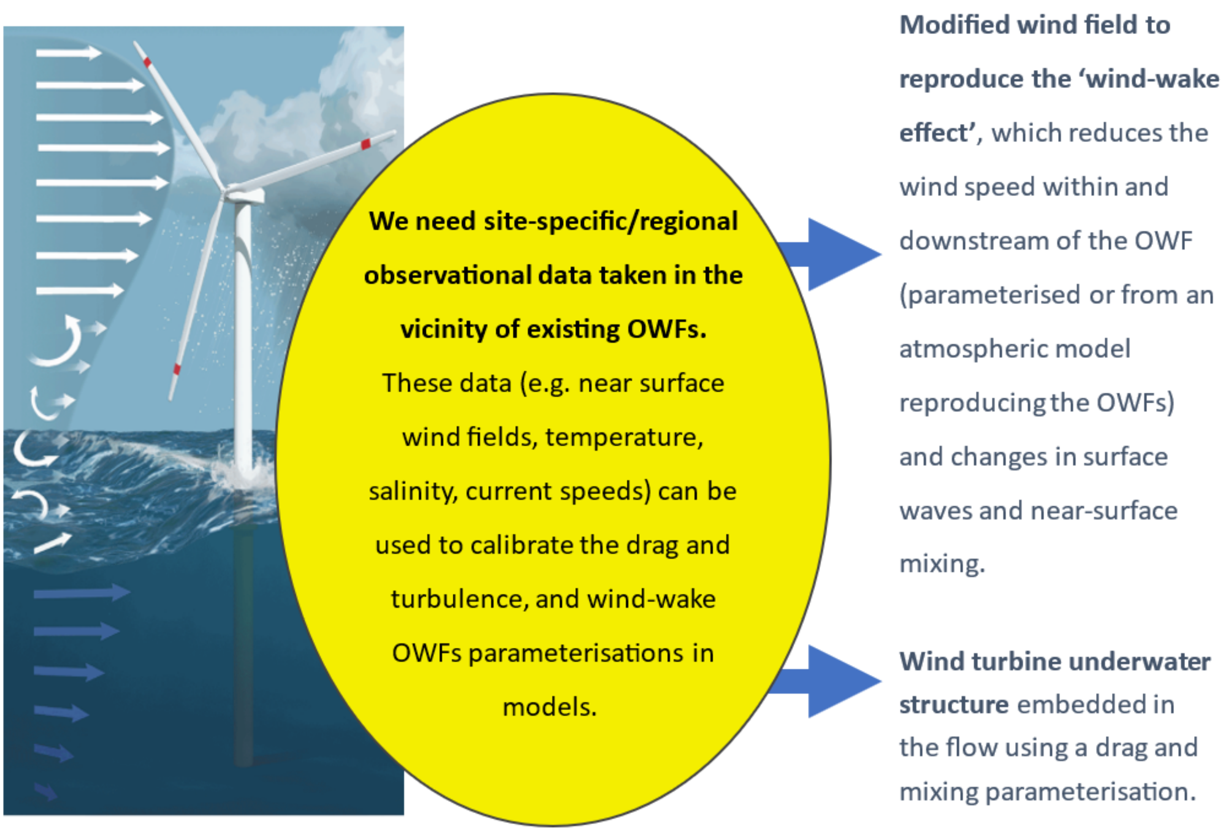
The mechanisms/pathways through which an OWF can change the physical water column are (Figure 3.2):

i. Induced drag of the underwater structures (fixed or floating) and mixing in their wake within OWFs, and
ii. Change of the wind field in the wake of the OWT/OWF (wind-wake effect), within and extending beyond the area of individual OWFs.

Note that, although changes to seabed conditions due to placement of infrastructures such as anchors, substructures cables, etc. on the seabed are also relevant at an impact assessment level, these types of impacts are outside the scope of this project and therefore are not discussed in this report.

3.1.1 Underwater structure effects

To date only two studies have been reported observing OWF foundation-induced mixing in occasionally stratified waters in the German Bight, North Sea. Floeter et al. (2017) performed surveys using a TRIAXUS (a remotely operated towed vehicle, ROTV), through two non-operating OWFs. This means they were able to measure the effects of the fixed underwater structures only. Water property transects through the OWF (with 80 foundations) revealed a weakening of the local summer stratification and effects extended into the surrounding area. Upwelling at the edges of the OWF was also observed. However, they concluded that it was difficult to disentangle OWF-induced changes from natural variability.



We need site-specific/regional observational data taken in the vicinity of existing OWFs. These data (e.g. near surface wind fields, temperature, salinity, current speeds) can be used to calibrate the drag and turbulence, and wind-wake OWFs parameterisations in models.

Modified wind field to reproduce the 'wind-wake effect', which reduces the wind speed within and downstream of the OWF (parameterised or from an atmospheric model reproducing the OWFs) and changes in surface waves and near-surface mixing.

Wind turbine underwater structure embedded in the flow using a drag and mixing parameterisation.

Figure 3.2. Schematic of predicted impacts and data needed for model parametrisation. Image modified from Shaw et al. (2022).

Schultze et al. (2020) measured the wake of a single monopile using a chain of CTD sensors. This was done twice in two different years. In one survey, during weak stratification, the disruption of background stratification by the wake was observed within a narrow region of up to 70 m width that reached at least 300 m downstream of the monopile. However, in a second survey, with stronger stratification, no clear signal from the monopile could be identified which stood out from the naturally occurring variability. Schultze et al. (2020) concluded that, depending on the strength of stratification, single monopiles can significantly alter the vertical structure of the water column within its wake.

Both the Floeter et al. (2017) and Schultze et al. (2020) studies were in shallow waters (< 40 m). To-date, no observations of OWF effects have been completed in deep waters, seasonal or permanently stratified shelf seas. These conditions are the subject of the PELAgIO programme, which is underway during 2024 with results still unpublished. Recent studies have addressed the potential consequences of OWFs using models. Existing models evaluating foundation impacts can be divided into two categories: models of relatively small spatial extent (1 - 2 km) that are high-resolution non-hydrostatic models (usually micro-scale Large Eddy Simulations (LES) models) with individually resolved support towers or turbines focused on effects local to turbine foundations within and close to individual OWFs; and model spanning much larger spatial extents (10s - 100s km) of lower resolution such that individual OWTs or OWFs are parametrised using (usually) sub-grid scale models and suited to capturing far-fields effects across coastal shelf regions. The surveys described in Schultze et al. (2020) were complemented by LES simulations of flow past a single monopile which was simulated under different levels of background stratification. Turbulent Kinetic Energy (TKE) dissipation rate was found to be up to two orders of magnitude larger with the monopile and persisted far downstream of the cylinder.

In this chapter we will mainly focus on the large-scale changes to physical processes potentially caused by OWFs foundations and how these may impact higher trophic levels. Structure-induced mixing has rarely been addressed at regional scales, and research is being undertaken to determine regional implications of the additional mixing generated by OWFs foundations. Since fixed OWFs foundations typically have diameters of the order of 5 - 10 m, mixing induced by structures is usually introduced as a sub-grid scale parameterization in large-scale ocean models (Rennau et al., 2012; Carpenter et al., 2016; Christiansen et al., 2023). Cazenave et al. (2016) used an unstructured grid where the wind monopiles are explicitly described in the grid, i.e. enabling representation of individual (cylindric) OWT foundations with no need for sub-grid specific parameterization of structure-induced hydrodynamics and mixing. This approach has been further tested by Christiansen et al. (2023) and compared with the sub-grid parameterization. With the grid resolving OWT foundations, Christiansen et al. (2023) encountered numerical problems due the high resolution and hydrostatic approximation. They instead recommend the sub-grid parameterization as a suitable method for assessing the large-scale impacts of structure-induced mixing.

The sub-grid parameterization of foundation drag and wake turbulence has been described in Rennau et al. (2012), Carpenter et al. (2016) and Christiansen et al. (2023). It is based on an additional quadratic friction term in the momentum equations as well as additional production terms in the dynamic equation for TKE and its dissipation rate (further details of this methodology is presented in 'Induced drag and mixing of the underwater structures (fixed or floating)' of Appendix C).

Review of this subject shows that no published literature is available on the combined potential impacts of fixed foundations effects and wind-wake effects (see sub-section 3.1.2). Additionally, no published literature is available on how water column changes imposed by the fixed foundations may translate into biogeochemical changes.

3.1.2 Wind-wake effects

The operational principle of an OWF is to extract kinetic energy from the atmosphere and convert it into electricity. This results in the creation of a region of reduced wind speed in the shadow zone of an OWF, the so-called wind-wake (Figure 3.2). Examples of earlier studies and new approaches investigating the oceanic response to wind stress anomalies in models are presented in 'Wind-wake effects' in Appendix C.

In the North Sea, an expansion of wind energy means OWFs are being developed in seasonally stratified deeper waters with lower tidal velocities, where natural tidal mixing effects are weaker and any changes in vertical transport and density distribution are more significant due to stronger stratification. In conclusion, it is not only atmospheric conditions that determine the impact of OWF wakes on the ocean, but also the regional hydrodynamic conditions in the respective environment.

Based on results of studies summarised in Appendix C, the wind-wake can generate changes in the surface mixed layer depth and dipoles in the sea surface elevation, which can affect the stratification and indicate potential impact on marine ecosystem processes. The atmospheric and the regional hydrodynamic conditions will determine or modulate the impact of the wind-wakes on the ocean. The combination of both wind-wake and underwater structure effects has not been addressed in any study; thus, it is unknown if one effect has a greater impact than the other and if they interact.

3.1.3 Physical and biogeochemical changes impacting ecosystem function via 'bottom up' trophic cascades.

Changes to the physical marine environment can propagate to the wider marine ecosystem. At ecosystems levels, effects of OWFs may or may not be severe, and could be positive or negative (Daewel et al., 2022). The evaluation of ecosystem effects through Before-After-

Control-Impact (BACI) surveys, although possible, is challenging. The aim of the BACI method is to estimate the state of the environment before and after (BA) any change and to compare changes at reference sites (or control sites) with the actual area of impact (CI; the OWF area). Any set of ecosystem/environmental variables can be monitored within a BACI-type survey, but investigations are usually limited to abundance and diversity metrics for selected fish and sea bird species (van Berkel et al., 2020). If sampling is sufficiently representative, the measurements should, in principle, allow the disentanglement of OWF impacts from exterior regional trends. However, a number of factors make it difficult for a BACI survey to disentangle the potential impacts of OWF-induced physical and biogeochemical changes in the water column from natural variability and from regional/global trends (e.g. climate change), as well as from other concurrent impacts of other human activities like changes in fishing effort, noise levels or eutrophication (van Berkel et al., 2020).

BACI studies will also be limited by the local scale of the survey, while indirect impacts via 'bottom up' trophic cascades on the pelagic and benthic ecosystem can be complex and non-local. The modifications in mixing and stratification will change nutrient availability in the uppermost part of the ocean. The complexity arises from:

i. The changes in nutrients, starting a cause-effect chain that translates into changes in primary production, altering the food chain.
ii. In dynamic systems with strong tidal and residual currents, changes in nutrients are non-local because they are modulated by advective processes.
iii. Changes will be different with different hydrodynamic conditions, making it difficult to disentangle changes induced by OWFs from natural variability.

Numerical modelling studies are the only way to build BACI studies with the ability to simulate with and without OWFs scenarios, with data then required to ensure that the interdependences within and between modelling tools are fully understood to provide confidence in the predictions made. The first study to use a modelling approach to investigate ecosystem changes was van der Molen et al. (2014), which used a low resolution hydrodynamic and ecosystem model to simulate the impacts of a single OWF in a shallow well-mixed area of the North Sea (Dogger Bank). The OWF was parameterised simply as a 10% wind speed reduction only within the wind farm (and not in the wake of the wind farms). They found that the OWF would lead to a general increase in primary productivity, with the effects mostly limited to the OWF area. This is probably due to the very simplified parameterization used and to the weak currents in the area studied.

More recently, Daewel et al. (2022) demonstrated that large scale OWF developments can have a substantial impact on the structuring of coastal marine ecosystems at basin scale. The wind-wakes effects on the hydrodynamic conditions propagate at the ecosystem level. Large-scale changes in annual primary production can reach up to +/- 10% locally, and they are not only in the location of the OWFs but distributed over a wider region. Daewel et al. (2022) also found an increase in sediment carbon in deeper areas of the southern North Sea due to reduced current velocities, and decreased oxygen inside an area with already low oxygen concentration.

In summary, numerical modelling studies are the only way to build BACI studies with the ability to simulate with and without OWFs scenarios. A high-density suite of physical and biological observations data is then required to ensure that the interdependences within and between modelling tools are fully understood to provide confidence in the predictions made. There are no studies available on the impacts of the underwater structure of OWFs on the ecosystem functioning. Daewel et al. (2022) is the only study addressing how and to what extent atmospheric changes generated by large OWF clusters could affect marine productivity. However, there are no studies available on how those impacts could further propagate in the food chain.

3.2 Modelling the chain of impacts: how it can feed into the planning and impact assessment process, and modelling tools

Modelling tools are essential to explore potential pathways and impacts of OWF developments, allowing marine spatial planners and developers to understand the complex environmental impacts of any new installation. The aim of modelling studies can be to reduce uncertainty in cumulative impact assessments. Models can cover the continuous range of processes from physics through chemistry, to ocean productivity, prey and predators. This allows assessment of the potential cumulative impact on marine physics and biology in the water column and at the seabed. Typical modelling tools used for these impact assessments are hydrodynamic and wave models such as NEMO, FVCOM, TELEMAC, SWAN, WaveWatchIII, and TOMOWAC (Figure 3.3). They can give information about changing currents, waves, seawater characteristics (salinity, temperature) and mixing/stratification. The physical models must then be coupled with biological processes models to inform ecosystem models such as ERSEM, and particle tracking models, to give information about the ecosystem functioning and productivity (Figure 3.3).

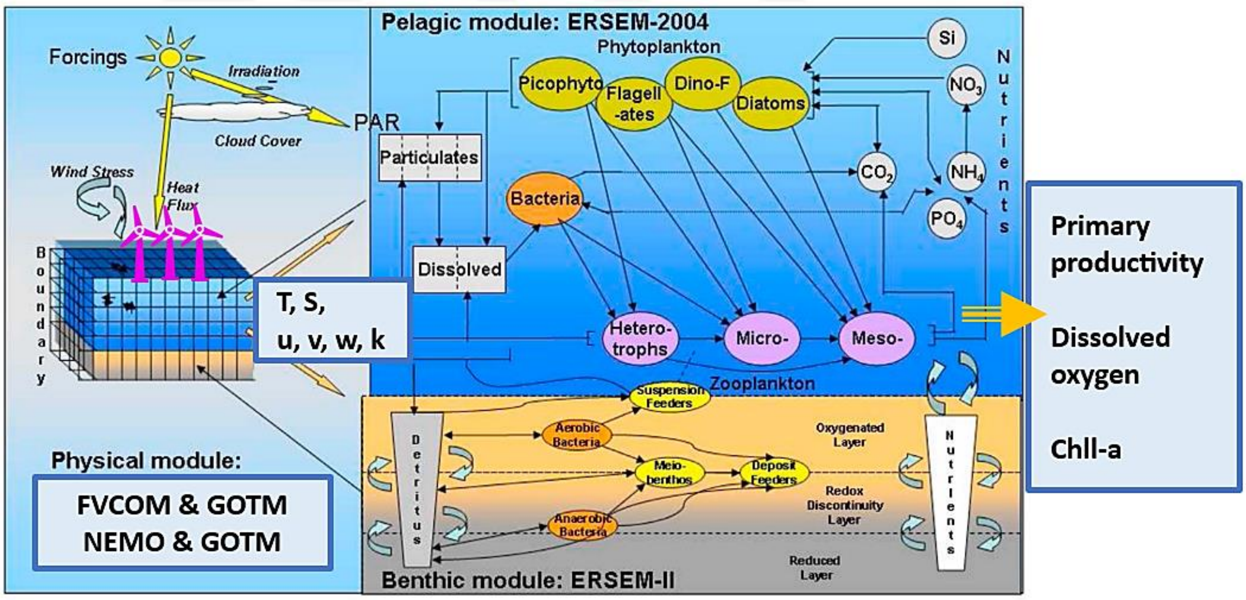


Figure 3.3. Example of sub-models coupled at the same temporal and spatial resolution as the physical model, to capture the complex effects of the 3D hydrodynamics on the biogeochemical cycles (modified from Ciavatta et al., 2011). T = Temperature; S = Salinity; u, v = Horizontal current velocity components; w = Vertical velocity; k = Diffusivity; Chl-a = Chlorophyll-a.

3.2.1 Models enable investigation of local and non-local effects of OWFs

While essential for planning, local (in-situ) observations at OWF sites can only present part of the picture. Numerical models can be used to investigate both near-field and far-field impacts, and to cover the range of scales from device-scale to far-field effects in the wider regional seas and spanning a range of timescales. The choice of modelling tools must be fit for the scale, e.g. computational fluid dynamics code for device scale, unstructured models to represent turbines, shelf-scale models to understand far-field impacts of OWFs.

3.2.2 Models enable investigation of future scenarios

Using numerical tools, we can explore both present and future impacts, and ‘what-if’ future scenarios. This can be the placement and layout of new OWFs, as well as the interaction between turbines and the marine environment in a changing climate. Models can also suitably address different time scales, to understand both immediate and long-term environmental impacts. With deterministic simulations, we can understand the chain of processes that alter the environment and may identify surprising and unanticipated consequences of OWF installation. This ‘future knowledge’ would be impossible with observations alone, while at the same time observations are required to validate models before using them in a predictive mode. These exploratory scenarios use model realisations and storylines to engage stakeholders in conversations and to understand and manage competing needs.

Ocean and biogeochemical model predictions could then become a very powerful tool at the planning stages to help determine the size and locations for future OWFs in order to minimise the perturbations on the natural environment. Ocean simulations could also be used to understand the integrated and cumulative impacts with regard to the interactions between several individual OWFs. Understanding of the integrated and cumulative impacts can be used to optimise the utilisation of the offshore space, making sure that future OWFs are laid out in a way that minimises cumulative effects on the environment. However, as the number of turbines grows, so does the uncertainty related to their combined effect. This is especially true of emergent fields e.g. FLOW, where little data exists.

3.2.3 Models are essential to disentangle potential OWF effects from natural variability, climate change and other external pressures

Any set of ecosystem/environmental variables can be monitored within a BACI-type survey, however, a number of factors make it difficult for a BACI survey to disentangle the potential impacts of OWF-induced physical and biogeochemical changes in the water column from the natural variability and from the regional/global trends (e.g. climate change), as well as from other concurrent impacts of other human activities like changes in fishing effort, noise levels or eutrophication (van Berkel et al., 2020). Other than high-density spatial and temporal physical and biological observations, numerical modelling studies are the only way to build BACI studies with the ability to simulate with and without OWFs scenarios.

Ocean simulations are essential for understanding the relevance of the environmental effects. Any OWF installation will perturb the environment, and defining which is the acceptable limit of change is a difficult task for decision makers. Models could help improve understanding if the environmental effects observed are within the natural variability, i.e. if they are within the natural fluctuations of the ocean system. Climate change will also perturb the system (beyond its natural variability) and understanding if the modelled environmental effects of OWFs are larger or smaller than climate change effects is also important. OWFs could also interact with climate change effects either to exacerbate, or to mitigate. As stated in Dorrell et al. (2022), the introduction of wind turbine structures into deeper stratified water will provide a new, artificial, source of turbulence (Section 3.1). This increased turbulence could potentially offset the impacts of climate change on stratification and increase the supply of nutrients to the surface layer and oxygen to the deep water. Careful wind turbine design and layout (guided by models) could therefore potentially provide an important tool in mitigating impacts from climate change.

Some examples of ‘ongoing modelling efforts’ are summarised in Appendix C.

4 Where and when to observe change - sustained observation programmes

There are only three observational studies that detected water column changes associated with submerged OWTs and surface wind-wake effects, with several modelling studies that have started to investigate both effects (Dorrell et al., 2022; Carpenter et al., 2016) (Figure 4.1). More observational studies are therefore needed to support modelling approaches, to develop and validate parametrisations and to validate simulation results.

Some indication of the potential effects of OWF infrastructure at the current construction levels is emerging which suggest that multiple wind farms could have a cumulative impact at a regional scale (Christiansen et al., 2023).

A total of 867 findings on pressures due to wind energy devices and impacts on ecosystem elements were extracted from 158 publications as part of this project. Half of the analysed publications (51%) presented empirical evidence, while 36% of the studies were based on modelling approaches, including the modelled propagation of underwater noise. Literature reviews accounted for 11% of the publications, and only 1% of the studies were based on expert judgement. A continuous increase in the number of publications was identified, especially in the last eight years (74% of the scientific publications), which is in line with the increase of OWFs and installed production capacity.

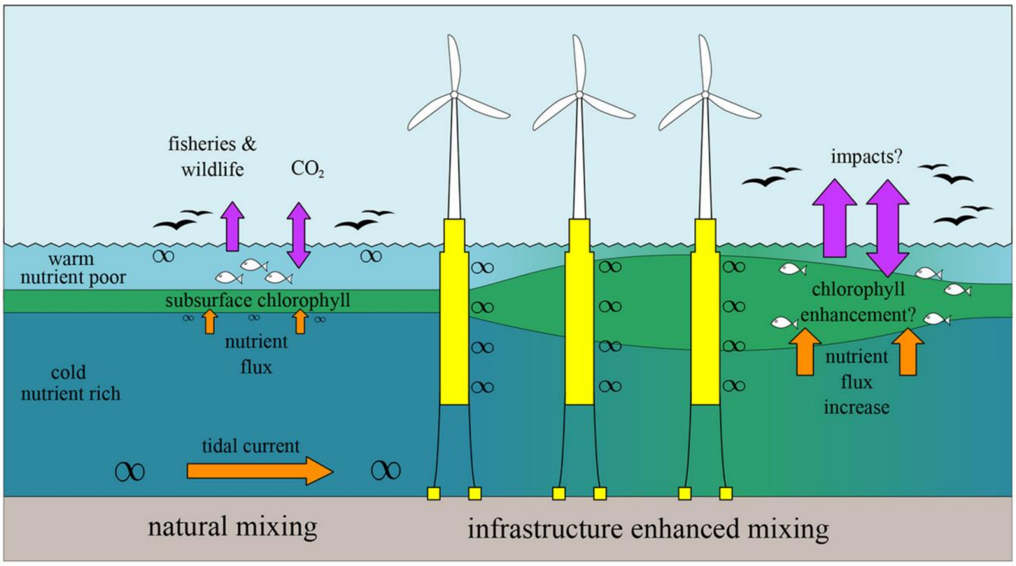


Figure 4.1. Offshore wind infrastructure adding wake turbulence throughout the upper water column, including directly at the thermocline. Swirl symbols indicate turbulence intensity arising from near seabed, near surface and flow-structure induced shear. Wake turbulence mixes cold nutrient rich bottom water with warm nutrient poor surface water, reducing the strength of stratification and potentially enhancing plankton growth in the subsurface chlorophyll layer. Changes in the subsurface chlorophyll layer would have further impacts on nutrient pathways, ecosystem functioning and oceanic carbon sequestration (Dorrell et al., 2022).

Studies have been conducted in shallow seas (North Sea, 66% of the publications), during the operational phase (64%), in shallow waters (90% at < 30 m depth), close to the coast (56% < 20 km offshore), with few turbines (80% with < 81 turbines), low production capacity (63% with < 160 MW), and a small area (67% < 70 km^2).

There is a general shortfall in the coordinated prioritisation of issues to be addressed by observational and monitoring programmes. Much of this lack of prioritisation stems from an incomplete evidence base across all aspects of the potential impacts of OWFs, which has hampered the objective selection of priority topics. However, the quantity and breadth of peer-reviewed evidence continues to accumulate and has now allowed some to conduct meta-analyses and identify which impacts are of greatest concern (Galparsoro et al., 2022), as well as the remaining thematic gaps within the current evidence base.

Amongst the theme of observational programmes, this chapter focuses on:

- Gaps in existing observational/monitoring programmes (**Section 4.1**).
- Priority variables and monitoring techniques for impacts directly or indirectly mediated by water column processes and pelagic biodiversity (**Section 4.2**).

4.1 Gaps in existing observations/monitoring programmes

A comprehensive analysis of the gaps associated with water column observational / monitoring efforts within OWFs can be split into the following groups:

i. Gaps and failings associated with the design, execution, interpretation and reporting of monitoring activities (sub-section 4.1.1).
ii. Gaps associated with the observation of complex interactions within a heavily utilised ecosystem (sub-section 4.1.2).
iii. Gaps associated with specific components or processes of the ecosystem, and consequently, the collection of specific abiotic and biotic variables (sub-section 4.1.3).

4.1.1 Gaps associated with the design, execution, interpretation and reporting of monitoring activities

The cost of monitoring activities will always constrain the spatial and temporal extent of monitoring programmes. Most compliance-based monitoring programmes are often impact-driven (rather than cause-effects) and locally specific (Bean et al., 2017). Equally, most monitoring programmes are configured for the detection of short-term, high-magnitude changes (Lindeboom et al., 2011). It is widely recognised that longer-term changes are poorly covered (Lindeboom et al., 2015). This is a particular weakness when considering the likely duration of some of the processes of interest due to OWFs, and due to climate change. Spatially and temporally limited observations hamper our ability to scale issues in areas (e.g. from turbine to farm-to-farm cluster or capturing spatially offset far-field impacts) and over time (e.g. understanding change associated with long trajectory processes). This impact-driven approach has not always enabled areas of high model uncertainty to be reduced.

Any monitoring programme must present uncertainty and confidence estimates alongside their output. Ideally, methods for calculating uncertainty would be standardised across monitoring efforts. Equally, the required level of uncertainty needed for a specific regulatory aspect or management action should also be stated (Franco et al., 2015); the combination of an uncertainty value with a specific threshold of quality for a management action derives a level of confidence.

Ensuring that monitoring methodologies are fit for purpose at the point of commissioning requires minimum detectable change (MDC) or effect sizes to be specified and associated with target variables i.e. what magnitude of change needs to be detected within the programme (Franco et al., 2015; Lindeboom et al., 2015). Specifying these values ensures there is enough replication within the monitoring programme to reliably report on change concerning the MDC. However, specifying MDC values is complicated by the limited understanding about the natural variability of the baseline and how relevant deviations from this baseline are. Equally, the level of heterogeneity within monitored areas is often inadequately accounted for, thereby increasing the apparent natural variability within datasets, and consequently reducing the ability to reliably detect change at a specific level.

4.1.2 Gaps associated with the observation of complex interactions within a heavily utilised ecosystem.

Across the collective monitoring effort, some programmes need to be tasked to consider both negative and positive changes of high magnitude. The need to reliably observe negative change is obvious. Changes seen to be positive also require dedicated monitoring effort. Recording positive change is necessary so that indirect or trophic cascades are documented and considered during holistic assessments. Furthermore, the use of compensation as a management tool for achieving no net loss (Hooper et al., 2021) / balancing net gain within an area will also rely on the accurate estimation of both negative and positive changes associated with specific human activities or structures. Finally, the monitoring of positive changes should also be sustained over a substantial time scale so that the longevity of the benefits can be assessed and how benefits will also scale both spatially and temporally. Although an old issue, the inherent complexity represented by multiple trophic levels, pressures from a single human activity and multiple human activities remains daunting. As such, other than simplistic additive approaches (e.g. Halpern et al., 2008 - for multiple pressures and activities), there remains a lack of evidence that prevents the constriction of tools to accurately represent these complexities within inherently complex ecosystems in a heavily utilised environment (Lindeboom et al., 2015). Long-term processes, such as climate change and ecosystem change following the cessation of fishing are high priorities for merging with more acute changes. However, as there are few opportunities to observe these trajectories now, it makes their integration in cumulative impact assessments particularly difficult (ICES, 2020). There is a lack of a ‘total ecosystem’ approach (Bean et al., 2017).

Observations are not currently integrated into a modelling system, and this limits the development of consistent understanding of cause-effect, transferability, future change, cascading and indirect effects, and cumulative impacts. The total ecosystem approach is described as a “coherent evidence-to-advice package” that relies, at its heart, on “a dynamic model of the ecosystem function and its responses to pressures based on process relationships” (Bean, et al., 2017). Rather than interpreting monitoring data directly, the information is used to refine the parameterization of the model. The modelled ecosystem response could then be used to interpret change rather than the monitoring data directly. There are many benefits to this approach which include:

- Specific datasets update the relations of many variables and processes within the model;
- Feedback can be given to the value of the new information added to the model, thereby supporting adaptive approaches to marine monitoring; and
- Modelled outputs can be reported in a quantitative manner using specific units of monitoring, management or scientific value.

4.1.3 Gaps associated with specific components or processes of the ecosystem, and consequently, the collection of specific abiotic and biotic variables

Having discussed some of the broader gaps on how modelling programmes are designed (i.e. move from ‘local impact driven’ to ‘drive refinement of the model framework’), the following section will look at specific processes and the individual variables best used to monitor them. Variables will be flagged when these are not collected routinely, using an appropriate method for informing on processes within OWFs or through existing programmes. Table 4.1 highlights the following processes, and associated variables, that are only partially covered by existing efforts and are therefore inadequately observed for providing informative cause-effect relationships or robust monitoring conclusions. Topics and variables represented in Table 4.1 focus particularly on hydrodynamic conditions associated with water column mixing. Sentinel variables are:

- Profiles of current speed and direction, turbulence and suspended load.
- Profiles of physical-chemical properties of seawater (i.e. temperature, salinity, dissolved gas, nutrients, chlorophyll and suspended particulate matter).

Table 4.1. A ranking of (i) the importance of impact topics (limited to impacts directly or indirectly mediated through water column changes); (ii) the value of specific variables characterising these topics; and (iii) the cost-effectiveness of monitoring methodologies in collecting these variables. Importance score from 1 to 3, where 3 indicates the top score, based on review by the authors of this report. Note that all topics have been ranked as top score in terms of importance and existing uncertainty by Galparsoro et al. (2022).

Descriptor: Hydrodynamic conditions associated with water column mixing.

Sentinel variables	**Sentinel priority**	**Possible methodologies**	**Specific information value of method**	**Cross-descriptor value**	**Ease and reliability**	**Active monitoring in place**	**Cost**	**Topic total**
Profiles of current speed and direction, turbulence and suspended load	Very high	Monitoring using ship mounted ADCP	2	1	3	2	1	9
		Monitoring using AUV mounted ADCP	3	1	2	2	2	9
		Monitoring using ADCP on mooring or seabed lander	3	1	2	2	2	9
Profiles of physical-chemical properties of seawater	High / Very high	Monitoring using CTD profiling and water sampling from a ship	2	1	3	1	1	8
		Monitoring using CTD profiling from an AUV	3	2	2	1	2	9
		Monitoring using a CTD sting on a mooring	3	2	2	1	2	9
		Monitoring using remote sensing (satellite imagery)	2	2	1	1	2	9

4.2 Priority variables and monitoring techniques for impacts directly or indirectly mediated by water column processes and pelagic biodiversity

Galparsoro et al. (2022) summarised priority monitoring gaps, weighted by the methodology used, suggesting the following ranking:

High priority (Table 4.1):

- Hydrodynamic conditions associated with water column mixing.

Medium priority (not considered further in this report)

- Biodiversity of benthic habitats influenced by water column processes.

Low priority (not considered further in this report)

- Seafloor integrity (i.e. the loss and gain of natural and artificial substrata, and also included as turbine surfaces transect the water column).

This report focuses on the high-priority topics associated with changes in water column properties, although it recognises that water column mixing can have consequences on the biodiversity of pelagic and benthic habitats as well as fish aggregation and recovery post-fishing. These high-priority topics were rated as being important as they represented a significant source of uncertainty within the holistic understanding of potential OWF impacts. Equally, the existing monitoring activities provided by statutory sampling programmes, industrial surveys/compliance monitoring (all sectors) and scientific investigations reveal little existing coverage of this topic in terms of spatial or thematic alignment.

Using a coarse ranking of monitoring methods for examining water column properties suggested that in-situ or the use of MAS is likely to be the most cost-effective monitoring technique long term. These monitoring methods also scored highly on their ability to provide either high spatial extent and/or temporal resolution. Remote sensing techniques for identifying turbidity plumes downstream of turbines are also an established technique for providing proxies of mixing. However, site-specific conditions can mean that a surface turbidity plume, indicative of water column mixing, is not always present (van Lancker & Baeye, 2015). Equally, the availability of cloud-free days around the UK limits the reliability of this technique as a monitoring tool (Kumar et al., 2021).

With regard to plankton sampling, both ship-based sampling and moored, in-situ instrumentation scored highly (Galparsoro et al., 2022). Although the ship-based techniques are expensive and lack the temporal resolution provided by in-situ instrumentation, they provide the ability to undertake a range of monitoring techniques (e.g. ADCP and CTD profiling) and thereby improve the cost-effectiveness of a multiparameter monitoring cruise. Crucially, ship-based monitoring allows the collection of water and plankton samples for analysis in the laboratory, yielding measurements of biogeochemical parameters (with low uncertainly) unobtainable from MAS. Concerning stock assessment work within the zone of influence of OWFs, scientific trawling within the footprint of OWF may not be possible. This means traditional scientific trawling may be restricted to the edge of the OWFs, which provides a more ambiguous assessment of fish aggregation, recovery and potential spill over. Alternatively, vessels using scientific acoustic fish finders that do not deploy fishing gear may be more likely to be able to access OWFs. Although less quantitative, this monitoring method also benefits from being able to be undertaken from smaller, cheaper vessels (or even MAS).

5 Roadmap towards sustained observational programmes supporting Offshore Wind

This chapter provides recommendations in support of the delivery of impact assessment strategies and observational/monitoring programmes targeting the interaction between OW infrastructure and the marine water column environment. Recommendations build on the review provided by Chapters 1-4 of this report, and on the outcomes of the discussions held during the multistakeholder workshop as part of this project. Reflecting the structure of the review presented in Chapters 2 to 4, Chapter 5 focuses on three thematic points:

i. Data and variables (**Section 5.1**).
ii. Model predictions (**Section 5.2**).
iii. Observational/monitoring programmes (**Section 5.3**).

A summary of recommendations is then provided (**Section 5.4**).

5.1 Data and variables

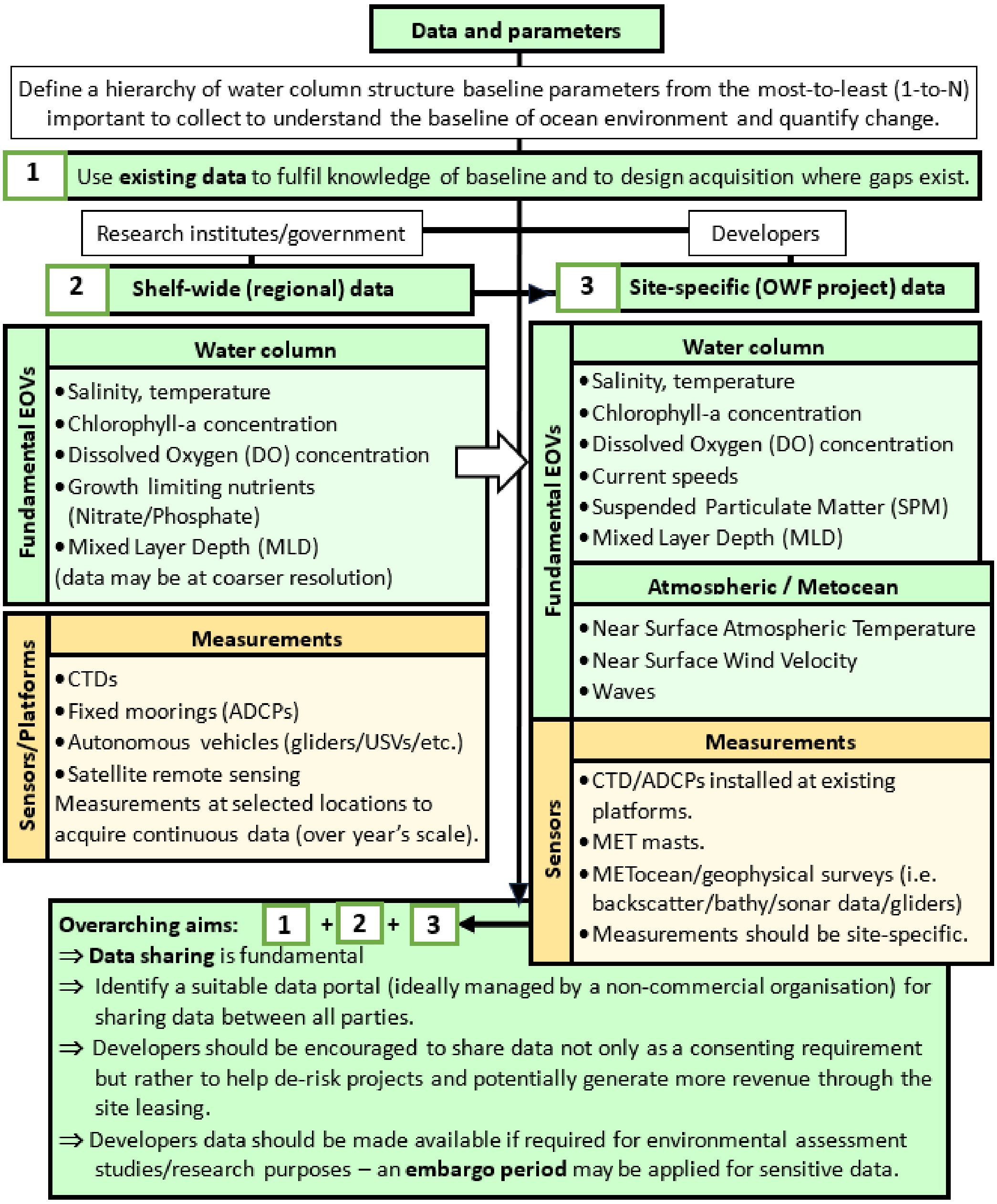
As discussed in Chapter 2, there are several Essential Ocean Variables (EOVs) that can be measured to assess the baseline condition of an ocean system in the absence of man-made infrastructure (e.g. OWFs). These variables can also be used to evaluate the potential interaction between anthropogenic activity and the local (and surrounding) environment. Relevant EOVs need to be chosen that enable a fundamental description and understanding of the baseline conditions and can be used as indicators of potential changes in the system due to human-related activities (i.e. OWFs).

As discussed in Chapter 2, to be able to define EOVs we first need to clearly define:

i. The objectives: what are we trying to monitor/observe/establish via EOVs? E.g. reduce uncertainty in baseline conditions and/or quantify their changes due to the interaction between OW infrastructures and the water column structure.
ii. The current data coverage and data gaps: where are there sufficient data, in terms of spatial coverage and time series, and where are new data required?
iii. The scale of the challenge: what spatial and temporal resolution is required to ensure detection of change?

Regarding point (i), there are no substantial operational OWFs yet built in seasonally stratified waters, or at the scales expected in the next decades. Therefore, the definition of the objectives (what we need to measure/observe in order to detect the cumulative effects of OWFs on the water column) relies on expected/predicted changes only. Thus, the definition of the EOVs and their requirements for spatial and temporal resolution (point iii) should be guided by the predicted (and modelled) interaction between future OWFs and the water column structure within seasonally stratified waters. Our understanding heavily relies on the use of numerical modelling approaches, on existing data, and on the collation of data/parameters at the locations of present and future developments, which will help to validate model outputs and be used to improve model parametrisations and eventually future predictions of likely impacts expected from expanding OWFs (Section 5.2). Data collation is essential (point ii) to understand where/if gaps exist and to what extent (e.g. what are the missing EOVs). Efforts should therefore focus on data collation, prediction of change, validation of prediction and improved forecast (Figure 5.1).

Although there are few site-specific, wind farm focused, data focusing on the water column, existing data collation can be used to assess baseline conditions at a regional and/or local scale in the absence of OWF infrastructure. More specifically, a distinction should be made between ‘shelf-wide (regional) data’ (see sub-section 5.1.1) and ‘site-specific (OWF project) data’ (see sub-section 5.1.2) (Figure 5.1).



Data and parameters

Define a hierarchy of water column structure baseline parameters from the most-to-least (1-to-N) important to collect to understand the baseline of ocean environment and quantify change.

1 Use **existing data** to fulfil knowledge of baseline and to design acquisition where gaps exist.

Research institutes/government

Developers

2 **Shelf-wide (regional) data**

3 **Site-specific (OWF project) data**

Fundamental EOVs

Water column

- Salinity, temperature
- Chlorophyll-a concentration
- Dissolved Oxygen (DO) concentration
- Growth limiting nutrients (Nitrate/Phosphate)
- Mixed Layer Depth (MLD)

(data may be at coarser resolution)

Sensors/Platforms

Measurements

- CTDs
- Fixed moorings (ADCPs)
- Autonomous vehicles (gliders/USVs/etc.)
- Satellite remote sensing

Measurements at selected locations to acquire continuous data (over year's scale).

Fundamental EOVs

Water column

- Salinity, temperature
- Chlorophyll-a concentration
- Dissolved Oxygen (DO) concentration
- Current speeds
- Suspended Particulate Matter (SPM)
- Mixed Layer Depth (MLD)

Atmospheric / Metocean

- Near Surface Atmospheric Temperature
- Near Surface Wind Velocity
- Waves

Sensors

Measurements

- CTD/ADCPs installed at existing platforms.
- MET masts.
- METocean/geophysical surveys (i.e. backscatter/bathy/sonar data/gliders)
- Measurements should be site-specific.

Overarching aims: 1 + 2 + 3

⇒ **Data sharing** is fundamental

⇒ Identify a suitable data portal (ideally managed by a non-commercial organisation) for sharing data between all parties.

⇒ Developers should be encouraged to share data not only as a consenting requirement but rather to help de-risk projects and potentially generate more revenue through the site leasing.

⇒ Developers data should be made available if required for environmental assessment studies/research purposes – an **embargo period** may be applied for sensitive data.

Figure 5.1. Diagram showing the hierarchical approach to use when identifying EOVs for environmental impact assessment studies looking at the interaction between OWF and the water column baseline conditions: 1st – Use existing data to define baseline and identify data gaps (to aid decisions on where further acquisitions are needed); 2nd – Define the regional baseline conditions, focusing on the acquisition of essential water column variables at a few sampling locations using long-term measurement systems and remote sensing. The so defined baseline can be used to 3rd – Integrate developers' parameters from specific OWF sites (including water column and atmospheric parameters) that can support numerical modelling simulation prediction of change (see Figure 5.2).

5.1.1 Shelf-wide (regional) data

Shelf-wide (regional) data are required to define the regional baseline conditions regarding water column mixing/stratification in absence of OWFs. Where these data exist, they should be made available to the developers for use in EIAs at future OWF development sites. The same data could be used to validate regional (coarse) 3D models which help define the expected, positive and negative, cumulative impacts of OWFs in the water column (see Section 5.2). Shelf-wide (regional) data include two fundamental sets of EOVs (Figure 5.1):

i. Water column variables, and
ii. Atmospheric and metocean variables.

Informed by literature review (Chapter 2) and by workshop discussions with stakeholders, this report identified the key water column variables that should be measured for a good understanding of the regional baseline conditions regarding water column mixing/stratification in absence of OWF; these key water column variables (point i) include full water profiles of (Figure 5.1 and Table 5.1):

- Salinity, temperature
- Chlorophyll-a (Chl-a) concentration
- Dissolved oxygen (DO) concentration
- Growth limiting nutrients (Nitrate/phosphate)
- Mixed layer depth (MLD) (calculated from temperature and salinity vertical profiles)

It is recommended that atmospheric and metocean data (point ii) are also collected, where possible (see sub-section 5.1.2); these data would be the same parameters outlined for site-specific (OWF project) data (see sub-section 5.1.2).

Water column variables are generally detected using sensors deployed by vessel-based multicomponent surveys, MAS (including gliders), CTD on moorings, and to some extent also satellite remote sensing, at selected sites (see Section 5.3). A variety of organisations can play a role in providing collation, access and storage (i.e. recognised repositories) of these data such as research institutes, public bodies and government (Figure 5.1). Salinity and temperature are particularly important in the detection of tidal mixing fronts and in the definition of stratification duration (start/end) and strength. To ensure accurate detection, CTD samples should ideally be acquired at weekly resolution, therefore resolving different stages of the tidal cycle (spring and neap tides) and thus tidal mixing; this sampling should be undertaken during times of the year in which the water column is stratified, or is expected to transition from mixed to stratified conditions (spring and summer), as OWFs are likely to impact the marine environment via alteration of stratification and mixing. Detection of inter-annual/decadal variability is also required in order to isolate the OWF-induced impacts from natural variability and climate change. In terms of spatial resolution, vertical sampling across various water column depths is required to resolve the pycnocline. The spatial extent and horizontal resolution of sampling would likely be dependent on the site and scale of the individual OWF though, as highlighted within this scoping study, the footprint of OWFs may impact 100s of kilometres from the structures. MAS such as gliders are capable of travelling and collecting data over 20 km/day and therefore could adequately resolve the horizontal sampling resolution needed to cover potential footprints of OWFs.

Although we may already have a good spatial coverage for the EOVs described above, extra-measurements are needed in the areas with largest predicted/modelled changes to stratification due to OWFs/climate change (see discussion on model prediction in Section 5.2). Finally, sufficient observational data with appropriate temporal coverage in Scottish shelf seas currently does not exist to capture:

- Duration and strength of stratification, and
- Start/end of stratification over several years.

Therefore, appropriate data collation and additional data are needed to make sure we appropriately assess the water column structure in seasonally stratified settings before and after OWF development at the predicted scale. To inform future data acquisition, suggestions on recommended parameters to be collected for shelf-wide (regional) scale assessments, the platforms and sensors to be used, the sampling duration and recommended temporal and spatial (vertical) resolutions are presented in Table 5.1.

Table 5.1. Parameters for shelf-wide (regional) monitoring.

Parameter	Observation type	Platform	Sensor	Sampling duration	Recommended temporal resolution	Recommended vertical resolution
Temperatur	Fixed	Mooring chain	Thermistor/CTD	Would need to cover	Hourly resolution	5 m

Parameter	**Observation type**	**Platform**	**Sensor**	**Sampling duration**	**Recommended temporal resolution**	**Recommended vertical resolution**
e		within OWF/fixed to structure		the spring/summer stratified period (> 3 months).	over this sampling period.	
	Dynamic	Small long-endurance MAS (ASVs or gliders)	CTD	Would need to cover the spring/summer stratified period (> 3 months).	Gliders can provide 1 second resolution of this data for months at a time.	1 m
	Remote	Satellite observations	Remote measurements of SST	Continuous	Dictated by satellite coverage	n/a
Salinity	Fixed	Mooring chain within OWF/fixed to structure	Thermistor/CTD	Would need to cover the spring/summer stratified period (>3 months).	Hourly resolution over this sampling period.	5 m
	Dynamic	Small long-endurance MAS (ASVs or gliders)	CTD	As for temperature	As for temperature	1 m
	Remote	Satellite observations	n/a	n/a	n/a	n/a
Chlorophyll (Chl-a)	Fixed	Mooring chain within OWF/fixed to structure	Fluorometer	As for temperature	As for temperature	5 m within the surface mixed layer, and above, within and below the thermocline if possible/ practical
	Dynamic	Small long-endurance MAS (ASVs or gliders)	Fluorometer	As for temperature	As for temperature	1 m
	Remote	Satellite observations	Remote observations of Chl-a	Continuous	Dictated by satellite coverage	n/a

Parameter	Observation type	Platform	Sensor	Sampling duration	Recommended temporal resolution	Recommended vertical resolution
Dissolved oxygen (DO)	Fixed	Mooring chain within OWF/ fixed to structure	Optode	As for temperature	As for temperature	Surface and bottom
	Dynamic	Small long-endurance MAS (ASVs or gliders)	Optode	As for temperature	As for temperature	1 m
Growth limiting nutrients (nitrate and phosphate)	Dynamic	Small long-endurance MAS (ASVs or gliders)	Microfluidic sensors/UV optodes	As for temperature	As for temperature	1 m
	Remote	Satellite observations	n/a	n/a	n/a	n/a

5.1.2 Site-specific (OWF project) data

Site-specific (OWF project) data will be required, and should be used (and provided), by developers to assess OWF-induced variability in the system (Figure 5.1). Site-specific data collected by developers are expected to be at higher resolution compared to shelf-wide data. Therefore, these can be used to refine/validate the 3D models that are used to assess the magnitude of impacts due to (cumulative) OWF effects at specific water column settings (see Section 5.2). Thus, site-specific data can aid the understanding of how OWF-induced changes compare in magnitude with natural variability and expected climate change effects predicted by coarse 3D models.

Given the absence of existing infrastructure to provide data, in the case of future FLOW developments, this assessment must be supported by model predictions (Section 5.2); thus, it is recommended that the necessary data are made publicly available (where they are not otherwise available) for environmental assessment studies (e.g., a data repository which is accessible for EIA purposes). Developers could access these data for their EIAs, integrating them with data at a higher resolution than regional-scale data, potentially obtained by wider sustained observation programmes, helping to validate prediction tools used to assess how water column variables can be observed to detect near- to far-field changes. The development of modelling guidelines will be essential for future EIA modelling strategies.

Informed by literature review (Chapter 2) and by workshop discussions with stakeholders, this report identified the key water column variables at a site-specific (OWF project) scale; these include (Figure 5.1 and Table 5.2):

- Salinity, temperature
- Chlorophyll-a (Chl-a) concentration
- Dissolved oxygen (DO) concentration
- Current speeds
- Suspended Particulate Matter (SPM)
- Mixed Layer Depth (MLD)

Similarly, this report identified the key atmospheric and metocean variables at a site-specific (OWF project) scale (and also at shelf-wide, regional scale, where possible; see sub-section 5.1.1); these include (Figure 5.1 and Table 5.2):

- Near Surface Atmospheric Temperature
- Near Surface Wind Velocity
- Waves

Measurements of the system’s hydrodynamics (in three dimensions) from ADCP, surface waves capturing wind-wake, SPM and Chl-a, combined with available site bathymetry and surficial sediments information, are key at future development sites. Furthermore, anything related to wind and currents is likely to be assessed by the developer before OWF construction, as this impacts profit, site’s risk and engineering design considerations. Ideally, all these measurements should continue during construction and operation. Near surface wind and related lower atmospheric parameters are relevant information for developers, and they are specific to operating conditions; thus, those parameters are typically continuously monitored during operation. Sharing of such data with stakeholders should be encouraged, through a mechanism that protects proprietary information.

To inform future data acquisition, suggestions on recommended parameters to be collected for site-specific (OWF) scale assessments, the platforms and sensors to be used, the sampling duration and recommended temporal and spatial (vertical) resolutions are presented in Table 5.2.

Table 5.2. Parameters for site-specific observations.

Parameter	**Observation type**	**Platform**	**Sensor**	**Sampling duration**	**Recommended temporal resolution**	**Recommended vertical resolution**
Temperature	Fixed	Mooring chain within OWF/fixed to structure	Thermistor/ CTD	Would need to cover the spring/summer stratified period (> 3 months).	Hourly resolution over this sampling period.	5 m
	Dynamic	Ship-based CTD profiles and/or small long-endurance MAS (gliders)	CTD	Would need to cover the spring/summer stratified period (> 3 months).	Ship-based: Weekly vertical CTD profiles would be ideal but would be dictated by developer survey/maintenance vessel schedule. Gliders can provide 1 second resolution of this data for months at a time.	1 m
	Remote	Satellite observations	Remote measurements of SST	Continuous	Dictated by satellite coverage	n/a
Salinity	Fixed	Mooring chain within OWF/fixed to structure	CTD	As for temperature	As for temperature	5 m
	Dynamic	Ship-based CTD profiles and/or small long-endurance MAS (gliders)	CTD	As for temperature	As for temperature	1 m
	Remote	Satellite observations	n/a	n/a	n/a	n/a

Parameter	Observation type	Platform	Sensor	Sampling duration	Recommended temporal resolution	Recommended vertical resolution
Chlorophyll (Chl-a)	Fixed	Mooring chain within OWF/fixed to structure	Fluorometer	As for temperature	As for temperature	5 m within the surface mixed layer, and above, within and below the thermocline if possible/ practical
	Dynamic	Ship-based CTD profiles and/or small long-endurance MAS (gliders)	Fluorometer	As for temperature	As for temperature	1 m
	Remote	Satellite observations	Remote observations of surface chlorophyll through ocean colour	Continuous	Dictated by satellite coverage	n/a
Dissolved Oxygen (DO)	Fixed	Mooring chain within OWF/fixed to structure	Optode	As for temperature	As for temperature	Surface and bottom
	Dynamic	Ship-based CTD profiles and/or small long-endurance MAS (gliders)	Optode	As for temperature	As for temperature	1 m
	Remote	Satellite observations	n/a	n/a	n/a	n/a
Current speed	Fixed	Mooring	ADCP	As for temperature	30 minutes	2 m
	Dynamic	Ship-based Vessel mounted	VM ADCP	As for temperature	5 minutes	4 m

Parameter	Observation type	Platform	Sensor	Sampling duration	Recommended temporal resolution	Recommended vertical resolution
		ADCP				
	Remote	Satellite observations	n/a	n/a	n/a	n/a
Suspended particulate matter (SPM)	Fixed	Mooring chain within OWF/fixed to structure	Particulate backscattering sensor	As for temperature	As for temperature	Surface and bottom
	Dynamic	Ship-based CTD profiles and/or small long-endurance MAS (gliders)	Particulate backscattering sensor	As for temperature	As for temperature	1 m
	Remote	Satellite observations	Remote observations of surface particulate optical backscattering	Continuous	Dictated by satellite coverage	n/a
Mixed layer depth (MLD)	Fixed	Calculated from temperature and salinity measurements	Calculated from temperature and salinity measurements	As for temperature	As for temperature	n/a
	Dynamic	Ship-based CTD profiles and/or small long-endurance MAS (gliders)	Calculated from temperature and salinity measurements taken from ships/gliders, but also can be gained from ship	As for temperature	As for temperature	n/a

Parameter	Observation type	Platform	Sensor	Sampling duration	Recommended temporal resolution	Recommended vertical resolution
			echosounder			
	Remote	Satellite observations	n/a	n/a	n/a	n/a
Waves	Fixed	Surface mooring /fixed to structure	Wave buoy	As for temperature	Hourly significant wave height, wave period and wave direction	n/a
	Dynamic	MAS such as Autonomous Surface vehicles (e.g. wave gliders)	n/a	As for temperature	Hourly significant wave height, wave period and wave direction	n/a
	Remote	Satellite observations	n/a	Continuous	Dictated by satellite coverage	n/a

5.1.3 Data management

A central, publicly available resource for managing regional-scale data as well as non-commercially sensitive project specific data could be a key tool. This would allow stakeholders to improve their understanding at both near-field site-specific and far-field scales within shelf seas. These data are currently missing as there are no substantial OWFs (in particular FLOWFs) yet built within deep, stratified water settings. Nevertheless:

- Data may be available for fixed structures in mixed waters such as O&G infrastructures, that could be relevant and useful.
- Some data may soon be available from fixed OWF structures in stratified waters, e.g. from the ECOWind programme, which could then be used to assess the wind farm-wake scale.
- There is a lack of data from FLOW infrastructures, with only a few demonstrator farms currently present. Data from the ECOFLOW programme will be available in the future, with data collection beginning in 2024-2025.
- There is an opportunity to set-up data sharing mechanisms now, in order to be ready for data as they become available.

- Furthermore, to make sure these data are collected and made available before, during and after OWFs are built in seasonally stratified waters, observational/monitoring procedures and stipulation of some specific action regarding data collection or data sharing should be considered at the stages of consenting or even leasing of sites.

Due to the current lack of empirical data available, modelling approaches should be utilised to understand potential water column impacts (see further information in Section 5.2). However, models also rely on the iterative process of predicting change and validating model results, the latter ultimately comes from targeted data acquisition activities. In the absence of direct sampling at FLOWFs, the impact of floating structures, cables etc. could be assessed using 3D models within an EIA. It is recommended that data for model parametrisation (where available) be made available by all parties (e.g. developers, research institutions and government) to improve the confidence in model predictions.

As discussed in Section 5.2 of this report, standard industry-accepted 3D models could be developed, that suitably resolve and model perspective OWFs, for use by developers at the scoping and EIA stages. These models, and model outputs, could be made available to developers for use in scoping studies, enabling them to scope in/out certain processes/impacts with a higher degree of confidence. Such models would most likely be ‘precautionary’, e.g. consider ‘worst case scenarios’ with simplistic parameterizations of OWFs (Figure 5.2). Nonetheless this approach could standardise the scoping stage and make EIAs more efficient. These same precautionary models could be used by developers within EIAs, either as they are, or refined, or used in conjunction with additional observational data and enhanced modelling. The approach recommended above should be taken into consideration for the future definition of guidelines around the implementation of modelling procedures.

The uploading of environmental data collected by industry into a public portal should be considered as a lease condition. Thus, portals like the TCE open data portal could be used to collate and make OWF data publicly available. However, as discussed during the stakeholder engagement workshop, there may be commercially sensitive data. For instance, developers might be interested in wind-wake issues due to the potential impacts on profitability; thus, data on atmospheric variables are well studied by industry but are also commercially sensitive and therefore hard to access. The 'Dutch' model for baseline/pre-consent data gathering may be an effective solution, consisting of the use of public funds to gather baseline information to (i) de-risk investments for industry, (ii) increase bidding for leases, (iii) maintain data ownership in the public domain.

To overcome data sensitivity and ensure support from developers, careful engagement is required with industry; it is recommended that a follow-up to this report includes a workshop on data sharing, including representatives from developers, CES/TCE, research institutions and government.

5.1.4 Data for baseline conditions

Existing data/surveys and new technologies can be used to define baseline parameters, validate models for predicting changes, assess water column change, and design new data collection to improve prediction at future OWFs. These existing data/surveys and new technologies include:

- Developer's metocean/geophysical surveys can provide a spatial picture of 'habitat' types, levels of stratification, areas of high SCM Chl-a.
- Some data from offshore O&G may be relevant as these existing infrastructures sit in deep and stratified water settings - see INSITE programme. Government-led engagement with the O&G industry to identify data sources that can be shared is recommended.
- Any existing long-term moorings could potentially be equipped with additional sensors (fluorescence, O_2, temperature, etc.) which could support these preliminary data: locating them in contrasting sites (with and without OWFs, and potentially at sites which models indicate are at risk of changes, from stratified to not stratified) for longer term data collection. Note that many of the latest ADCP instruments have integrated echo sounders enabling bio-physical studies and can be integrated on autonomous vehicles (i.e. gliders) for wider scale data collection and assessment of impact.
- Industry data from surveys used before selecting a site/construction e.g. lidar, wave buoys, wind speeds, ADCPs (which are left offshore for 1-2 years collecting data).
- CTDs and water samples, which are often part of semi-permanent offshore monitoring stations.

- Sensors could be located on the OWF structures themselves, potentially providing real time data from instruments powered from the structures.

Further information on data, surveys and new technologies are presented in Section 5.3 and a summary in Figure 5.1.

5.1.5 A pragmatic approach looking forward

To ensure that a better understanding of the potential environmental impact is developed in a pragmatic manner (e.g. minimising monitoring effort), measurements need to be fit for the purpose of detecting changes at the right time of year. Substantial observational programmes should be conducted on a few (potentially early) large OWFs, especially at sites which models indicate are at risk of OWF-induced water column changes, in order to gather a strong evidence base to support future development and future (more minimal) monitoring effort. Thus, a Joint Industry Project (JIP) could prove beneficial, sharing costs across stakeholders. Such a project would need to focus on an early deepwater (FL)OWF gathering evidence to help the consenting of subsequent OWFs across the industry. It is also important for government, industry and research institutes to cooperate in data sharing. These efforts should aim to:

- Identify a suitable data portal for sharing data between all parties.
- Use industry baseline data for model validation and direct future sustained monitoring programmes.
- Encourage developers to share their (non-commercially sensitive) data in order to help de-risk future development sites. Data sharing from a health and safety (H&S) perspective could also be explored, e.g. G+ global health and safety organisation (further information available in Global Offshore Wind Health and Safety Organisation (2024).
- Sensitive data from developers could be collected and managed by a non-commercial body, which would ideally make data from environmental acquisitional programmes publicly available after a certain period of time (embargo period).

5.2 Model predictions

Modelling approaches are necessary tools for predicting the interaction between offshore infrastructures and the marine environment, essential to disentangle infrastructure-induced changes from natural variability and climate change. As such, modelling techniques, informed by direct information and data from OWF sites and other locations, are increasingly likely to be key in decision making. As stated in the previous section, models can be used: (i) for the definition of the EOVs and their requirements for spatial and temporal resolution; (ii) for selecting time of the year and location when/where largest OWF-induced changes will be happening; (iii) as early 'screening' for site selection. Model predictions can be used to quantify present and future environmental changes due to OWFs, in the absence of direct information and data from existing sites or complementing existing information with future predictions. Fundamentally, the cumulative impacts due to OWFs or due to other long-term processes such as climate change cannot be assessed a priori without numerical predictions and models can be used to optimise the planning of future OWF sites (e.g. minimising environmental change). However, there remain some fundamental improvements that need investment in research to increase the accuracy of models' predictions:

- Shelf-wide (regional) scale models can be used to effectively assess baseline conditions as well as the natural seasonal, inter-annual and decadal variability of the system, and can be designed to also account for the effects of climate change (Figure 5.2) (Holt et al., 2022, 2018, 2016; De Dominicis et al., 2018; Tinker et al., 2016; Mathis et al., 2018; Schrum et al., 2016; Wakelin et al., 2015; Mathis & Pohlmann, 2014). However, existing models (e.g. NEMO, FVCOM) need to be correctly parametrised and validated, to predict changes due to OWFs.
- Site-specific (OWF project) scale models used by developers, are usually high-resolution, but cover a limited area. In order to correctly parametrise both site-specific (OWF project) scale models and shelf-wide (regional) scale models, site-specific/regional observational data taken in the vicinity of existing OWFs need to be integrated to calibrate models (e.g. atmospheric parameters, drag coefficients, turbulence), and used to validate their prediction (Figure 5.2).

- Model simulations can be used to optimise observational programmes at existing and future OWFs sites. This needs to be an iterative process: (i) data collection can be informed by model predictions, and (ii) the models will be improved/validated by using the data collected in the observational programme. Although models may have a dynamic role (as they are built by feeding in new observations), using them could significantly reduce monitoring requirements. Figure 5.3 shows an example study from PELAgIO at an OWF where models have been used to drive data acquisition.
- There is a lack of theoretical understanding of water flows around a structure in a stratified body of water, which needs to be addressed to improve parameterizations within ocean circulation models. Data from laboratory environments are currently the only data available to understand stratified water flows, e.g. by trialling different densities of water alongside surface winds. Jointly funded projects (across government, industry and academia) could represent a good opportunity to develop lab-scale projects complemented by field measurements and modelling work, as well as favour future cooperation and data acquisition at specific OWFs, when these are developed and become operational.
- It is important to define how often the models would need to be run and updated (e.g. does this need to be done operationally, as a one-off or associated with a planning or statutory reporting cycle). Who would be responsible for running the models, will depend upon the aim(s) of the models/what the models are used for, e.g. developers may run them for licence applications, government could run them for planning purposes, academia may run them for research purposes. Ensemble modelling approaches/model intercomparison should also be considered, where feasible, as it could help reduce the uncertainty associated with modelled parameters such as PEA and change in PEA due to OWFs (Figure 5.3). Ensemble modelling outputs could be used to: (i) target data collection (instead of using just one model) and (ii) compare the OWFs-induced changes obtained from different models to understand models' sensitivity and uncertainties.

5.2.1 A proposed cumulative/combined impact assessment approach

As discussed in sub-section 5.1.3, coarse, regional 3D models could be used to account for the cumulative effect of OWFs in an area, thus providing 'precautionary' model outputs for use during scoping and EIA (Figure 5.2). Such models could be used to predict the magnitude of cumulative and/or combined OWF-related changes pre-construction. An example is the Scottish aquaculture industry, where SEPA performs modelling for screening using an industry accepted model. Another example is the aggregate industry, where collective industry-wide modelling of a region is performed (Regional Impact Assessment, RIA), which assesses cumulative impacts and can be used for individual EIAs for specific developments.

Similarly to the aquaculture and aggregate industries, standard industry-accepted 3D models and model outputs could be developed to define the expected cumulative/combined effects of OWFs in Scottish stratified waters. These outputs can be used to drive the understanding of how the infrastructure cumulatively affects the environment, as well as providing precautionary models to be used by developers for their EIAs.

It is therefore recommended that standard industry-accepted 3D models should be developed to inform scoping and EIA; these models should include cumulative and combined effects due to multiple OWF developments. Creation of model data repositories where developers can access data needed for scoping and EIA would also be beneficial.

Thus, the following are recommended:

- Developing a screening/scoping procedure based on far-field modelling at an early stage of project development.
- Produce 3D far-field hydrodynamic models that take a precautionary approach to representing the mixing effects of OWFs. These models could then be used at project scoping and EIA to assess the level of predicted mixing caused by the infrastructures. There is a need to include both benefits as well as disadvantages related to the presence of OWFs, and the need to consider other effects, e.g. wind deficit due to the presence of the turbines, which may re-balance the infrastructure-induced mixing, reducing the underwater infrastructure effect. Therefore, the parameters used for these 3D models, the selected boundary conditions, and their outputs, should be carefully explained.
- Share 3D far-field model results with developers, which would help with risk-management of developments whilst also providing guidance on pre-construction data acquisition needs.

The precautionary 3D model could be augmented by site-specific modelling performed by developers. Developer modelling could be conducted using models of their choice and be refined by site-specific (OWF project) data, which should be used to demonstrate if their project falls within the coarse model-predicted magnitude of OWF-induced change (precautionary model). Thus, the developers should use precautionary model outputs to scope in/out processes and impacts from EIA, plan pre-construction data acquisition to ensure environmental impacts (both positive and negative) are fully understood and consider refined modelling approaches for EIA.

5.2.2 Modelling approaches

There are several shelf-wide (regional) scale models (including both physics and biogeochemical models) which could be used to inform an initial impact assessment in early planning, site selection and pre-construction. As mentioned in the previous sub-section, this approach could help developers to de-risk future developments at an early stage through an initial screening of a site. Developers could then perform their 3D models (potentially using refined versions of the 3D models) using their data, thus improving the impact assessment. However, this would be at the discretion of the developer.

Although not a straightforward task, it is important to define impact modelling guidelines and a threshold of change to be used; the latter, should be defined and agreed before using these models and tested within the impact assessment. Definition of those thresholds, as well as the definition of modelling guidelines, will require further work beyond the scope of this report and is recommended as a follow-on project/workshop.

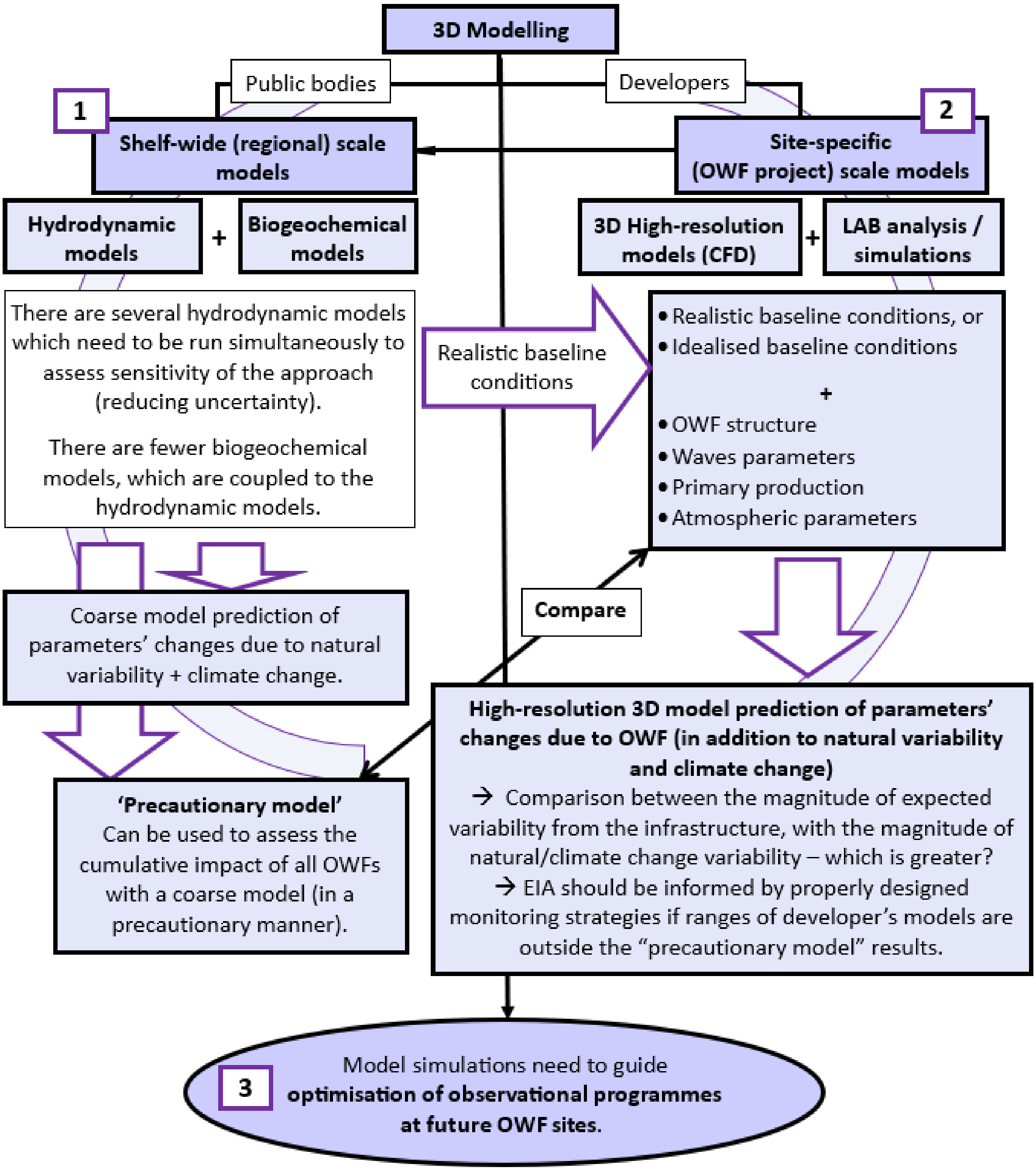


Figure 5.2. Workflow for numerical modelling approaches to the prediction of regional (shelf-wide) scale baseline conditions and their natural variability (and climate change), and to the prediction of site-specific (OWF project) scale changes due to the infrastructure. Ideally, standard industry-recognised, low-resolution precautionary 3D models should provide initial impact assessment; the developer could then prove/disprove those regional model results using higher-resolution models based on physical parameters from their development site. Models' results should ultimately guide observational programmes (see Figure 5.3).

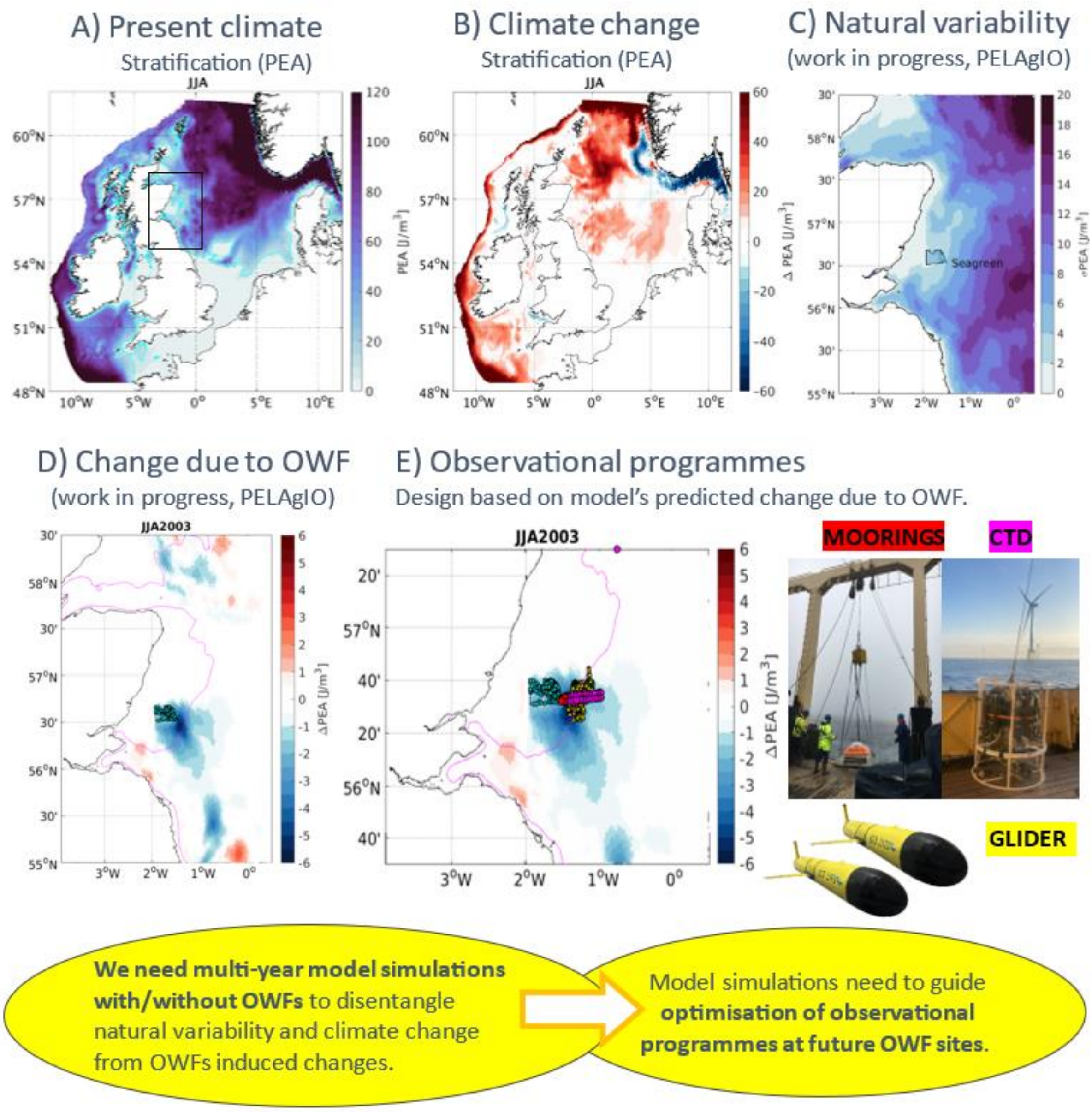


Figure 5.3. Example study using models to assess the present climate (A), the effects of climate change (B), the natural variability at a geographical location (C) and the changes due to OWF infrastructures (D). Results can drive the minimum requirements for an integrated observational programme acquiring data relevant to detect the OWF impacts and their footprint - e.g., CTD, moorings and gliders data (E). Multi-year model simulations are needed to disentangle natural (and climate change) from OWF-induced variability, thus optimising model's results (source: PELAgIO project).

5.3 Observational/monitoring programmes

Due to the absence, at present, of extensive OWF (especially FLOW) in Scottish seasonally stratified waters, data mining is essential to inform impact assessments using model predictions and to guide future observational programmes. Therefore, we should aim to utilise as much of the existing data as possible from, for example, managed repositories storing data from regional scale acquisitional programmes as well as data from developers before further data collection is undertaken. Developers' data should include data from the O&G industry, as they have been operating for decades with structures in stratified water settings.

New data collection should be informed by impact assessments (models) and performed pragmatically so that acquisition is done at the minimum required specification allowing cost-effective collection of the necessary data while fulfilling our understanding of the potential impact(s). This report provides recommendations for the minimum data collection to inform data collection programmes.

5.3.1 Existing data for initial impact assessments

Existing data sampling EOVs which are considered fundamental for the definition of water column baseline conditions as well as for enabling the detection of any possible environmental change (as discussed in Section 5.1), should be used to answer the following questions:

- What do we want to measure/observe?
- Define the main parameters needed to be able to parametrise models and detect any OWF-induced variation in the water column. For this it is important to:
    - Define the strength of stratification.
    - Define the threshold to alter the stratification (based on existing OWFs and model's predictions).
    - Measure through onset and breakdown of stratification and use models to confirm when this happens.

To define the above parameters, and to support the initial impact assessment, which should then drive the programme's design, it is therefore recommended that the following should be done at a strategic level:

- Collate existing data including data from OW and O&G, as well as data acquired for different purposes and accessible from public repositories e.g., environmental assessment, fisheries, etc. into a single managed data repository, located in an official and recognised webpage, e.g. The Crown Estate Scotland.
- Use the data above to define baseline conditions and to assess natural variability (Section 5.1).
- Use numerical modelling to identify where additional data are necessary to detect OWF effects, providing guidance on who will need to collect those data and how (Section 5.2).
- Encourage developers to share their data highlighting the advantages of data sharing (e.g., early-stage de-risking of developments and improving health and safety).
- As discussed in sub-section 5.1.3, provide coarse, industry-recognised models that can be used to simulate the cumulative impacts of OWFs. Results from these models should provide a 'precautionary model' that developers could then compare against refined fine-scale models based on OWF project parameters including e.g. loads from currents and waves based on drag coefficients, wind deficit, foundation types, parameters to simulate atmospheric wake, etc. (Figure 5.2).

Research/academic institutions should also contribute to data gathering, sharing cooperative efforts through e.g. Marine Data Exchange (see ECOWind programme). To aid this the following could be undertaken:

- Co-development of best practice guidelines with experts from government, academia, and industry, to help researchers and OWF developers collaborate effectively when access to OWF sites is requested for research purposes.
- Ensure evidence from research is applicable to integrate or update guidance for environmental impact mitigation and supports strategic observational programmes and decision-making.
- Propose multidisciplinary approaches (e.g. combining remote satellite sensing, fixed sensors acquisition, improvements to existing site surveys) that can foster innovation, improve industry performance, and pave the way for efficiently meeting national climate targets.

- Adherence to these best practices enabling the establishment of effective communication channels, mutual understanding, and safety considerations for accessing OWF sites for research.

The aim is to ultimately encourage the development of a collaborative offshore environmental observational network (Figure 5.4).

5.3.2 Future programmes

When it comes to future observational programmes in areas with/without OWF, their location and spatial-temporal resolution should be data and models' results-driven (Figure 5.3; Figure 5.4). Furthermore, to enable timely and cost-effective acquisition while ensuring fundamental parameters are collected, it is recommended to integrate various approaches. Three types of observational strategies can be used:

i. **Fixed** (long-term) measurements.
ii. **Dynamic** (MAS/ship-based) measurements.
iii. **Remote** (satellite) observations.

It is important to keep existing, **fixed** (long-term) measurements (e.g. moorings, buoys) at selected locations without OWFs, as well as placing them at future OWF development sites. These measurements can provide information about the natural variability of the system, as well as helping to estimate the magnitude of the OWF-induced variability (in terms of contribution to the natural/climate change driven variability). Fixed upstream and downstream monitoring points can be used at development sites included as part of the development process. Multiple fixed locations should also be used to collect atmospheric data. It is also important to select measurement locations that are informed by model outputs, and by where there are uncertainties within and between models (i.e. identify sites at which large-scale deployments are expected to change stratification away from the baseline). Monitoring of base ecology data (e.g. CTD/O_2/visual/eDNA) would also be of value (Figure 5.4).

However, in order to optimise fixed sensor's acquisition at future infrastructures such as floating platforms, sensors could potentially be integrated into the structure themselves at a design stage (e.g. the integration of sensors into foundations). The selection of the sensors and/or provisions for maintainable data collection would need to be considered to ensure these approaches are economically and technically practical.

Dynamic measurements at locations where OWF impacts are predicted (as identified by models) are also needed. Dynamic measurements can include the combined use of ships and MAS to observe seasonal cycles like stratification (getting locations from model results), build upon existing monitoring programmes and use of existing infrastructure or maintenance operations – e.g. utilising an asset inspection ROV to collect other data, collection of aerial data, the expanded use of technology like gliders/USVs augmented by more targeted and precisely piloted MAS deployments (e.g. Autosub Long Range, ALR) (Figure 5.4). Ship-based surveys should also be considered, as they can be convenient (especially when utilising already planned observational programmes) for assessing the extent of stratification, a key variable for the type of assessments discussed within the remit of this programme. The extent of stratification can be estimated from MLD which can be measured using echo sounders exploiting, for example, boats performing regular work to and from the OWFs.

Remote observations (satellite data) are also key, and they represent a low-cost option for monitoring parameters such as sea-surface temperature (SST), Chl-a concentrations and wind speed (Figure 5.4).

Recommendations for parameter acquisition at future observational programmes, and the fixed, dynamic and remote strategies in which those parameters should be collected, are presented in Table 5.1 and Table 5.2.

Future observation/monitoring efforts should focus on obtaining measurements at the right time and location, by adhering to the following key principles when programmes are designed:

- Focus on the transition between mixed and stratified water columns e.g. spring/autumn, as well as throughout the stratified period (summer).
- Monitor the transition zones where there is marginal water column stability or intermittent stratification (e.g. changes through spring-neap cycle) and use this to parameterise and validate models.

- It would be preferrable to have multi-year data, thus the need to access sustained data collection which is publicly available on top of new data acquisitions. However, some locations may need longer duration and sparse data collections; other locations may instead need shorter duration and more detailed data. Programme design and data requirements should be informed by models.
- Prioritise sustained observations from fixed platforms at/near early OWFs in stratified waters.
- Consider the addition of e.g. CTD sensors to other planned, or existing, moorings used for marine mammal/passive acoustic detection and eDNA, providing valuable ecological data that can complement the enhanced understanding of stratification.
- Ensure monitoring plans look beyond the project level and consider strategic sustained observations and methods to fund these e.g. governments and/or industry funded “sentinel” monitoring stations collecting long time series data. Lease funds could be used for this purpose, and they could provide valuable data to validate and parametrise models.
- Ensure future programmes link to existing sustained observation programmes (both national and international). It would be useful to consider whether these existing programmes could be altered slightly to gain data that is valuable for OWF EIA/SEA.
- Ensure consideration of the latest technologies for ongoing data collection. If instruments are to be added to OWF infrastructure, then developers and manufacturers should engage early to ensure this is included at engineering design.

Observational programmes should provide data that follow accepted international standards (FAIR). Data sharing (now and future) is fundamental, and a project to collate industry data could be a useful starting point for this.

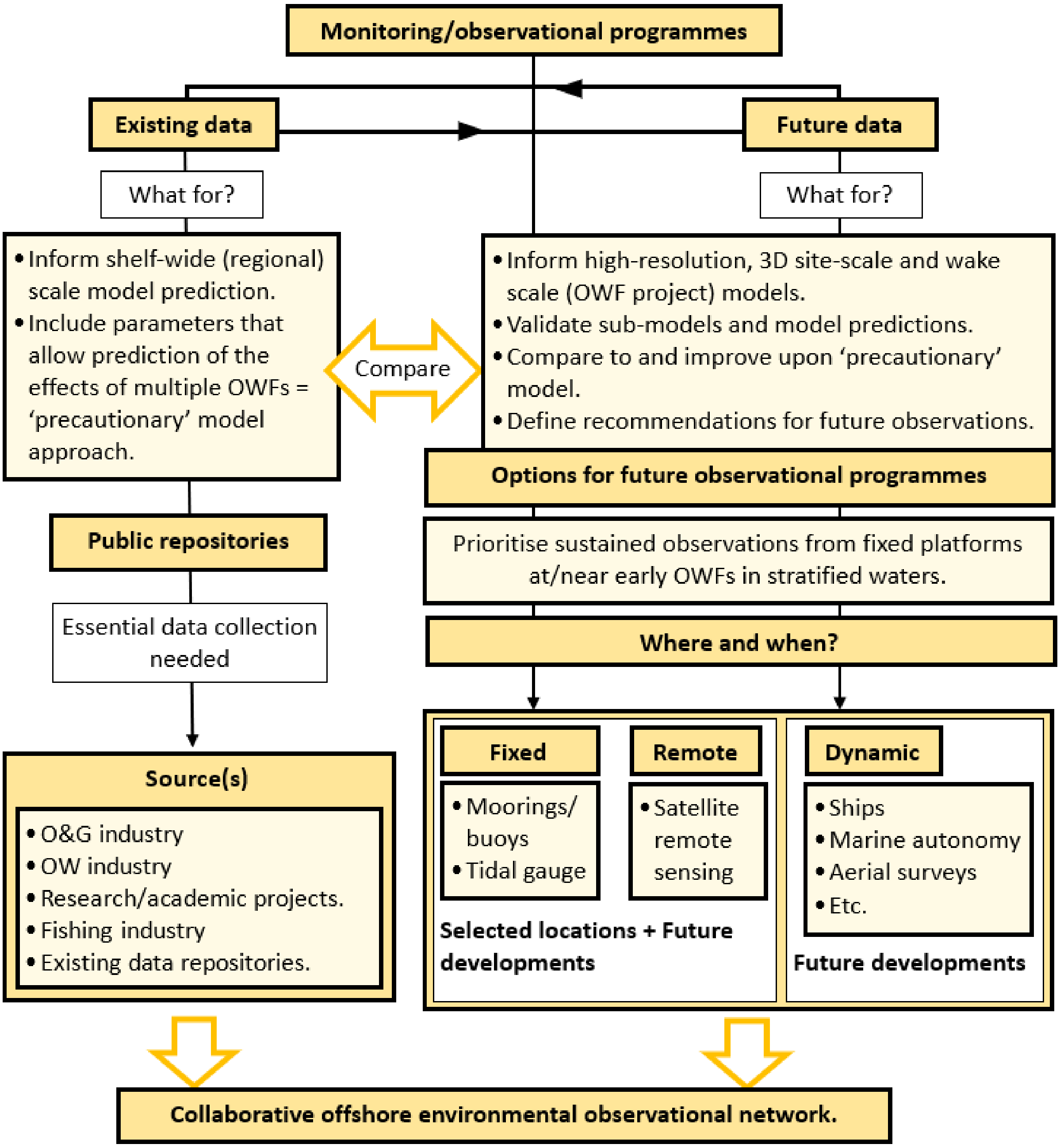


Figure 5.4. Diagram showing the 'best-practice' approach to sustained observation programmes. Left) It is priority to take advantage of existing data, therefore data collection and storage in recognised repositories is key. Right) Developers should use their data to inform future observational programmes that, depending on the expected type and magnitude of change, should be designed integrating three data collection approaches: fixed, dynamic and remote data collections.

5.4 Summary of recommendations

Table 5.3 summarises some key recommendations from this literature review and stakeholder engagement process, providing an indicative assessment of ‘cost’, ‘delivery difficultly’, ‘lead time’ and ‘impact’ resulting from undertaking the work/task. Each category has been qualitatively scored ‘low’, ‘medium’, and ‘high’ based on the multistakeholder feedback from the workshop and review within the Scottish Government Offshore Wind Directorate. The objective of this table is to allow easy review of recommendations to inform decisions on which to take forwards, depending on the time and resources available. For example, defining key parameters for data collection has a low cost, low difficulty and short lead time with a good impact versus a development of a regional monitoring programme which is considered to have a high impact potential, but is more challenging to deliver in the near term. Lastly, it should be considered that many of these recommendations will have inter-dependencies or mutual benefits: using the previous example, defining key water parameters to measure feeds into requirements for site and regional modelling.

The categories and qualitative scores are broadly defined as:

- Cost – direct cost of undertaking an action. A high-level assessment has placed each in the following bands: low <£100,000, medium £100,000 – £250,000, high >£250,000.
- Difficulty – qualitative assessment of the challenges associated with each recommendation. This has considered technical difficulties and/or other challenges such as stakeholder engagement. For example, multistakeholder negotiations around legal agreements have been considered of high difficulty, whereas defining parameters for measurement (based on published sources) has been considered low difficulty.
- Lead Time –the following broad scales have been used for the purposes of assigning a qualitative score: low <6 months, medium 6-24 months, high >24 months.
- Impact – refers to the predicted influence/relevance expected from undertaking the recommended task. This impact has been assessed on a case-by-case basis using the workshop output, author’s expertise, and discussion with Scottish Government Officials.

Figure 5.5 illustrates the summary information from Table 5.3, highlighting the relative qualitive scores as per the description above.

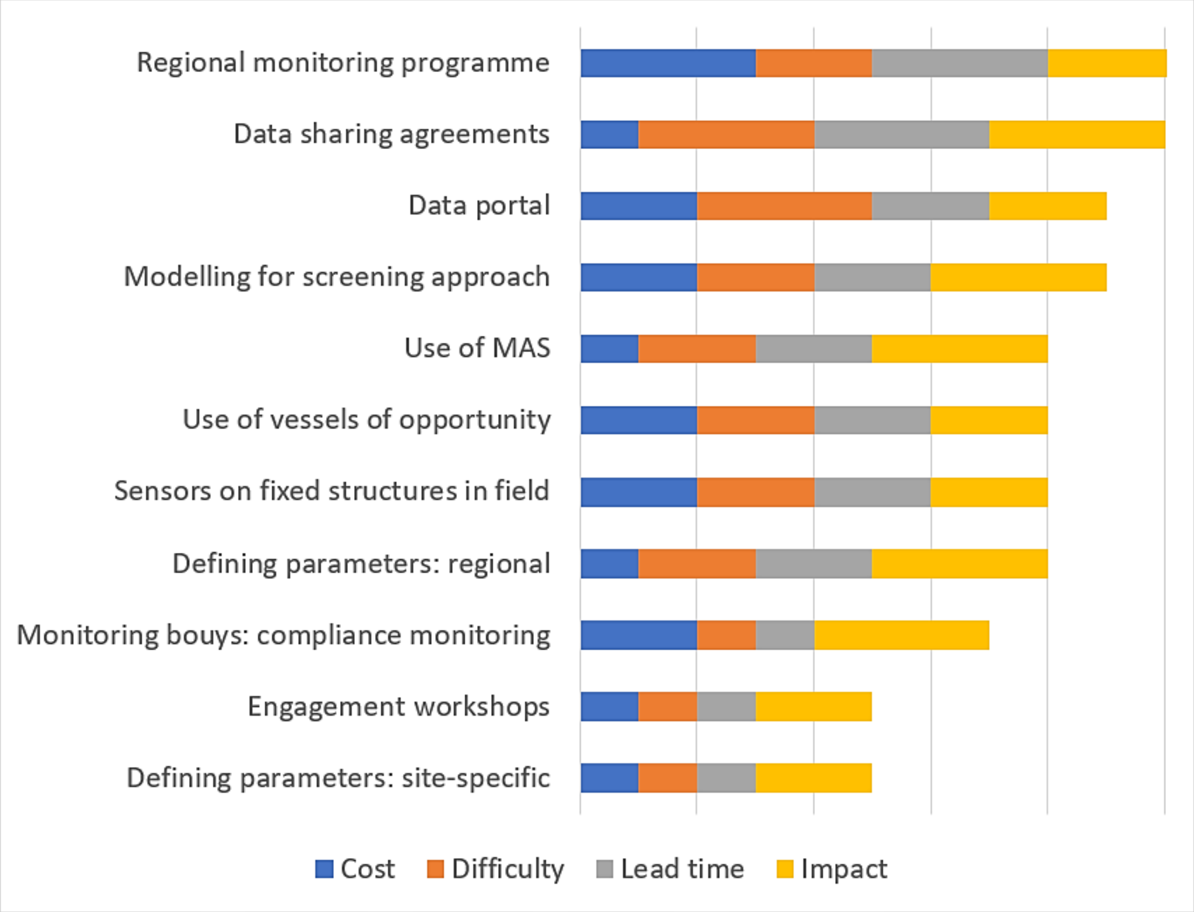
Table 5.3. Summary of recommendations. In columns 'Cost', 'Difficulty', 'Lead time' and 'Impact', a qualitative assessment is provided with a traffic light system and with a score: L = Low; M = Medium and H = High. Note that 'cost', 'difficulty' and 'lead time' are colour coded so that Low = green, Medium = yellow, and High = red. 'Impact' is colour coded so that Low (impact) = red, Medium (impact) = yellow, and High (impact) = green.

Item	Recommendation	Cost	Difficulty	Lead time	Impact	Commentary
1	**Defining minimum water parameters for data collection at site scale**	L	L	L	M	Set of recommended minimum water parameters for collection in field programmes that are suitable for impact assessments and validating models and ensuring standardisation of data used within impact assessments. This has minimal risk, cost and lead time but an instant impact on data provision and quality. Parameters may be expanded upon on a case-by-case basis, and recommendations keep under review (for example in periodic workshops) as the subject literature expands in line with increased deeper water renewable infrastructure. A set of recommended parameters is provided in Table 5.2.
2	**Continuing government/ industry engagement through workshops**	L	L	L	M	Following good engagement across stakeholders during production of this report, it is proposed that the structure of workshops continue, with future key themes suggested as: • Model selection (for far field, as per item 8 in this table), • Data sharing and access (e.g. portals), • Modelling and assessment guidelines for EIA, • Data formats. These workshops have impact with their outputs but will also serve to maintain momentum and continual assessment of the other proposals contained within these recommendations and further industry concerns.
3	**Installation of monitoring buoys at sites**	M	L	L	H	It is recommended that developers include water parameter monitoring buoys as part of site monitoring plans, located as a minimum up- and down-tidal stream of the OWF and collecting the minimum parameters as defined. Ideally these will be located based on modelled data (links to item 8). If included during other site field operations, costs can be kept to a minimum whilst the technical continuity with other requirements provides a low difficulty rating (although it is acknowledged this could be site-specific). This recommendation may not be for all developers to implement, but rather a plan-level task to determine a set of sites to be tested for this, collecting strategical data at potentially shared costs (see also item 11 in this table).
4	**Defining minimum water parameters for data collection at regional scale**	L	M	M	H	Government stakeholders to propose a set of recommended minimum water parameters for collection in field programmes that are suitable for inclusion into regional/far-field models, ensuring standardisation of data being used in impact assessments. Parameters recommended to be kept under review (for example in workshops) as the subject literature expands. A set of recommended parameters is provided in Table 5.1.
5	**Sensors on fixed**	M	M	M	M	Developers should consider installation of sensors on fixed

Item	Recommendation	Cost	Difficulty	Lead time	Impact	Commentary
	structures					structures as part of their impact mitigation for ongoing monitoring post construction. This could include wind turbine foundations, substations and other OWF infrastructure, with instrumentation providing the minimum parameters as defined. If included during other operations, costs can be kept to a minimum whilst the technical continuity with other requirements provides a low difficult rating. Timescales likely dependant on other site operations, and engagement with regulators and engineering design throughout will be vital.
6	**Use of vessels of opportunity for increased data collection at sites**	M	M	M	M	Developers should consider the use of vessels of opportunity, for example crew transfer vessels (CTVs) or vessels for monitoring operations, for collection of water parameters as defined in this report. Although this approach may be convenient in terms of costs, careful planning, discussion and agreement are required at a very early stage in the process, before vessels are hired, etc. Also, there will need to be clear Standard Operating Procedures (SOPs) developed for data collection to ensure appropriate procedure/data standards are kept. All these challenges increase the technical difficulty of this task. Furthermore, data acquisition will depend upon planned vessel mobilisations, therefore continuity/repeatability and necessary intervals for the data series could not be ensured. Alternatively, the use of MAS should be contemplated (see item 7).
7	**Use of Marine Autonomous Systems**	L	M	M	H	Marine Autonomous Systems (MAS) could be used for both regional and site-specific parameter acquisition programmes. Autonomy represents a low-carbon footprint alternative to vessel surveys. Although the cost of the technology can still be relatively high (especially if compared with vessels of opportunity - item 6 of this table, or to current mooring systems) there is cost-effectiveness in running a programme using MAS rather than utilising dedicated monitoring vessels (which have high costs for mobilisation, crew, downtime, etc.). Acquisition difficulty and lead time are valued here as medium, as they would depend on a number of factors, including site-specific settings, length of the programme, parameters acquired etc. However, the low-carbon footprint, the system's operability in various settings, and the flexibility of the system requiring little maintenance cost and human control element, makes it a high impact option. MAS would be able to facilitate safe data acquisition and ensure high resolution coverage, especially when used in combination with traditional methods (e.g., remote sensing, vessels, in-situ sampling, etc) to maximise results, costs and impact.
8	**Use of standard models to inform OWF scoping and EIA**	M	M	M	H	Standard industry-accepted 3D models could be developed, that suitably resolve and model perspective OWFs, for use by developers at the scoping and EIA stages. At project scoping, these model outputs could help scope in/out potential impacts from EIA. The developer may refine this with their own modelling from site-specific data collection or accept any associated risk of not validating with field data. The models could also be used by developers for EIA, as well as being augmented by more detailed modelling and data collection.

Item	Recommendation	Cost	Difficulty	Lead time	Impact	Commentary
		🟧	🟧	🟧	🟩	The models would be suitable for cumulative impact assessments, either strategically by government and/or by developers. This activity could have a high impact through standardising the scoping and EIA process as well as providing tools for cumulative impact assessment (potentially for sectoral marine planning). Who should undertake this modelling and how the models can gain industry acceptance needs to be considered. This activity therefore has a reasonably high level of technical difficulty, as well as cost and lead time associated with it.
9	**Data portal**	M	H	M	M	Further development is needed on what data portal should be used, how to use it, what to store in it, and where data will be collected from. Data storage needs to be accessible, transparent and searchable. Thus, a number of agreements need to be reached over the use, management and rules around existing data portal or bespoke portal for environmental assessment data. All of the above are existing complications, with further difficulties which are likely to arise through a need to agree data formats, and historic data formats not being consistent. For these reasons, although this task may have a medium impact (which is difficult to judge without being clear what data may be available), the level of difficulty for the task is quite high.
10	**Data sharing agreements**	L	H	H	H	Data sharing is considered a key requirement, and thus has a high impact rating. Agreement is recommended for sharing of non-commercially sensitive data, through an agreed portal, which can be accessed by any stakeholder. Industry data should be made available as required to allow improved assessment of the interaction between the physical water column and the impact at higher trophic levels. There are limited direct costs for this, however there is likely considerable legal complexity to address around the data, adding to a longer delivery time. Impact is considered likely to be high with potential for large amounts more site-specific data available to modelling programmes. Note that this may be simplified if item 9 is implemented.
11	**Regional monitoring programme**	H	M	H	H	Provision of a monitoring programme outside of site-specific data collection, providing regular data on regional scale for input into wider regional scale models. This recommendation has been given a high impact rating. Such a project would present operational and administrative challenges generating a high score for cost and lead time. A medium score for difficultly reflects that technologies are available that would be suitable, but these are probably not deployed at scale in such a routine at present. A joint data collection programme at a regional scale with the O&G industry should be considered.

Figure 5.5. Illustration of recommendations alongside qualitative cost, difficulty, time and impact assessment.



5.4.1 Primary recommendations for implementation of Offshore Wind sustained observation programme(s) for physical processes

Based on the discussions in Sections 5.1 to 5.3 and the summary in Table 5.3 above, the following recommendations are proposed as key for implementation of an Offshore Wind sustained observation programme(s) for physical processes:

- Water column parameters that should be measured for impact assessments to be well defined, and guidance produced (Item 1 from Table 5.3). Suggested parameters, durations, sensors and resolutions are listed in Table 5.1 and Table 5.2.
- Fixed monitoring stations should be established at/near OWFs which will be built in stratified waters. Ideally, these stations should be set up before construction of the OWFs and their placement informed by model outputs predicting the most likely location for impacts. Ideally this could form part of the consenting process (Items 3 and 5 from Table 5.3).
- Standard industry-accepted, far-field, precautionary 3D hydrodynamic models should be developed to (i) scope in/out potential water column impacts from EIAs, (ii) support EIAs, and (iii) enable cumulative water column impact assessments. Developers should then be able to propose the use of refined models to compare evidence provided by the standard precautionary models as part of the consenting process (Item 8 from Table 5.3):
    - Initial results from models should be used to guide/inform future observational/monitoring programmes, to optimise model validation and improve forecast, providing a more reliable parameterization of OWFs in models.
    - Models should also guide the selection of EOVs, the spatial-temporal scale at which those should be monitored and should be used to define their error margins.
- To facilitate a screening approach, a regional monitoring programme should be considered (Item 11 from Table 5.3). As per item 4 from Table 5.3, this regional monitoring should include:
    - Collection of the recommended minimum parameters, durations, sensors and resolutions as listed in Table 5.1 and Table 5.2.
    - Detection of inter-annual/decadal variability.

- Sharing of data between stakeholders. Sharing of data is considered key to allow accurate assessment of the interaction between the physical water column and the impact at higher trophic levels (Items 9 and 10 from Table 5.3). Regulatory bodies are recommended to engage with industry to:
    - Identify which datasets from industry are needed and why, e.g. specifications about individual operational turbines, specifications about certain turbine-types and/or foundation structure details. This information may be necessary to build and/or parameterise models.
    - Agree data access – this may be via an existing or new data portal (Item 10 from Table 5.3) and may be addressed through a workshop programme similar to this project (Item 2 from Table 5.3)
- Existing modelling techniques should be compared to assess the margin of uncertainty in modelling OWFs due to differences in model setups and parameterizations and to decide what models to use (and to make those models industry-recognised models). This should take the form of a programme reviewing options and opportunities and workshop suggestions with a diversity of stakeholders.

5.4.2 Secondary recommendations to support implementation of Offshore Wind sustained observation programme(s)

A suite of additional recommended approaches to support implementation of sustained observation programme(s) are listed below:

- Any projects where data are to be used in models should utilise an iterative approach of observation-model-observation-model.
- When designing post-construction monitoring programmes, cost-effective and low-carbon solutions should include integration of a diversity of approaches including remote satellite sensing, use of autonomous vehicles (MAS), existing vessel-based surveys and fixed-point observations (e.g., moorings). These should also consider methods of data collection not currently used as standard such as:
    - Sensors on fixed structure in the field (Item 5 from Table 5.3).
    - Use of vessels of opportunity (e.g. crew transfer vessel/maintenance vessels) for data collection at sites (Item 6 from Table 5.3).
    - Use of MAS as a low-carbon solution helping to optimise data collection continuity and coverage (Item 7 from Table 5.3).
- Continual engagement with stakeholders including industry, government and academia is vital as OW infrastructure increases in stratified water and resultant observation programmes develop. Regular discussion should be held by relevant experts and stakeholders to identify key needs and further development in observational and monitoring strategies (e.g., organising workshops) (Item 2 from Table 5.3).
- Public bodies should coordinate data collation and collection from various sources/stakeholders, including developers’ data.
- Joint Industry Projects (JIP) should be encouraged, e.g. to provide evidence from early deep water OWFs/FLOWFs to support a sustainable development of the industry or fund laboratory studies.
- To reduce the cost burdens on developers and/or public bodies from additional data collection and modelling, alternative funding approaches should be reviewed: this could be a JIP complementing publicly funded activities focusing on other spatial data gathering methods (e.g. MAS or ship-based surveys).

- The O&G industry should be engaged, to explore if they have data for offshore assets in stratified waters that may be shared.

6 Conclusions

This project aimed to provide recommendations for designing a programme focusing on sustained observations of physical and biogeochemical water column processes, to improve the evidence base and support the sustainable development of the OW industry within, but not limited to, the Scottish sector of the North Sea.

Based on a review of the current state of knowledge about the North Sea water column structure, previous and ongoing observational programmes and current efforts in understanding the interaction between fast-growing large-scale infrastructures and the ocean environment, this report provides a series of recommendations. These have been broken down into:

i. A set of recommendations for the fundamental EOVs to be collected at future observational/monitoring programmes at shelf-wide (regional) and site-specific (OWF project) scales, alongside recommendations around data collation and sharing.
ii. Recommendations on the use of existing modelling approaches and on their implementation to allow prediction of cumulative OWF-induced environmental impact(s).
iii. Recommendations for future observational/monitoring efforts and collaborative approaches.

Regarding points (i) and (ii), this report outlines that:

- Fundamental EOVs at a shelf-wide (regional) scale should include water column variables such as temperature, salinity, Chl-a, dissolved oxygen concentrations and growth-limiting nutrients. Atmospheric and metocean parameters including near surface atmospheric temperature, near surface wind velocity and waves should also be acquired, where possible.
- Fundamental EOVs at a site-specific (OWF project) scale should include water column variables such as temperature, salinity, Chl-a and dissolved oxygen concentrations, current speeds, suspended particulate matter and mixed layer depth. Furthermore, atmospheric and metocean parameters including near surface atmospheric temperature, near surface wind velocity and waves are also necessary.

- Existing data (including data from OW, O&G, EIAs, fisheries, etc.) should be collated, made publicly available and used to validate 3D models.
- 3D models should be used to understand the water column baseline conditions (in absence of OWFs), predicting the effects of natural variability and climate change. However, efforts should be made to improve existing model's parametrisation to allow assessment of OWF-induced changes. Thus, existing and new data from observational/monitoring programmes should be used in conjunction with models to predict impact, but also to validate and refine models' predictions.
- 3D far-field hydrodynamic models that take a precautionary approach to representing the mixing effects of OWFs could then be used at project scoping and EIA to assess the level of predicted mixing caused by the infrastructures.
- 3D far-field model results should be shared with developers, which would help with risk-management of developments whilst also providing guidance on pre-construction data acquisition needs. The precautionary 3D model could be then augmented by site-specific modelling performed by developers.

Regarding point (iii), this report outlines that future observational/monitoring efforts should:

- Integrate existing and innovative approaches to achieve a cost-effective and pragmatic acquisition of the EOVs specified above, including a combination of fixed, dynamic and/or remote platforms and sensors. Recommendation for sampling duration and temporal and spatial resolutions have also been provided in this report, where possible.
- Focus on getting measurements at the right time and location, by adhering to the following key principles when programmes are designed (focus on the period of stratification, spring/summer, monitor the transition zones where there is marginal water column stability or intermittent stratification and use this to parameterise and validate models).
- Prioritise sustained observations from fixed platforms at/near early OWFs in stratified waters.
- Consider the addition of CTD sensors to other planned, or existing, moorings (e.g. on marine mammal/passive acoustic detection moorings and eDNA samplings) in order to add value to moorings by opportunistic monitoring of physical water column.

- Ensure monitoring plans look beyond the project level and consider strategic sustained observations and methods to fund these e.g. governments and/or industry funded 'sentinel' monitoring stations collecting long time series data. Lease funds could be used for this purpose, and they could provide valuable data to validate and parametrise models.
- Ensure a link to existing sustained observation programmes (both national and international).
- Undertake workshops and JIPs aiming to address issues around model selection, data sharing and accessibility (data portals), data standard and formats (FAIR), definition of observational and modelling guidelines.
- Consider the latest technologies (e.g. MAS) for ongoing data collection. If instruments are to be added to OWF infrastructure, then developers and manufacturers should engage early to ensure this is included at engineering design.

Our recommendations stem from both the workshop discussions and the reviews of the current state of the field contained within this report. There was consensus from all participants in the review that measuring water parameters in relation to the potential for change in the stratification regime as renewable infrastructure develops in deeper waters is an important topic. All stakeholders agreed that the field is currently data deficient, and that monitoring is important, particularly to further understand field effects over time in the context of wider impacts such as climate change. There was general agreement that modelling has a key role to play, and that models should be iterative, undergoing continual refinement as data is collected over larger areas and timescales.

As the development of deeper water renewable infrastructure is still nascent, likewise the monitoring requirements will be expected to develop as the data available increases. Thus, there is a strong need for the definition of observational and impact modelling guidelines to be implemented pre-, during and post-development phases. Based on all the above, recommendations within this report should be continually reviewed and updated, using the state of art in procedures, as the industry expands.

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Summary of appendices

This section of the report includes supporting material for the main text:

- **Appendix A** - Supporting information Chapter 1.
- **Appendix B** - Supporting information Chapter 2.
- **Appendix C** - Supporting information Chapter 3.

APPENDIX A. SUPPORTING MATERIAL (CHAPTER 1)

i. Overview of the offshore wind development landscape in the North Sea

The UK offshore wind (OW) development landscape can be summarised in terms of key policies and steps of implementation (Figure A. 1). Important dates within this development landscapes and related events are also presented in Table A. 1.

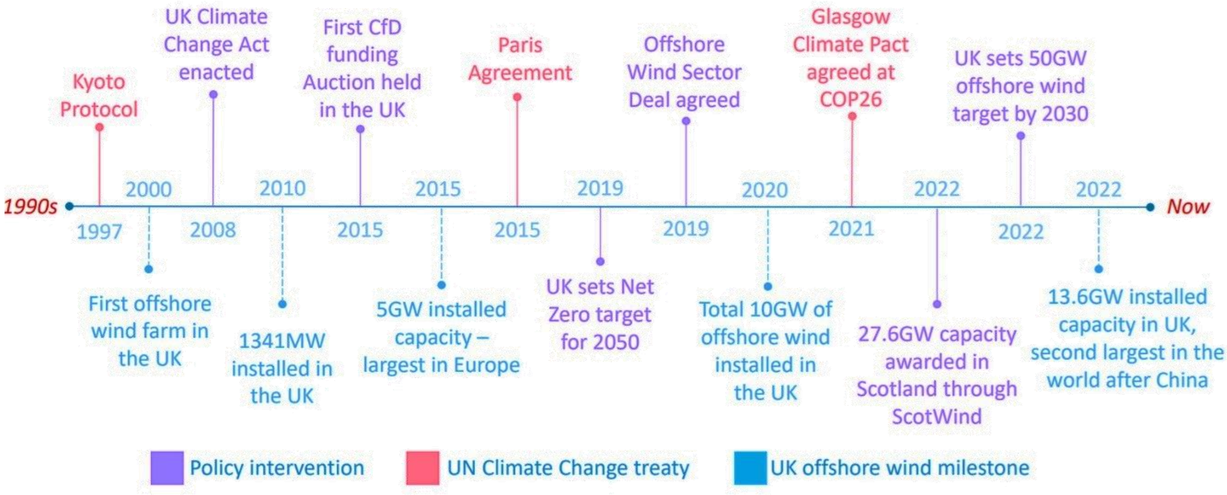


Figure A. 1. UK OW policy timeline (from Tait et al., 2023, and references therein).

Until 2017, Scottish offshore sites were leased by The Crown Estate (Rounds 1, 2 and 3), at the time a UK-wide body. The management of OW rights were devolved by the UK Government to Scotland in 2017 (Scotland Act 2016 and a secondary legislation approved in 2017) with the creation of the Crown Estate Scotland (CES) and the ensuing round of OW leasing in Scottish waters (ScotWind).

The Scottish Government, as planning authority for Scottish waters, developed the Sectoral Marine Plan (SMP) for OW energy to inform the spatial development of ScotWind (Scottish Government, 2020). This plan, adopted in October 2020, identified sustainable options for future commercial scale OW developments. The plan is currently undergoing a review, as part of the Iterative Plan Review (IPR) process, to ensure the plan remains reflective of current scientific understanding and knowledge, as well as the wider regulatory and policy context.

Table A. 1. Offshore wind development landscape in the UK – a timeline of key events.

Year	Event
2000	• UK's first demonstration OWF (Blyth OWF) installed off the Northumberland coast, North Sea (Figure A. 1). • The project consisted in two 2 MW Vestas turbines with rotor diameters of 66 m. • The first applications (Round 1) for seabed leases were presented to The Crown Estate (TCE).
2003	• UK's first commercial OWF (North Hoyle) was installed off the North Wales coast. • Other Round 1 projects brought the total Round 1 capacity to 1.2 GW. Five projects were withdrawn based on environmental grounds. • The results of Round 2 of seabed leasing were announced, with 15 projects awarded a total of 7.2 GW capacity.
2007	• Burbo Bank, off Liverpool, was the first UK OWF where 107 m rotor diameter turbines were installed. • The first two 5 MW turbines with a rotor diameter of 126 m were installed in the Moray Firth, Scotland, on the first jacket foundations installed in the OW, globally. • The Government announced a Strategic Environmental Assessment (SEA) as an early step to Round 3 of seabed leasing by TCE.
2008	• The Climate Change Act (2008) was enacted aiming to enable the UK to become a low-carbon economy and giving ministers powers to introduce the measures necessary to achieve a range of greenhouse gas reduction targets (Figure A. 1). • Round 3 seabed leasing was launched by TCE, becoming the largest OW development project taken forward in the world offering nine large zones with a capacity of around 30 GW.
2009	• The first 100 MW project started operation off the Lincolnshire coast, when the twin projects Lynn and Inner Dowsing were commissioned, consisting of fifty-four 3.6 MW Siemens turbines, totalling 194 MW. • UK installations pushed the UK past Denmark to take over as the global lead for OW installed capacity.
2010	• Thanet (southern North Sea) became the world's largest OW project and the first to have 100 turbines in 2010. It consists of 100 x 3 MW Vestas turbines. • The winners of the CE's Round 3 leasing competition were announced, the largest with capacity up to 10 GW.

2012	• UK's first 500 MW project (Greater Gabbard) started operation. It consisted of 140 x 3.6 MW Siemens turbines and became the world's largest OWF. • TCE published its flagship industry report on the potential for cost of energy reduction in offshore wind to 2020. Coupled with the output the Offshore Wind Cost Reduction Task Force, this set the direction of Government-industry collaboration in offshore wind for the next six years.
2013	• The first 7 MW turbine was constructed offshore in the Firth of Forth, Scotland. The prototype turbine, developed by Samsung, has a rotor diameter 171 m. • The first 6 MW direct-drive (gearless) Siemens OWTs were installed at Gunfleet Sands in the Thames Estuary. London Array, at 630 MW, took over as the world's largest OWF, consisting of 175 x 3.6 MW Siemens turbines. • The Government announced an intermediate step to a new auction market mechanism for OW, Contracts for Difference (CfD) as part of Electricity Market Reform. This step, known as Final Investment Decision (FID) Enabling for Renewables, led eventually to a range of OW projects obtaining strike prices of £140 to £155/MWh for projects delivered up to 2019. The first UK CfD auction announced in 2015 (Figure A. 1).
2017	• Seven years after obtaining an agreement for lease, the first OWF from the UK leasing Round 3 started operation (although it was not fully commissioned until 2018). Rampion, in the English Channel, consists of 130 x 3.45 MW turbines from MHI Vestas OW. • The world's first commercial FLOWF Hywind Scotland started operation. The 5 x 6 MW Siemens turbines were installed on spar-buoy foundations in water about 100 m deep off Peterhead in Grampian, Scotland. • The second CfD auction results for UK offshore wind were announced, with strike prices of £57 to £75/MWh (2012 prices) for projects to be delivered by 2023, showing a substantial cost of energy reduction since the previous auction.
2018	• The first contracts were placed for MHI Vestas 9.5 MW OWTs, which will be installed in 2021 and 2022 at the Triton Knoll and Moray East OWFs. Both MHI Vestas Offshore Wind and Siemens Gamesa Renewable Energy have 10 MW+ turbines and GE Renewable Energy announced its 12 MW+ turbine with a 220 m diameter rotor. • The record for the largest OWF was broken, with the 659 MW Walney Extension project in Morecambe Bay, consisting of 40 MHI Vestas 8.25 MW turbines and 47 Siemens Gamesa Renewable Energy 7 MW turbines
2019	• The 1,218 MW Hornsea 1 OWF began operation becoming the world's largest OWF consisting of 174 Siemens Gamesa Renewable Energy 7 MW turbines, almost double the

	capacity of the previous largest OWF. • The third CfD auction resulted in record low prices for OW, awarding strike prices (at 2012 prices) of £39.65/MWh and £41.61/MWh for projects commissioned in 2023/2024 and 2024/2025 respectively. • Projects in what was the Dogger Bank Round 3 Zone were awarded CfDs for a total of 4.8 GW. Following the CfD auction results, it was announced that two projects would be built without a CfD. These were the East Anglia 3 project (that will now be built alongside East Anglia 1 North and 2 projects as one large project called the East Anglia Hub) and an additional part of the Seagreen Phase 1 project. • The 4 MW Blyth OWF (the first OW project in the UK) was decommissioned. • The UK Government and the Offshore Wind Industry Council signed a Sector Deal for OW in the UK. The deal included a number of targets for the industry including a target of 30 GW of installed capacity by 2030, which has since been increased to 40 GW
2020	• There was only one OW project installed in the UK during 2020, the 714 MW East Anglia 1 project which was fully commissioned in July 2020. • Offshore construction began for the Triton Knoll and Neart na Gaoithe (NNG) projects. • Onshore construction started for the Dogger Bank A and B projects, which also reached FID. The projects will have a combined installed capacity of 2.4 GW. Dogger Bank A and B will also use GE Renewable Energy's 13 MW Haliade-X turbine, the first-time turbines of this size have been contracted. • Round 4 lease competitions run by the TCE and CES were delayed, including by COVID-19
2021	• TCE allocated areas for nearly 8 GW of OW capacity in the OW Leasing Round 4. The six winning bids will pay a combined £879 million every year throughout the development phase in option fees. • TCE also announced its plans to lease up to 4 GW FLOW in the Celtic Sea. • The UK Government launched the fourth CfD allocation round with a pot of £200 million allocated for OW, and an additional £24 million ringfenced specifically for FLOW. It also announced that CfD auctions will be conducted annually from 2023 onwards to increase the rate of installations. • Kincardine OWF (October 2021) is the largest FLOW to date, with an installed capacity of 50 MW. • The Hornsea 2 project generated its first power in December 2021, becoming operational on the 31st of August 2022 and generating 1.3 GW, overtaking Hornsea 1 as the largest OWF in the world.

2022	• Plans for the UK to meet its net zero and energy security commitments have received a major boost as six fixed OW projects, with the potential to generate renewable electricity (approx. 8 GW) for more than 7 million homes, have been given the green light by the Secretary of State for Business, Energy and Industrial Strategy to enter into an Agreement for Lease with TCE in 2022.
2023	• The UK Government's Energy Bill [HL] 2023 Part 12 (UK Parliament, 2023) amends the HRA process, helping reduce the time it takes to process new OW projects, whilst maintaining protection for wildlife and marine habitats.

ScotWind

ScotWind applications opened in January 2021, with water depths suitable for bottom-fixed and FLOW (Table A. 2). The outcome of the ScotWind leasing round from CES was announced on the 17 January 2022, with 25 GW being spread across 17 projects. The additional Clearing Round, announced on 22 August 2022, added a further three projects totalling 2.8 GW and with additional developer capacity being added to ScotWind this has raised the final round total to 27.6 GW (Offshore Wind Scotland, 2023) (Table A. 2).

Before ScotWind, UK OW developments have almost all been in shallow waters (10 – 60 m), with the majority of these being in waters off the east coast of England. Instead, many (13) of ScotWind developments are anticipated to use floating turbines, allowing increasing access in deeper waters, which are also the windiest areas. FLOW is seen as presenting significant opportunities for Scotland and the UK. Globally, it is estimated that about 80% of the technical OW resource sit at depths > 60 m and thus more suitable to FLOW.

The National Grid Future Energy Scenarios (FES) work suggests there is potential for more OW in Scotland beyond ScotWind, and there will be a need for more electricity supply as the heat and transport sectors decarbonise. The uncertain nature of future demand, the readiness of the electricity network and the contracting mechanism mean that the timing and nature of further leasing rounds are difficult to predict (Future Energy Scenarios, 2023).

INnovation & Targeted Oil and Gas (INTOG)

INnovation & Targeted Oil and Gas (INTOG) was launched as a new leasing opportunity for OWFs to help maximise value from commercial scale deployment and to reduce the carbon emissions associated with North Sea O&G production. The programme has two distinct elements:

i. Innovation (IN) which is for small scale innovation projects of 100 MW or less, and
ii. Targeted Oil and Gas (TOG) which is specifically designed for OWFs which target the electrification of O&G installations.

On 24 March 2023, it was announced that 13 projects of the 19 applications - five for IN and eight for TOG - had been offered Exclusivity Agreements (Table A. 1). CES will offer a seabed lease of 50 years for TOG projects and 25 years for IN projects. Exclusivity Agreements will cover projects with a proposed capacity of up to 499 MW for IN and 5 GW for TOG (Table A. 2). Projects will now go through planning, consenting, and financing stages.

Table A. 2. Scottish OWF projects, including: (a) Operational, (b) Under Construction, (c) Consented, (d) In Planning, and (e) Pre-Planning OWFs (in grey, the ScotWind projects; in pale blue the projects belonging to INTOG (Crown Estate Scotland, 2024). Note that table heading colour coding refers to developments in Figure 1.1 (in the main body of the report) and Figure A.2 (below).

(a) Lease description	Developer(s)	Project stage	Type	Capacity
Robin Rigg (East and West)	RWE Renewables UK	Operational	Fixed	0.17 GW
Methil Demo	ORE Catapult Ltd	Operational	Fixed	0.01 GW
Beatrice OWF	SSE Renewables/RED Rock Power	Operational	Fixed	0.6 GW
Aberdeen Bay	Vattenfall	Operational	Fixed	0.1 GW
Buchan Deep (Hywind) Demo	Equinor	Operational	Floating	0.03 GW
Kincardine	Kincardine Offshore WF (KOWL)	Operational	Floating	0.05 GW
Moray (East)	Ocean Winds	Operational	Fixed	1 GW
Seagreen Phase 1	SSE Renewables / TotalEnergies	Operational	Fixed	1.1 GW
Total generating capacity: 3 GW				

(b) Lease description	Developer(s)	Project stage	Type	Capacity
Neart Na Gaoithe (NnG)	EDF Renewables / ESB	Under Construction	Fixed	0.4 GW
Morray West	Ocean Winds	Under Construction	Fixed	0.9 GW
Total expected capacity: 1.3 GW				

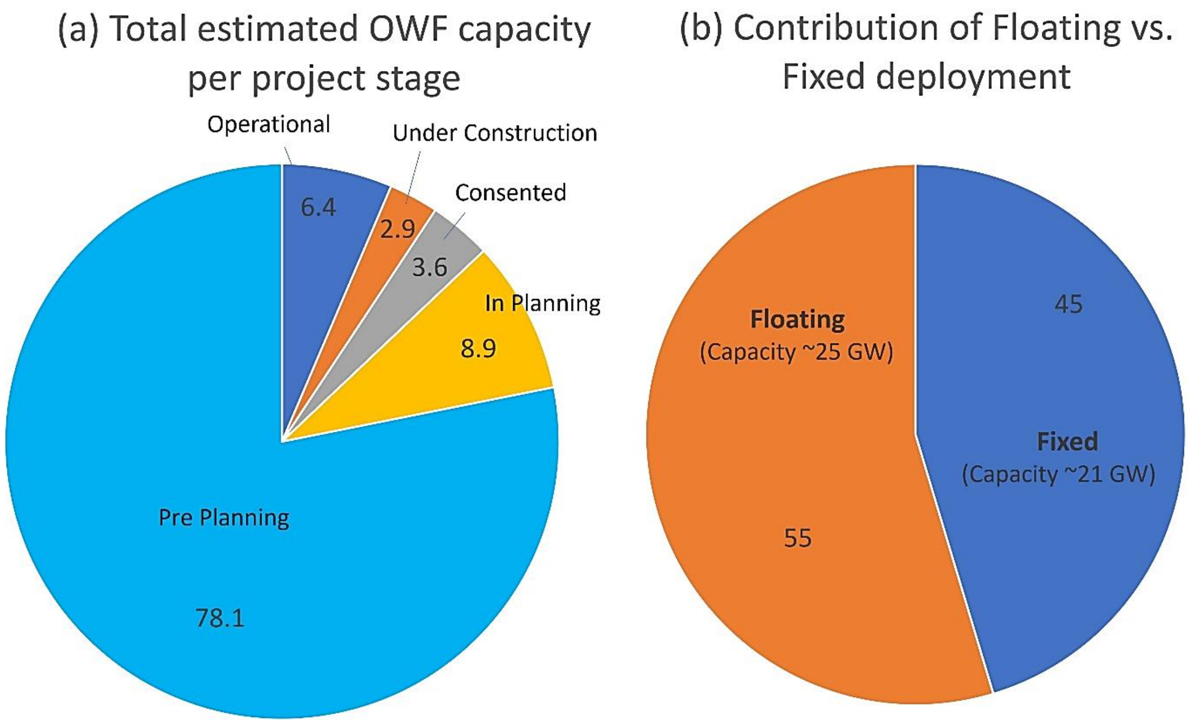
(c) Lease description	Developer(s)	Project stage	Type	Capacity
Inch Cape	RED Rock Power	Consented	Fixed	1.1 GW
Forthwind Methil Demo	Ciero	Consented	Fixed	0.01 GW
Seagreen 1A	SSE Renewables / TotalEnergies	Consented	Fixed	0.4 GW
Pentland	CIP	Consented	Floating	0.1
Total expected capacity: 1.6 GW				

(d) Lease description	Developer(s)	Project stage	Type	Capacity
Berwick Bank	SSE Renewables	In Planning	Fixed	2.3 GW
Marr Bank	SSE Renewables	In Planning	Fixed	1.8 GW
Total expected capacity: 4.1 GW				

(e) Lease description	Developer(s)	Project stage	Type	Capacity
Muir Mhor	Vattenfall / Freed Olsen Renewables	Pre-Planning	Floating	0.8 GW
Stoura (Shetland)	ESB Asset Management	Pre-Planning	Floating	0.5 GW
Ocean Wind (Shetland)	Mainstream RP / Ocean Winds	Pre-Planning	Floating	0.5 GW
Bowdun	Thistle Wind Partners	Pre-Planning	Fixed	1 GW
Ossian	SSE Renewables / CIP / Marubeni	Pre-Planning	Floating	3.6 GW
Buchan	Floating Energy	Pre-Planning	Floating	1 GW

	Alliance			
Stromar	Orsted / BlueFloat Energy / Renantis Partnership	Pre-Planning	Floating	1 GW
Broadshore	BlueFloat Energy / Renantis Partnership	Pre-Planning	Floating	0.9 GW
Bellrock	BlueFloat Energy / Renantis Partnership	Pre-Planning	Floating	1.2 GW
Marram Wind	Scottish Power Renewables / Shell	Pre-Planning	Floating	3 GW
Machair Wind	Scottish Power Renewables	Pre-Planning	Fixed	2 GW
Campion	Scottish Power Renewables / Shell	Pre-Planning	Floating	2 GW
Ayre	Thistle Wind Partners	Pre-Planning	Floating	1 GW
Spiorad na Mara	Northland Power	Pre-Planning	Fixed	0.9 GW
Tallisk	Magnora Offshore Wind	Pre-Planning	Floating	0.5 GW
Havbredey	Northland Power	Pre-Planning	Floating	1.5 GW
West of Orkney	RIDG / Corio Generation / TotalEnergies	Pre-Planning	Fixed	2 GW
Caledonia	Ocean Winds	Pre-Planning	Fixed	2 GW
Morven	BP / EnBW	Pre-Planning	Fixed	2.9 GW
Arven	Mainstream RP / Ocean Winds	Pre-Planning	Floating	2.3 GW
IN Sinclair	BlueFloat Energy / Renantis Partnership	Pre-Planning	Floating	0.1 GW
IN Scaraben	BlueFloat Energy / Renantis Partnership	Pre-Planning	Floating	0.1 GW
IN Flora	BP Alternative Energy Investment	Pre-Planning	Floating	0.05 GW

IN Malin	ESB Asset Development	Pre-Planning	Floating	0.1 GW
IN Salamander	Orsted / Simply Blue Group	Pre-Planning	Floating	0.1 GW
TOG Aspen	Cerulean Winds	Pre-Planning	Floating	1.0 GW
TOG Beech	Cerulean Winds	Pre-Planning	Floating	1.0 GW
TOG Cedar	Cerulean Winds	Pre-Planning	Floating	1.0 GW
TOG Culzean Demo	Total Energies	Pre-Planning	Floating	0.003GW
TOG Green Volt	Flotation Energy/Vargrønn	Pre-Planning	Floating	0.6 GW
TOG HE Project	Harbour Energy	Pre-Planning	Floating	0.02 GW
TOG Cenos	Flotation Energy/Vargrønn	Pre-Planning	Floating	1.4 GW
Total expected capacity: 36.5 GW				


(a) Total estimated OWF capacity per project stage

(b) Contribution of Floating vs. Fixed deployment

Figure A.2. Total estimated Scottish OW capacity contribution (in %) by (a) project stage and (b) floating vs. fixed deployment (data from the Crown Estate Scotland, 2024). Note that colour coding for development's project stages matches legend in Figure 1.1 and Table A. 2.

ii. Potential future changes to seasonal stratification

Simulations using computer models suggested that there is already a trend towards earlier onset of seasonal stratification (Sharples et al., 2020). Research found this onset occurred 8 days earlier in the western Irish Sea in 1999 compared with 1960. In the north-western North Sea, Sharples et al. (2006) found a weak trend in the earlier onset of stratification between 1991 and 2003 (1 day per year earlier). However, these trends are weak and natural variability in the timing of stratification is relatively large (standard deviation around the mean is ± 7 days). There are no clear trends in the strength of the stratification (both in seasonal warming and freshwater inputs (Sharples et al., 2020).

Climate models predict that the onset of stratification in spring will occur about one week earlier by the end of the century (Sharples et al., 2020). Similarly, projections suggest that, by 2100, breakdown of stratification in autumn will occur 5 - 10 days later than at present. This pattern is based on comparing the recent trends (1961 - 1990) with the projected conditions in future (2070 - 2098) in a business-as-usual scenario (see SRES A1B; Sharples et al., 2020). This pattern is due to the warmer air temperatures, although there is uncertainty as changes in wind patterns (especially the strength) may change stratification. Model projections suggest that the strength of stratification (the density difference between the two layers) will also intensify across the shelf sea regions, which will reduce upward mixing of nutrients and therefore will have an impact on primary productivity of the marine ecosystem (Sharples et al., 2020).

For the northern North Sea, changes in the strength of the exchange with the North Atlantic Oscillation (NAO) are also likely to occur, leading to possibly permanent stratification due to salinity differences in winter and due to temperature differences in summer (Holt et al., 2018; Sharples et al., 2020). Changes in stratification could have an impact on other properties, such as dissolved oxygen concentration due to longer periods of reduced air-sea exchange and productivity from phytoplankton and lower trophic levels due to reduced upward mixing of nutrients from the deeper layer.

APPENDIX B. SUPPORTING MATERIAL (CHAPTER 2)

i. Prevailing physical properties of the North Sea waters

Water circulation

The North Sea is characterized by its broad connection to the ocean and by strong continental impacts from north-western Europe. This results in the substantial interplay of oceanic influences such as tides, the North Atlantic Oscillation (NAO), and the North Atlantic low-pressure systems, as well as continental influences such as freshwater discharge, heat flow, and input of pollutants. These complex interactions generate specific physical and biogeochemical regimes (Sündermann & Pohlmann, 2011).

In the northern half of the North Sea water properties are largely dominated by North Atlantic inflow (Queste et al., 2016). To the south, a small inflow via the English Channel occurs (Figure 2.1). Atlantic waters enter the northern North Sea between Orkney and Shetland and then generally circulate anticlockwise, following the Scottish coast southward before turning east and crossing North Sea north of Dogger Bank (Figure 2.1). Along the west coast of Scotland, the influence of the land run-off from the estuaries and sea lochs significantly reduces the salinity close to the land and impacts the circulation locally.

Tidal currents

North Sea tides are characterized by strong semi-diurnal component, with current speeds ranging from 1.6 cm/s in the Skagerrak to 67 cm/s in the Fair Isle Channel between Orkney and Shetland (Vindenes et al., 2018). There are several localised areas around the Scottish seas that also experience very strong tidal currents (the Pentland Firth, off the Mull of Kintyre and Hebrides).

Otto et al. (1990) provided a map of the rate of tidal energy dissipation for the tide; this is a measure of tidal heating or tidal working which occurs due to tidal friction processes. The results of (Otto et al., 1990) indicate that the southern, more shallow North Sea has higher rates of tidal energy dissipation than the northern North Sea concurrent with the shallower bathymetry there.

The North Sea (and surrounding) waters have been under investigation for decades. Large datasets and monitoring programmes were initiated also due to the O&G industry and its activities in the North Sea waters, providing a legacy of information that can be utilised, if available, to understand how environmental parameters have changed through time. Data collection has been undertaken by academic surveys, statutory authorities and industry; however, programmes and approaches have been driven by different aims and objectives. Below, we highlight some of the relevant data collection/sea-trial programmes completed and underway within the context of OW.

ii. Relevant data collection from past and current programmes

Relevant Scientific projects in the North Sea

The UK project AlterECO (an Alternative framework to assess the marine ECOsystem) took part in the North Sea between 2017 – 2019 with the aim to demonstrate the suitability of solely using Autonomous Underwater Vehicles (AUVs) for monitoring ecosystem health and functioning (Palmer et al., 2020). As part of this project, 19 gliders were deployed providing measurements of temperature, salinity, chlorophyll, turbulence, dissolved oxygen, primary production, nitrate, phosphate and turbidity. The project maintained a continuous 100 km transect over an area in the North Sea prone to seasonal oxygen depletion for 18 months. The Marine Autonomous Robotic Systems (MARS) centre at the National Oceanography Centre (Southampton, UK) was responsible for deploying, piloting and recovering many of the gliders, with a user interface so that scientists were able to monitor the data in real-time and alter missions accordingly (Figure B. 1).

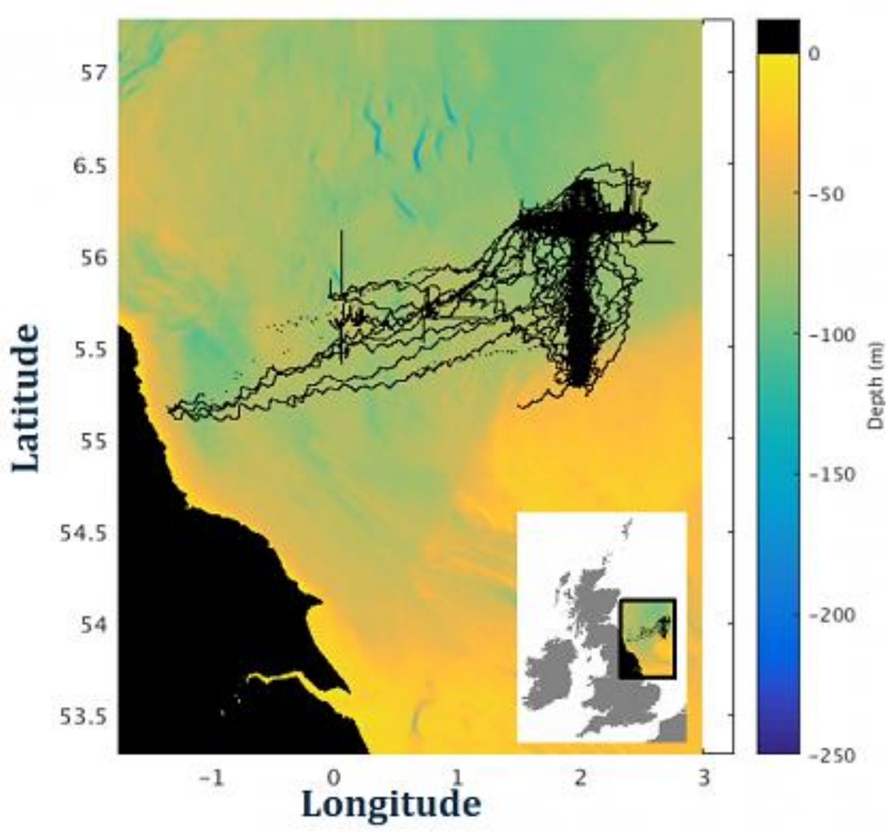


Figure B. 1. Map showing the glider tracks made in the North Sea between 2017-2019 by 18 gliders collecting data on temperature, salinity, chlorophyll, dissolved oxygen, turbulence and turbidity (see AlterECO project; Palmer et al., 2020).

The Marine Autonomous Systems in Support of Marine Observations (MASSMO) project is a pioneering multi-partner series of trials and demonstrator missions that aim to explore the UK seas using a fleet of marine robots. So far, the project is in its 4th phase and has monitored both the marine environment (MSFD Descriptor 7, D7) marine life (MSFD Descriptor 1, D1; Descriptor 4, D4) and marine noise (MSFD Descriptor 11, D11) around both the North Sea and Celtic Seas (OSPAR, 2020). The project has provided valuable information on marine mammals and fish and uses weather information from the Met Office and the Royal Navy, satellite data from Plymouth Marine Laboratory (PML) and tidal information from NOC to inform piloting the gliders.

The ECOWind programme (2022 - 2026) has funding of ~ £7.5 million provided by The Crown Estate's Offshore Wind Evidence and Change Programme (OWEC) and the Natural Environment Research Council (NERC) to investigate and understand how OWFs effects ecosystems and interactions between species. Furthermore, through the four key projects outlined below, ECOWind aims to enhance marine observations through innovative technology combined with numerical simulations to understand the effects of OW on marine life.

PELAgIO (part of the ECOWind programme) will explore the impacts of OW development across all levels of the food chain including physical changes to the mixing and stratification induced by structures. Relevant data will be collected via two field programmes in 2023 and 2024. Ship based and AUV observations of temperature, salinity, turbulence, chlorophyll, dissolved oxygen, fish and seabird abundance during the stratified spring-summer period. The project will develop existing models to predict impacts of stratification and mixing changes on marine mammals and seabirds.

The Fully Autonomous Marine Protected Area Seafloor Survey (Shetland ALR trial) has been commissioned, with the overarching objective to carry out a fully autonomous survey in an offshore marine protected area to demonstrate the concept and produce the data necessary to test the appropriateness of the technique to generate UK policy-relevant assessments of natural capital and ecosystems. The mission aims to demonstrate survey repeatability, water column oceanographic survey, detailed 2D seafloor mapping and general seafloor transecting survey.

Government frameworks in the North Sea

There are a number of policies and frameworks in place to monitor fisheries to support the integration of European environmental and fishery management (Jennings & Le Quesne, 2012). The main policies driving this integration are the Habitats Directive (Council Directive 92/43/EEC), the Common Fisheries Policy (Council Regulation (EC) No, 2371/2002) and more recently the MSFD (Council Directive, 2008/56/EC) (Bean et al., 2017; OSPAR, 2010).

Across the UK the monitoring of contaminant concentrations and their biological impacts in offshore marine waters is funded by Defra. At offshore locations, the long-term contaminant monitoring programmes are derived from our commitments to OSPAR Joint Assessment and Monitoring Programme (JAMP) carried out through the Co-ordinated Environmental Monitoring Programme (CEMP) (Bean et al., 2017). The UK is also a signatory to several water-related directives for the protection and maintenance of coastal and marine water quality. Various EU directives consider the assessment of eutrophication through measurement of key indicators such as concentrations of nutrients, Chl-a and DO (Devlin et al., 2011), e.g. the Urban Waste Water Directive (Council Directive, 91/271/EEC), the Nitrates Directive (Council Directive, 91/676/EEC), the Habitats Directive (Council Directive, 92/43/EEC), the Water Framework Directive (Council Directive, 2000/60/EC) and the MSFD (Council Directive, 2008/56/EC), the Oslo Paris Convention (OSPAR, 2003a, 2003b; Bean et al., 2017).

Non-Indigenous Species (NIS), also known as non-native or alien species are monitored via a number of international measures; The Regional Seas Conventions (e.g., OSPAR in relation to the UK); the EC Regulation on the use of Alien Species in Aquaculture (Council Regulation (EC) No, 708/2007); the MSFD descriptor two (Council Directive, 2008/56/EC); the Water Framework Directive; the EC Regulation on Invasive Alien Species of EC Concern (Council Regulation (EU) No, 1143/2014); and the International Maritime Organizations International Ballast Water Convention (e.g., Olenin et al., 2016; Bean et al., 2017). Although these programmes are focused on marine wildlife, they could also provide relevant data regarding water column physical and biogeochemical structure.

Industry in the North Sea

Driven by the increasing demand by the general public, government regulators and environmental organizations, the energy industry sector has had an increasing need to assess, monitor and reduce its environmental impacts. Reports on EIAs provide a useful tool in gathering and documenting environmental impact data. These assessments also assist decision makers to quantify impacts of proposed activities and plan for appropriate mitigation measures.

There are different types of environmental assessments, each having specific purpose(s) and addressing specific audience(s). In depth, environmental assessments are typically carried out on behalf of offshore energy operators by a broad range of industry survey and consultancy organisations. This assessment work is typically carried out during the site selection and pre-construction phases of an offshore site development in order to gain consents. However, there can be comparatively little ongoing environmental assessment conducted in the post-construction phases, if it is not part of a consent condition. The impact of this is that most of our understanding about the true environmental impacts of these structures, and on how they continue to affect their surrounding environments, comes from other areas including the research and academic sector.

The physical impacts of an OWF on the surrounding environment can be significant. Below are some examples of what is currently monitored as standard by industry stakeholders:

- OWF scour and sediment transport studies: Many areas around the UK coastline where OWFs have historically been built contain highly mobile sediments. Mobile sediments, coupled with the fact that many OWFs are built in water depths < 60 m means that significant quantities of sediment can become suspended in the water column and transported away. In some waters around the Scottish coastline there have already been events where some turbines have had to be removed due to extreme sediment transport altering the bathymetry of the surrounding environment. This is a phenomenon that is being studied increasingly by industry due to the cost and efficiency implications. This is typically assessed ~ yearly/every two years through bathymetry surveys. Other physical processes are thoroughly studied and investigated throughout the pre-construction phases, such as the assessment of the following parameters:
    - Conductivity, temperature and density (CTD) water column profiles
    - Waves – significant wave height, maximum wave height, wave period and direction
    - Currents – surface and water column

  However, ongoing measurement is primarily limited to current and projected physical site conditions to aid with operations and maintenance activities, such as determining if it is safe for maintenance vessels to enter the site and transfer personnel onto the structures.

  Generally, the effects on the physical and biogeochemical processes are thought to be less significant for developments in deeper water, such as those sites being looked into for FLOW developments. Therefore, there is less monitoring conducted to investigate currents, scour and sediment transport in more remote offshore areas (including for O&G).
- O&G developments, associated archived data and ongoing data collection: From the beginning, it became evident that the challenging conditions in the North Sea,

> particularly in the northern regions, required a special focus on environmental considerations throughout the entire development process (Larminie et al., 1987). No one had previously tackled the task of developing oilfields or laying large-diameter pipelines in waters of such depth and distance from the shore. Reliable baseline data about the physical and biological environment was limited. The initial focus was on the physical environment and substantial efforts were needed to gather information on various factors, such as wind speed, wave heights (including the 100-year wave), wave amplitudes, velocities, and frequencies, sediment conditions on the seabed (pertinent for platform foundations and pipeline installation) and bottom currents. Even at this stage biological information was needed, as fouling was an important consideration for platform design and maintenance.

Concerns about the industry's impact grew. The risks to human safety were highlighted by the 1988 Piper Alpha disaster. Environmental concerns were also increasingly voiced at around the same time, particularly as the central and northern North Sea supports a large proportion of the North Sea fish catch as well as significant O&G activity. It was not until 1984, over ten years after the first production platforms were placed in position, that the first statutory obligation for environmental monitoring was put on operators to monitor the environmental impact of their activities (Declaration of the International Conference on the Protection of the North Sea, Bremen, 1984). Though there was no legal requirement for environmental studies initially, many operators conducted them to assess environmental status, particularly on the seabed in the vicinity of the platforms (Kingston et al., 1987). Initially, it was thought that the major input of oil contaminants would be in the form of oily water resulting from platform drainage and production and formation water (Department of the Environment, 1976). Predictions of broad scale areas affected by these platform discharges meant that initial studies used extensive grids of 20-30 sampling stations for monitoring impacts. However, as more information became available, particularly on the impacts of oil-based drilling cuttings, the focus shifted from the midwater to the seabed closer to platforms. Surveys tended towards transect based approaches, radiating from the platform centre.

Over five decades, over 770 O&G structures have been installed in the UK North Sea alone. The balance between the economic gain and environmental costs of this industry have led to a complex policy landscape aimed at managing licensed activities and economic growth. Understanding the industry's impacts in the region is complex due to various factors including fisheries, shipping, and eutrophication. The North Sea's ecological baseline has been lost prior to being properly documented, making it challenging to assess the scale and persistence of historical industry impacts (Henry et al., 2017). Now, many developments in the North Sea are ending their useful life and are being decommissioned, leading to new requirements for monitoring to support decommissioning plans and monitor the long terms effects of removal options (Jones et al., 2019).

iii. Existing data and potential gaps

CTD / hydrographic data including turbidity

Ocean models based on the assimilation of all available ocean observations, can provide detailed information on the 3D structure of currents in an area of operations. From the 1990s, the offshore oil industry started to use 3D numerical models to estimate impacts of environmental conditions on offshore structures for both design and operational purposes (Skliris et al., 2021). Thirty years ago, the oil industry sponsored the North European Storm Study (NESS) to undertake modelling of North European Continental Shelf wind, wave, and current conditions (Peters et al., 1993). This was followed up by another oil industry consortium, the North-West Approaches Group (NWAG), investing in measuring the current regime west of Shetland and developing a 3D ocean model (Turrell et al., 1999).

Structures and Seafloor

Offshore O&G infrastructure has long been known to be rapidly settled by attached marine life and known to support large populations of mobile animals, like fishes (Fujii, 2015) and influence feeding interactions (Fujii, 2016; Russell et al., 2014). These artificial reef complexes support diverse and productive marine communities (Claisse et al., 2014). Increasing use of imagery collected during routine structural surveys is revealing the spatial and temporal dynamics of these communities. However, there are no broad datasets available yet for the North Sea. It is clear that the biological response to installation is rapid (e.g. Todd et al., 2019; Redford et al., 2021) and changes over time (Gates et al., 2019). Structures can host species of conservation importance (Gass & Roberts, 2006) and can provide an interconnected network of hard substratum that is environmentally important at the scale of the North Sea (Thorpe, 2012; Henry et al., 2018).

Most of the early wells were drilled using diesel-based drilling fluids, as these were cheap and readily available. It became clear relatively quickly that these were having a major impact on the seabed (Hartley et al., 2003). Monitoring programmes focussed on these impacts and efforts were made to reduce the environmental impact, through switching to synthetic and eventually water-based drilling fluids.

There are generally two main approaches to most environmental studies of the seafloor carried out in the North Sea: sediment analysis and monitoring of benthic macrofauna. Obtaining reliable quantitative samples of offshore sediments with its fauna is difficult. The method employed in almost all early North Sea surveys has involved the use of some sort of seabed sampler, such as a grab or corer. For example, a 0.1 m^2 area grab sampler has been commonly used to sample stations placed, 200, 500, 800, 1200, 2500 and 5000 m from the installation (Kingston, 1992). More recently, seabed imagery has provided non-destructive data (Jones et al., 2019) and other innovative approaches are also being assessed, for example environmental DNA (eDNA) sampling (Mauffrey et al., 2021).

In terms of available data, much of what is available from these sampling programmes is held in the UK Benthos Database. Currently, (v.4.06) it contains data from 11,353 stations across 351 structures including platforms, wells and manifolds, which were mapped and made available online during the North Sea Interactive project (BGS, 2014). Although the data originate from numerous separate surveys and have many issues that complicate synthesis, they have been used successfully to demonstrate that effects were limited to within 1 km from the platform and persist for at least 6-8 years in the northern and central North Sea (Henry et al., 2017).

There are a variety of other datasets that would be useful to understand the seafloor environment of the North Sea. Acoustic data on seafloor depth and hardness are particularly informative, helping to map seafloor habitats, developments and disturbances. Some of these data are collected through dedicated surveys, for example using side-scan sonar or multibeam bathymetry. Others are inferred from principally sub-surface seismic surveys.

These data are compiled and presented through initiatives such as the General Bathymetric Chart of the Oceans (GEBCO).

iv. Strategic assessment

Data collection efforts have been made as part of O&G Strategic Environmental Assessments (SEAs) carried out by UK Government through the Department for Energy Security & Net Zero (DESNZ) formerly DTI, BERR, DECC and BEIS. The SEAs collected and brought together data in various areas of the UKCS (SEA areas 1-8), in addition to an SEA for Round 2 wind leasing. These were more recently combined as offshore energy SEAs (OESEA, OESEA2, OESEA3 and OESEA4) incorporated the entire UKCS (with the exception of Northern Ireland and Scottish territorial waters for renewable energy, and Scottish territorial waters for carbon dioxide transport and storage), for technologies including O&G exploration and production, gas storage and offloading including carbon dioxide transport and storage, renewable energy (including wind, wave and tidal power), and offshore hydrogen production and transport. The SEA includes amongst other things an assessment of the environmental characteristics of areas likely to be significantly affected, an assessment of any existing environmental problems and the likely significant effects of activities on the environment at a regional level. The government has maintained an active SEA research programme; identifying information gaps (some of which are outlined in previous SEA Recommendations) and commissioning new research where appropriate. This has been part of the department's offshore SEA programme since 1999.

v. Current state of the art and adopting future technologies

Projects like e.g. ECOWind Accelerate at operational wind farms in Liverpool Bay, have demonstrated the use of autonomy for environmental data collection (AUV seafloor imaging, water column sensor and geophysical data).

The O&G industry conducts environmental monitoring in offshore areas where exploration, development, production and decommissioning activities take place. The information collected supports environmental management activities, assists in meeting regulatory requirements and provides valuable data on the state of the marine environment.

As outlined by Jones et al. (2019), hundreds of O&G structures in the marine environment are approaching decommissioning, and operations in such areas will need to be supported by environmental assessment and monitoring potentially over the life of any structure left in place. Monitoring of the general seabed environment and water column properties can incur in relevant costs for industry and the public, meaning that pragmatic and cost-effective solutions need to be considered.

Thus, traditional methods of marine monitoring, used during the development of the UK O&G industry, are now being supplemented by new, often automated monitoring techniques (Bean et al., 2017). Already available marine autonomous systems provide a wide range of solutions, allowing to collect acoustic, visual, and oceanographic data via sensors deployed on MAS. Besides the cost savings, autonomous solutions can provide a substantial improvement in the temporal and spatial resolution of environmental monitoring; however, the advances in marine autonomy require also the development of effective and efficient approaches for the purposes of monitoring.

Effective evaluation of impacts, and therefore evaluation of the optimal approach for monitoring associated with e.g. decommissioning, is aided by clear guidance on the most relevant environmental factors to consider (Table B. 1).

Unmanned, self-contained autonomous vehicles (MAS, including AUV, ROV, USV, etc.) have been used to monitor the marine environment for over a century (e.g. Ekman recording current meter; Sverdrup et al., 1942). The greatest revolution in MAS, to date, started with the Swallow float (Swallow, 1955) and led to the global ocean autonomous monitoring network ‘Argo’, an array of ~ 4000 autonomous sensor systems now surveying the upper 2000 m of the world's ocean (e.g. Medhaug et al., 2017). These ‘simple’ floats have further evolved to sophisticated particle sensing and capturing instruments (Lampitt et al., 2008), and to highly successful underwater gliders (e.g. Rudnick et al., 2004). The last two decades have seen a dramatic rise in the numbers and types of autonomous systems operating in the marine environment, and in the types of sensors these systems now carry (Wynn et al., 2014). Autonomy lends itself well to cost-effective long-term and large-scale monitoring programmes and is important in a variety of contexts (Danovaro et al., 2016).

The basin-wide decommissioning of the North Sea O&G infrastructures may be an important case to be considered also in parallel with other contexts, e.g. OWFs, where infrastructures posing, operation and decommissioning stages may have a relevant impact on the local environment. The environmental monitoring of these activities presents a challenge with the standard approaches used that can be solved for the future using MAS. Table B. 1 provides some examples of established versus potential autonomous methods for marine environmental monitoring which, for the purpose of this document, focuses on the water column.

The capability and use of autonomous/semi-autonomous devices has increased rapidly in recent years, enabling oceanographic observations at spatial and temporal scales impossible from traditional ships (Rudnick et al., 2004; Hartman et al., 2012). Autonomous vehicles are increasingly applied in marine geoscience (Wynn et al., 2014), habitat mapping (Robert et al., 2014), and benthic ecology (Morris et al., 2016), and can be divided into static, Fixed-Point Observatories (FPO; Cristini et al., 2016), and a variety of mobile platforms. The latter can be broadly split into underwater gliders, autonomous underwater vehicles (AUV), unmanned surface vehicles (USV), and seabed landing and crawling vehicles.

Existing data (e.g. samplings of the water column properties) and recommended procedures for environmental monitoring at O&G sites can be used to provide baseline information in the North Sea area and guidance for designing monitoring programmes at OWF sites.

When investigating primary oceanography data, MAS can provide a trade-off between monitoring efficiency and costs, as they greatly increase temporal and spatial resolution, they can be scoped for remote intervention in the form of adaptive surveys (depending on monitoring needs), and they represent an excellent support for satellite monitoring. However, we also need to consider disadvantages such as the limited physical sampling capability of the MAS. Note that requirements for environmental monitoring are likely to vary between environments, perceived threats, and jurisdictions. Thus, to optimise the use of this type of technology, we need to clearly define the information that should be used to establish as an environmental monitoring norm, including:

- Consider the monitoring objectives.
- Define whether the physical sample is essential.
- Directly address primary ‘Essential Ocean Variables (EOVs)’.
- Consider the spatial and temporal resolution needed for the sample collection.

Similar to the case of O&G developments, long-term monitoring of OW developments is likely to be necessary. Current standard practice does allow monitoring of the water column; however, the temporal and spatial resolution of that effort is typically limited by the high cost of ship time. MAS do offer significant potential to reduce that financial and carbon-footprint cost and reduce human risk of seagoing operations; however, its ability to offer a major uplift in the temporal and spatial resolution of environmental monitoring data should also be given serious consideration. Also, to maximise monitoring strategies considering the lifespan of an offshore project, it is important to integrate:

- Evolution of data needs throughout the lifecycle of an offshore project.
- Measurement variables and sampling techniques to address in monitoring programmes.
- Use of established methods for monitoring versus the use of autonomous systems.
- Data management and quality assurance methods to improve confidence in monitoring results and ensure the long-term usability of data.
- Use of numerical modelling in the design of monitoring programmes.
- Application of results from monitoring programmes.

Table B. 1. Comparison between established versus potential autonomous methods for environmental monitoring of the water column (case study based on decommissioning of O&G sites; Jones et al., 2019).

Characteristic	**Purpose**	**Established method**	**Established indicator**	**Autonomous method**	**Most similar indicator from autonomous approach**	**Compatibility of indicators**
Oceanography	Primary environmental charactersation	Moored (FPO) and ship-deployed instruments	Temperature Salinity, Oxygen, pH, Turbidity, Current speed; etc.	Sensors deployed by glider, AUV or FPO	Temperature Salinity Oxygen, pH, Turbidity, Current speed; etc.	Common instrumentation
Water quality	Monitoring contaminants	Physical sampling and sensors from surface vessel; in-situ ecotoxicology	Contaminant concentration	Sensor deployment by glider, (cruise / hover) AUV; USV, FPO; very limited sampling capacity	Contaminant concentration or proxy value	Largely sensor only; limited sampling capability

Zooplankton	Biological effects	Physical sampling, acoustic/visual survey from surface vessel (tow-body/ROV)	Zooplankton abundance and composition	Visual and acoustic survey by (cruise/hover) AUV, FPO and USV (acoustic)	Zooplankton abundance and composition	Common instrumentation for visual and acoustic methods; limited sampling capability
Fish	Biological effects	Physical sampling, acoustic and visual survey from surface vessel (tow-body/ROV)	Pelagic fish abundance and composition	Visual and acoustic survey by (cruise/hover) AUV, FPO and USV (acoustic)	Pelagic fish abundance and composition	Common instrumentation for acoustic and visual methods; no sampling capability
Marine mammals	Biological effects	Visual survey; passive acoustic monitoring	Marine mammal abundance and composition	Visual survey by AUV; passive acoustic survey by AUV/USV/ FPO	Marine mammal abundance and composition	Common instrumentation for acoustic and visual methods; no sampling capability

APPENDIX C. SUPPORTING MATERIAL (CHAPTER 3)

i. Induced drag and mixing of the underwater structures (fixed or floating)

The sub-grid parameterization of the foundation drag and wake turbulence has been described in Rennau et al. (2012), Carpenter et al. (2016) and Christiansen et al. (2023). It is based on an additional quadratic friction term in the momentum equations as well as additional production terms in the dynamic equation for TKE and its dissipation rate. In their method, the drag by a vertical cylinder perpendicular to an unstratified flow can be expressed as:

$$\vec{F_d} = -\frac{1}{2}\rho C_d A|\vec{u}|\vec{u}$$

where ρ is the density of the fluid, C_d is the drag coefficient and A is the frontal area of the cylinder that is exposed to the free stream and u is the velocity of the free stream, with a negative sign indicating that the drag force is acting in the opposite direction of the free stream. Although the parameterization was developed for unstratified flow, Rennau et al. (2012) suggested that the basic principles of the approach also apply for stratified flow. To account for deceleration at grid cells containing offshore wind turbines, the drag retarding force has to be added to the hydrostatic momentum equation (with equations depending on the hydrodynamic model used).

In order to account for the production of sub-grid wake turbulence, the driving assumptions is that the turbulence produced by foundations is equal to the power lost to drag, P_d,

$$P_d = \frac{1}{2}\, C_d A(u^2 + \, v^2)^{3/2}$$

is then included as further production term in the TKE equation and as a source term into the dissipation rate as well, scaled by an empirical parameter c_4. Rennau et al. (2012) derived the c_4 parameter by calibrating an extended k-epsilon turbulence closure model by comparing LES simulations of stratified flow past 10 m diameter cylinders. The physical meaning of this parameter could be identified to be connected to the structure induced mixing efficiency. It was found that a value of $c_4 = 1.4$ resulted in mixing slightly smaller than predicted (20% mixing efficiency) and $c_4 = 0.6$ (50% mixing efficiency) resulted in an overestimation of mixing.

In general, the results of the parameterization of the foundation drag and wake turbulence are strongly dependent on the choice of scaling parameters. While Rennau et al. (2012), Carpenter et al. (2016) and Christiansen et al. (2023) assumed that C_d is constant in reality it is variable and dependent on the Reynolds number, surface roughness and structure geometry. The drag is also likely a function of depth and time and will vary with background shear and Froude number (Dorrell et al., 2022).

In terms of water column changes, Cazenave et al. (2016) compared hindcast scenarios without OWFs and with 242 fixed WTs installed in the eastern Irish Sea. Localised regions of decreased velocity extend up to 250 times the monopile diameter away from the monopile. Changes in tidal amplitudes were found to be up to 7%. The turbines enhance localized vertical mixing which decreases seasonal stratification, the horizontal extent of this disturbance is significantly larger than the sum of the footprint of the monopiles.

For seasonally stratified tidal flow, Carpenter et al. (2016) calculated that the loss of tidal energy to turbulence is between 4 - 20% of the energy loss due to bottom friction in the German Bight. The existing 160 fixed turbines in the German Bight in 2016 would not significantly decrease stratification there. However, extensive installations covering large parts of the German Bight could lead to a measurable large-scale reduction in stratification (Carpenter et al., 2016).

Christiansen et al. (2023) found that in the German Bight the additional turbulence production is the main driver of changes in both current velocities and stratification, with magnitudes of about 10%, similar in magnitude to regional annual and interannual variabilities. However, the magnitude of these changes should still be interpreted with caution: the choice of the drag parameters (C_d and c_4) is decisive for the magnitude of the model results and lead to uncertainties in the local mixing of more than 100% with the drag coefficient having the largest influence. In general, more observations are needed to validate the modeling approaches and to support the simulation results. Nevertheless, the expected dimension of the structure-induced effects of offshore fixed wind infrastructure at the current construction levels is emerging and emphasizes that these processes must be considered at a regional scale for impact assessment.

Expansion of the OW sector to deeper waters is predicated on development of floating foundations, which are finite in depth and anchored to the seabed. Finite depth structures induce complex dynamics within stratified fluids, especially if structures intersect sharp density gradients (Dorrell et al., 2022). Although the sub-grid parameterization of the foundations can be tuned for floating foundations (by calibrating the C_d and c_4 parameters), no published literature is available on the impact of floating foundations.

ii. Wind-wake effects

Earlier studies started to investigate the oceanic response to wind stress anomalies in idealized model approaches (Broström, 2008; Paskyabi & Fer, 2012; Paskyabi, 2015). The studies demonstrated the occurrence of an elevation pattern and corresponding up- and down-welling at the sea surface, which results from the changes in wind-driven Ekman transport. The resulting vertical transport, with vertical velocities of the order of m/day (with wind speed of 5 - 10 m/s), induces perturbations of the pycnocline and can influence the temperature and salinity distribution in a stratified water column (Broström, 2008; Ludewig, 2015). Less wind stress at the sea surface also causes decreasing horizontal surface currents behind OWFs, which are of the order of centimeters per second (Ludewig, 2015).

These studies formulated prerequisite conditions for the generation of OWFs wind-wake induced upwelling/downwelling dipole: (i) the characteristic width of the wind-wake has to be at least the internal radius of deformation (Broström, 2008); (ii) an almost constant wind direction for at least 8 - 10 h with moderate speeds 5 - 10 m/s (Ludewig, 2015).

Few empirical data of the wind-wake effects on the ocean dynamics are available, Floeter et al. (2022) provided observations of the existence of the upwelling/downwelling dipoles, using a TRIAXUS (a remotely operated towed vehicle, ROTV). In the summer stratified area of the North Sea, a distinct structural change in mixed layer depth and potential energy anomaly inside the wind-wake area of the OWFs was shown over a distance less than 5 km and a diagonal thermocline excursion of 10 - 14 m over a dipole dimension of 10 - 12 km.

The changes in the surface mixed layer depth can influence the pelagic ecosystem. A shallowing of the summer mixed layer depth brings the lower regions of the thermocline, and with it, high concentrations of nutrients and phytoplankton upward into more illuminated water depth levels, and it can be expected that the phytoplankton organisms immediately increase their production.

Christiansen et al. (2022) used an observational-based empirical approach to parameterise the atmospheric wakes in a hydrodynamic model. Due to the vertical changes of the wake pattern (Frandsen et al., 2006; Emeis, 2010; Fitch et al., 2012; Akhtar et al., 2021), the empirical and analytical models that have been developed to parameterise the down-stream wake effects in the atmosphere in the past cannot directly be used for processes near the sea surface boundary (Christiansen et al., 2022 and references therein). Christiansen et al. (2022) adjusted former model assumptions using Synthetic Aperture Radar measurements so that they become applicable for numerical ocean modeling. The wind reduction formulation is based on earlier studies from Frandsen (1992), (2006) and alters the undisturbed wind field by the wind speed deficit. The deficit consists of two components describing the downstream wake recovery, described by an exponential decay function, and the width of the wake structure, described by a symmetric exponential function scaled by the wind farm width. Christiansen et al. (2022) generated wakes with constant dimensions, which, in terms of the different wind farm properties (e.g., the number of turbines and turbine density) or the changing atmospheric conditions, lead to over- and under-estimation of the actual wake dimensions.

The wind reduction is on average around 1 - 2% relative to the mean undisturbed wind field and can reach even beyond 5% in areas of clustered wind farms. Both wind speed and wind stress exhibit continuous deficits over several tens of kilometres, which do not fully recover in between adjacent wind farms and are particularly strong in the case of superimposed wakes. The wake effects lead to unanticipated spatial variability in the mean horizontal currents and to the formation of large-scale dipoles in the sea surface elevation. Ultimately, the dipole-related processes affect the stratification development in the southern North Sea and indicate potential impact on marine ecosystem processes (further investigated in Daewel et al., 2022).

Spatial differences in the magnitude of wake effects occurred, despite similar changes in wind forcing. As further investigated in Christiansen et al. (2022b), tides and mixing play an important role in the changes in hydrodynamics causes by atmospheric wind farm wakes:

i. Tidal currents can deflect and even inverse wake-induced processes. The alignment between wind and tidal currents determines the magnitude of the wake effects, the periodic tidal currents can mitigate the impact of the wind speed reduction over time due to opposing changes in the horizontal flow, resulting in hydrodynamic changes only half as strong as those without tides. This tidal mitigation can translate into the development of sea level dipoles.
ii. Stratification conditions and tidal mixing rates determine the impact on vertical transport and density stratification. Changes are much more pronounced in stratified waters, whereas in well-mixed waters the impact of wake effects on the density distribution appeared weaker (tidal stirring attenuates the impact).

Different from earlier studies, Daewel et al. (2022) used a high-resolution atmospheric model (COSMO-CLM) including a parameterization of OWFs as a momentum sink and a source of TKE, which takes into account the size of the wind farm and the number of turbines (Akhtar et al., 2021) and estimates the impacts not only on the wind field but on the full atmospheric physics. The atmospheric model has been used to force a fully coupled physical-biogeochemical model, showing that the changes in atmospheric conditions will propagate through the ocean hydrodynamics and change stratification intensity and pattern, slow down circulation, systematically decrease bottom shear stress, increase sediment carbon, change primary productivity and dissolved oxygen distribution (Daewel et al., 2022).

Raghukumar et al. (2023) also used a high-resolution wind model, the Weather Research and Forecasting model with Wind Farm Parameterization (WRF–WFP) (Fitch et al., 2012), which represents WTs as a momentum sink and turbulence source, using turbine parameters such as hub height, rotor diameter, power curve, and thrust coefficients to calculate the magnitude of the source and sink terms (Lee & Lundquist, 2017). WRF is an established and validated operational weather model, WRF–WFP has been utilized in a number of studies to evaluate the effects of wind farms on mesoscale weather patterns (Jiménez et al., 2015; Huang & Hall, 2015; Eriksson et al., 2015; Raghukumar et al., 2022). The model accounts for turbine-turbine and wake-turbine interactions and thereby provides an accurate assessment of the wind field around an OWF (Churchfield et al., 2012). Raghukumar et al. (2023) found that wind speeds at 10 m height are reduced by approximately 5%, with wakes extending approximately 150 km downwind of the OWF. The wind fields (computed in the absence and presence of WTs) were used to force a regional ocean circulation model. It was found that the net upwelling, in a wide coastal band of the California coast, changes relatively little due the wind speed changes, but the spatial structure of upwelling within this coastal region can be shifted outside the bounds of natural variability. The consequences of these changes in physical upwelling structure on the ecosystem are currently unknown.

iii. Ongoing modelling efforts

PELAgIO and ECOWind-ACCELERATE (ECOWind programme) are developing/implementing numerical models for wave, hydrodynamics and biogeochemical predictions. These models will feed into a rapid evidence assessment of how climate change and OWF installation combine to impact seabed, water column, marine wildlife, and wider ecosystem structures. Local and regional scale models can simulate the interaction between offshore infrastructure and the environment in the near-field. UK shelf-wide models can provide insights on the cumulative effects of multiple offshore infrastructures (OWFs) and their interaction with the environment in the far-field. Particularly important is the integration of physical and biogeochemical modelling (hydrodynamics, sediment transport, water quality and productivity), as it is only in this holistic way that the full environmental impact can be understood. ECOWind projects are also combining climate projections of future storminess and sea-level rise: changing baseline against which OWF will also alter the environment.

Particle tracking simulations can yield information about connectivity between OWFs. OWFs provide a hard substrate habitat for benthic marine species which can spread between sites in their larval stage and can modify the natural ecological connectivity acting potentially as a source and sink of larvae: which means they can act as ‘stepping stones’ and have positive (enhancing resilience of protected species) or negative (spreading non-native invasive species) effects on the environment. Particle-tracking models simulations can help understanding how future planned OWFs or decommissioning of existing ones at the end of service, contribute to changes in larval connectivity.

A particle-tracking dataset and connectivity matrices has been developed in the CHASANS project (INSITE programme), the dataset can be interrogated to understand the connectivity of existing and future artificial structure in the northern North Sea for guidance on planning, decommissioning and derogation of man-made artificial structures.

As well as models dealing with specific physical processes, modelling approaches have also been used to represent bio-geochemical processes in OWFs (e.g. van der Molen et al., 2014) as well as trophic interactions (e.g. Halouani et al., 2020). For example, the Ecopath with Ecosim modelling package has been extensively used to model the response of both pelagic and benthic assemblages in OWFs. Halouani et al. (2020) use the Ecospace module within Ecopath to make spatially explicit predictions of spillover effects within, near, and far from OWFs. Trophic models, such as Ecopath, are parameterised using high-quality observation data, often provided by monitoring programmes. In the case of Halouani et al. (2020), observation data used in the parameterization of the model included fisheries data, satellite imagery, and reference values from the scientific literature. More recently, Pezy et al. (2020) also used nine Ecopath with Ecosim models to estimate the biological changes (inclusive of all trophic components from phytoplankton through to marine mammals) for OWFs spanning three sedimentary habitats at three temporal stages (winter, summer, and whole year). Following this exercise, Pezy et al. (2020) highlight the value of trophic modelling in OWFs for their ability to: (i) capture structural and functional change; (ii) merge and improve the interpretation of several sources of observational data; and (iii) capture, and meaningfully report on ecological complexity.

Bringing multiple models together offers an opportunity to capture more complexity. An example of a coupled model that integrated a physical-biogeochemical model with other physical models is well represented by the work of van der Molen et al. (2014). This study merged the output from a model wave, a physical-biogeochemical model (i.e. European Regional Seas Ecosystem Model), and an acoustic energy flux sound field model. The coupled model successfully estimated several physio-chemical and biological variables simultaneously for the study region containing a hypothetical OWF. One apparent issue with coupling so many models was the differing spatial resolution of the models and the representation of spatial scale for different processes. For example, noise propagation was the localised impact whereas the ecosystem impacts were estimated to be the most diffuse and spread over a larger area. This highlights a major difficulty in producing models for larger model domains as the working resolution needs to account for processes that occur at the finest spatial, and/or temporal, scale. This determines the working resolution of the model and may have significant implications for the computational power needed to run the model for large extents. Interestingly, the coupled model produced by van der Molen et al. (2014) did predict that the overall impact generated for a specific amount of energy collection would be less as turbines become progressively larger and more powerful. Predictions like this highlight the value of model outputs for the transferability of cause-effect mechanisms addressing future scenarios or new settings.

Other examples of coupled models include the merging of a hydrodynamic model with a microplankton-detritus model and dynamic energy model to estimate the local pelagic and benthic effects of blue mussels attached to OWF foundations and turbines (Maar et al., 2009). Burkhard et al. (2011) coupled a bio-geochemical model (ERSEM), with Ecopath and a hydrodynamic model (MIKE21) to estimate the overall change in ecological integrity of an OWF in the German North Sea.

The examples of coupled models provided above all directly utilise large numerical or mechanistic models that are computationally demanding. By comparison, Pınarbaşı et al. (2019) used Bayesian Belief Networks to model the spatial distribution of OWF feasibility both in the Basque Country and for the North East Atlantic/Western Mediterranean. Bayesian Belief Networks are extremely flexible models that can accept various inputs and formats (including expert judgement, spatial data, and large, quantitative datasets). Furthermore, BBNs also incorporate estimates of uncertainty and can be used to estimate, and trace, the total propagated error through these models, For the BBN models used for the Basque Country, Pınarbaşı et al. (2019) were able to integrate: (i) technical and economic variables; (ii) three biological components (i.e. seabirds, marine mammals and macrobenthos); and (iii) ten other variables reflecting interactions with other anthropogenic activities and socio-economic factors. Pınarbaşı et al. (2019) highlight the value of BBNs for their ability to integrate many different sources of information within a probabilistic framework that is computationally quick to compile. Although spatially explicit estimates of OWF feasibility were estimated by Pınarbaşı et al. (2019), BBNs can be designed to simulate any number of response variables including specific ecological impacts, marine net gain, functional indices, or total ecosystem service provision. Given their flexibility, it is clear when several of the ECOWind projects (i.e. PELAgIO and BOWIE) have adopted the use of BBNs for considering tropic cascades/combined effects and in-combination impacts (i.e. pressures from multiple activities on multiple receptors).

Finally, ecosystem services can then be classified to understand the costs and benefits of OWF installations. Models can ultimately be designed to interface with socio-economic systems. For example, Haraldsson et al. (2020) used a Social-Ecological-System model to estimate the impacts of the future expansion of OWFs in the Eastern English Channel. The ecological subsystem of the model included nine biological components. The social subsystem has six sectors (e.g. tourism, fisheries, OW industry). Ultimately, the Social-Ecological-System model estimated ‘perceived environmental quality’, ‘perceived well-being’, and the loss or gain experienced by each industrial sector. Haraldsson et al. (2020) concludes that these types of coupled models are particularly helpful for representing the complexity inherence in environmental systems that also include socio-economic considerations. Furthermore, the Social-Ecological-System was found to capture both indirect and unexpected changes within the modelled domain.

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