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Advancing multi-scale physical modelling and bespoke monitoring for offshore wind foundations through the national research infrastructure ProWind

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ABSTRACT: ProWind is a new Norwegian national research infrastructure supporting the transition and sustainable development of offshore wind foundation systems. Funded by the Research Council of Norway, ProWind supports research across three integrated nodes: 1) an experimental node in Oslo, featuring advanced element test equipment for dynamic and multi-directional soil testing across a broad range of strains, a geotechnical mini-centrifuge for versatile enhanced-gravity model testing, and a model test bin equipped with a bespoke 4 degree-of-freedom actuator for 1-g experimental modelling; 2) a mobile node with a portable, high-capacity bespoke load actuator and full-size instrumented suction bucket for field-scale foundation installation and testing under realistic offshore environmental loading conditions; and 3) an offshore environment node, including the Marine Energy Test Centre, focusing on comprehensive monitoring of meteorological conditions, floating structure response, and anthropogenic effects on marine ecosystem dynamics through an integrated suite of instrumentation and observation technologies. All nodes are interoperable and supported by a shared digital infrastructure. ProWind aims to reduce design conservatism and facilitate novel foundation designs, promote education and research collaboration across geotechnical and environmental engineering disciplines, and enhance the efficiency, reproducibility, and relevance of physical modelling and monitoring. This paper presents the vision, background, technical scope, and implementation strategy of ProWind, and invites the international community to engage with the platform in advancing offshore geotechnical engineering and environmental monitoring.

1 INTRODUCTION

Offshore wind is being rapidly scaled up globally. Both Norway and the European Union (EU) recognize offshore wind energy as critical to achieve the net-zero carbon emission targets in the EU's Green Deal strategy and accelerated wind energy deployment ambitions of REPowerEU plan. 83 GW offshore wind capacity has now been installed (Williams et al., 2025), and despite recent undersubscribed auctions and project cancellations resulting from geopolitical unrest, supply chain challenges and increasing costs, the IEA still predicts the global offshore wind capacity to reach 140 GW by 2030 (IEA, 2025). The Norwegian Government has set an export objective of a 10% share of the global market and allocate areas for development of 30 GW of offshore wind by 2040. In contrast to the oil & gas sector, however, offshore wind energy requires a rapid scale of deployment. Although the 88 MW floating turbine project Hywind Tampen was opened in 2023, and two offshore wind leases have been awarded (Sørlige Nordsjø II and Utsira Nord), Norway has yet to develop a commercial-scale offshore wind farm. Efficient utilization of offshore wind energy with a reduced levelized cost of energy (LCOE) requires installation of larger-capacity turbines in deeper waters on scale. The goals of safeguarding nature in the new global biodiversity framework must also be achieved. Significant knowledge gaps remain across several areas and targeted, long-term research will support informed decision making. Applied research is needed to reduce costs, improve reliability and adapt technologies and solutions to local conditions, including deep water environments. Strong research environments also develop competence, support innovation, and lowering risk for early projects. Public investment in research and innovation through national and European funding mechanisms is therefore a key enabler of environmentally sustainable and economically viable renewable energy. Among the funding schemes offered by the Research Council of Norway (RCN), the National Infrastructure Programme *INFRASTRUKTUR* plays an important role. This framework funds Research Infrastructure (RI) initiatives of national importance, and projects supported by this framework must serve a broad national interest and offer access to multiple users from academia, research groups, public sector and industry. Both the Norwegian roadmap for Research Infrastructure and the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap highlight a pressing need for developing infrastructure dedicated to renewable energy production and ocean technologies to bridge gaps in the existing infrastructure landscape.

This paper presents the background of the ProWind RI (Figure 1) and provides an overview of its experimental nodes and their capabilities, equipment under development, and brief project governance structure.

2 BACKGROUND

Europe needs to install thousands of offshore wind turbine generator (WTG) foundations, anchors and mooring lines over the coming decades. WTG substructures and foundations represent a major cost driver, accounting for 19-36% of the investment cost (ETIPWind, 2021; Oh et al., 2018). Bottom-fixed turbines typically fall at the lower end of this range, while floating technologies occupy the upper end due to their complexity and deep-water requirements. Long-term research and foundation optimisation efforts therefore have significant potential to reduce costs and improve project viability. There is a strong need for increased understanding of several aspects relevant to offshore foundation and anchor technologies, including:

- the interaction of foundation systems and new mooring line or cable concepts with the seabed;
- flow-induced soil scouring around foundations;
- reduced noise emissions from foundation installation;
- efficient and scalable anchor concepts for floating wind turbines;
- long-term multi-directional cyclic loading effects on the soil surrounding the foundations and mooring lines;
- anchor shapes and cluster arrangements for optimal design and material consumption;
- structure life prediction and extension technologies.

Moreover, biodiversity effects are expected to be highly technology and site- dependent, meaning that knowledge from a shallow water bottom-fixed WTG site in the southern North Sea may not be extrapolated to the deep waters on the west coast of Norway, where floating technology is more relevant. Current scientific literature on ecosystem effects is skewed, with approximately 90 % of studies focusing on bottom-fixed structures in water depths of less than 30 m and examining single-factor effects only (Galparsoro et al., 2022). This highlights a critical knowledge gap for the ecosystem impacts of floating wind. Key knowledge gaps relevant to environmental and biodiversity effects include:

- the interaction of foundation systems and new mooring line or cable concepts with the seabed, water column and marine species;
- The spatial extent and proliferation of offshore wind ecosystem impacts;
- Effects of underwater noise on species and habitat function:
- Cost-effective semi-automatic and safe methods for high-resolution long-term monitoring of the marine environment, species and habitats;
- Cumulative impacts and the co-existence of offshore wind with different ocean industries.

Despite these challenges and unknowns, there is currently no integrated research infrastructure capable of delivering the support for and combined capacity of: 1) experimental modelling of soil behaviour; 2) small to medium-scale testing of foundation and anchor models in both laboratory and field conditions; 3) advanced instrumentation and monitoring solutions for demonstrator or full-scale wind structures in real world environments offshore;

and 4) environmental monitoring to assess impacts of offshore wind structures on marine ecosystems. Addressing these gaps is essential given the substantial industrial opportunities, which are already being explored through major national and European research initiatives, including the RCN supported centres FME NorthWind, SFI BLUES, and WINDRISE, and the EU projects TAILWIND and GEOLAB. While numerical modelling can offer valuable insights and partial solutions, physical modelling delivers measured data for improved understanding and calibration of numerical models. Physical experiments and real-world monitoring can also support the development of new or adapted design approaches, regulatory frameworks and informed decision making. ProWind's purpose is to establish, operate, and maintain a suite of experimental and observational equipment to address existing and new challenges associated with offshore wind foundations. The RI will be made available to external users from academia, research groups, public authorities, and industry. While the focus is primarily on soil-structure interaction (SSI) and environmental research on ecosystem surrounding offshore wind developments, the infrastructure will remain open to a broad range of applications. It will also leverage existing Norwegian and European research infrastructure cooperation, such as the Norwegian GeoTest Sites (NGTS, L'Heureux and Lunne, 2019) and the Marine Energy Test Centre (METCentre), academic and industrial projects.

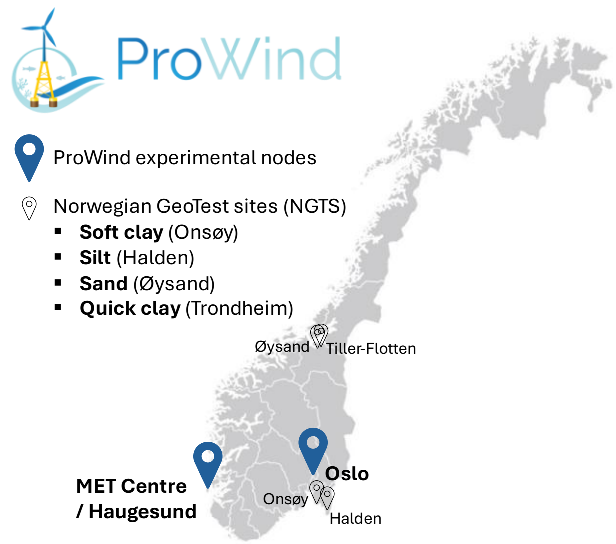

Figure 1. Overview of ProWind experimental nodes and NGTS (L'Heureux and Lunne, 2019) sites.

3 INFRASTRUCTURE GOVERNANCE

ProWind is a research infrastructure (RI) under development, funded by the Research Council of Norway (RCN) and owned by the Norwegian Geotechnical Institute (NGI). NGI leads the development and assumes the overall management responsibility (Work Package WP1), with Oslo Metropolitan University (OsloMet), the Norwegian Institute for Water Research (NIVA), Akvaplan-niva, and Marine Energy Test Centre (MET Centre) as research partners and with representatives in the different WPs and experimental nodes. The Steering Committee (SC) is composed of representatives from each partner, and the project is advised by an Advisory Board (AB), composed of internationally recognised researchers, representatives from the offshore wind industry, academia, and certification authorities (Figure 2).

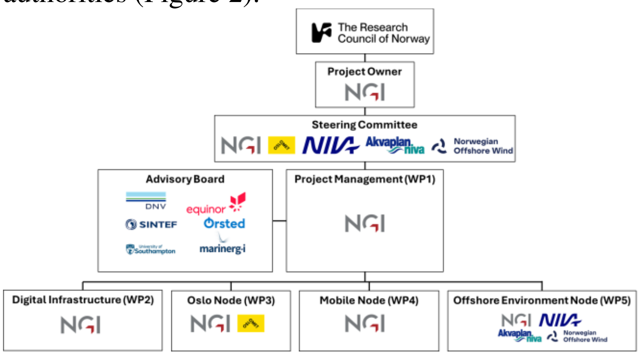

Figure 2. Organizational structure of ProWind, including the SC, AB, different WPs and experimental nodes.

4 EXPERIMENTAL NODES

The RI supports a continuous experimental pipeline and is designed for multiple model scales – from soil element level and small-scale foundation models in the laboratory, through onshore physical model testing in the field, to observation of full-scale foundation behaviour and marine ecosystem effects in real-world environments offshore (Figure 3). It includes three experimental nodes (developed as part of ProWind WP3 - WP5), which together cover these scales. A cross-node digital infrastructure (WP2) will support and manage the different types and volumes of data captured by the experimental nodes.

4.1 Oslo node

The first and second model scales are the geotechnical laboratory element and small-scale model testing, respectively, provided by the Oslo node. This node allows realistic simulation of soil and soft rock element behaviour and soil-structure interaction under the whole-life loading.

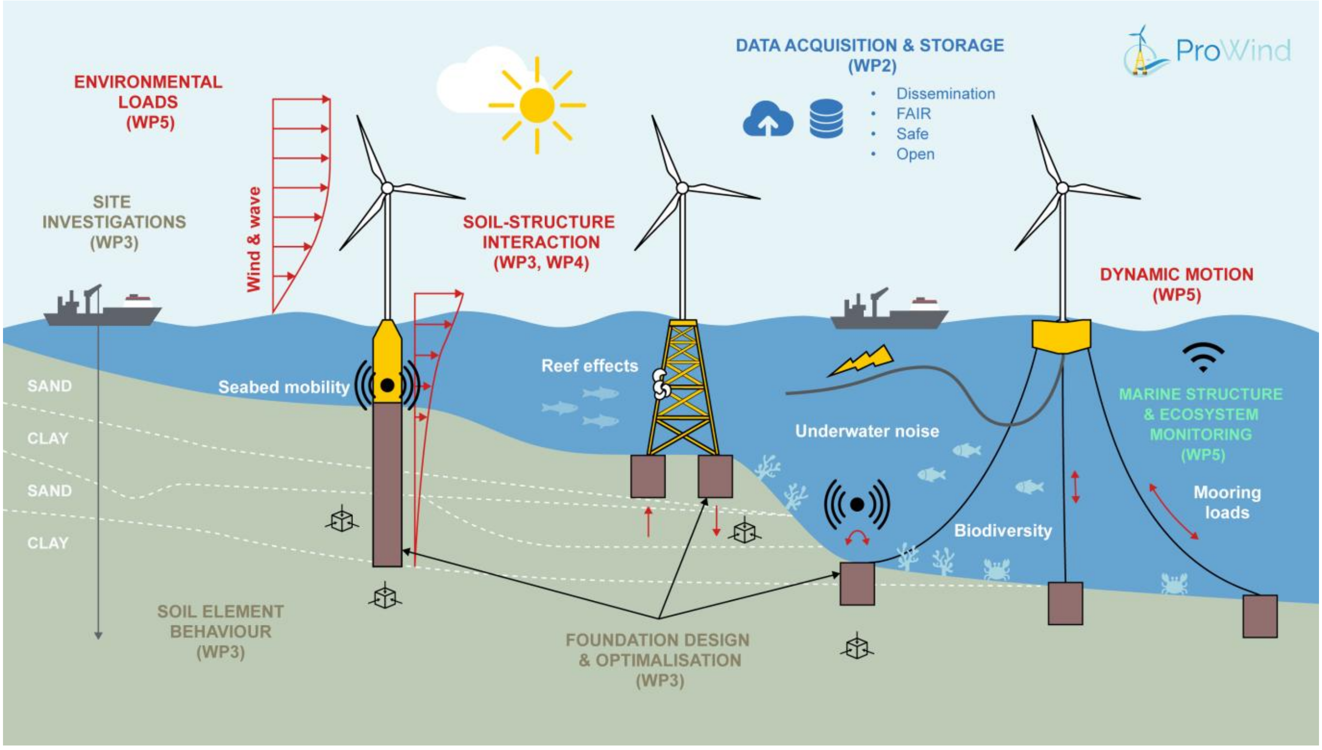

Figure 3. Overview of ProWind focus areas and experimental nodes (under development by work packages WP3-WP5).

To address the challenges for offshore wind developments associated with e.g., effects of long-term multi-directional cyclic loading, seabed scour and trenching, cluster arrangement etc. (see section 2 Background) this experimental node will encompass advanced geotechnical laboratory equipment and facilities for physical model testing in controlled environments. Soil element behaviour characterisation capabilities include:

- X-ray radiography and computed tomography (CT) of geotechnical and geologically challenging seabed samples;
- A state-of-the-art advanced Hardin Type Resonant Column (RC) Apparatus for soil stiffness and damping characterisation;
- A state-of-the-art, flexible and interchangeable Hollow Cylinder Torsional Shear Apparatus (HCA) and cyclic triaxial testing system from GDS (GDS Instruments, UK). This enables drained and undrained cyclic soil parameter definition;
- A Direct Simple Shear devices for single (DSS) and multi-directional (MDSS) cyclic soil parameter characterisation.

Laboratory physical model testing will enable ProWind to link fundamental soil behaviour to down-scaled foundation system performance and integrity, with capabilities that will include:

- Norway's first geotechnical centrifuge (Broadbent-Genesis Geotechnical Beam Centrifuge, radius 0.75 m) delivering accelerations to 300g with a capacity of 6 gT (Figure 4), and;
- Soil bins with a state-of-the-art multi-directional load actuator suit for instrumented physical modelling experiments in clay environments.

Figure 4. Example of the Broadbent-Genesis GT6 Centrifuge (Thomas Broadbent & Sons LTD, UK.).

Example infrastructure applications include the characterization of challenging soil conditions and cyclic behaviour of unconventional soil, such as transitional soils and silts, frequently encountered at nearshore wind energy sites. Figure 5 shows that under very similar one-way undrained cyclic triaxial loading conditions, two specimens from a North Sea offshore wind site, including a low plasticity silt specimen (plasticity index, I_P = 7%, and post-consolidation water content, w_c = 23.4%) and a low plasticity clay specimen (plasticity index, I_P = 12%, and post-consolidation water content, w_c = 22.5%), show distinct and very different behaviour. The silt specimen exhibits a higher rate of axial strain (ε_a) development than that of the clay specimen. This is evident both during the initial application of the average shear stress ($\tau_{avg} = 0.5\text{-}0.6s_{uC}$, where s_{uC} is the undrained shear strength in triaxial compression of the reference monotonic test) and throughout the subsequent cycles (N) of loading applied at a constant single-amplitude cyclic shear stress $\tau_{cy} = 0.5\text{-}0.6s_{uC}$. Normalised excess pore pressure ($2\Delta u/[\sigma'_{ac}+\sigma'_{rc}]$, where $p' = (\sigma'_{ac}+\sigma'_{rc})/2$ is the mean effective stress after consolidation) also differs significantly between the two materials. The silt specimen exhibits an immediate tendency towards dilation upon compression loading in the first quarter of each cycle, a response opposite to that of the clay specimen, and fails in average axial strain, ε_{avg} >10% after 8 cycles. These contrasting results shows the complexity and variability in unconventional soils and highlight the importance of robust cyclic testing programmes, behavioural frameworks and databases for transitional soil types. Leveraging advanced infrastructure for element-testing and small-scale soil-structure experiments such as that offered by ProWind provides valuable opportunities for detailed investigations at the master's, PhD, and post-doctoral research levels.

4.2 Mobile node

The third model scale provided by ProWind is the physical model testing for in field environments, provided by the Mobile node. This experimental node provides an accessible state-of-the-art load actuator and monitoring system for onshore field scale experiments, concept development and investigation of geotechnical innovations using e.g. the NGTS sites (Gundersen et al., 2019; Blaker et al., 2019 L'Heureux et al., 2019; and Quinteros et al., 2019), or other onshore field test sites. The load actuator will be designed as a flexible and mobile device enabling testing using a range of monotonic and cyclic load histories, multi-directional loading and easy relocation. Moreover, an instrumented full-scale suction bucket is available for deployment offshore (Figure 6). This equipment specifically enables evaluation of offshore wind anchor performance and an improved understanding of suction-assisted installation processes in challenging soil conditions. With a skirt length of 11.0 m, an outside diameter of 9.5m and a wall thickness of 60 mm, the suction bucket is equipped with a comprehensive suite of instruments to monitor installation and soil-structure interaction. The pump skid can include reference frame for external penetration measurements, echo sounder for determining seabed clearance and soil plug level, scanning sonar for profiling the soil plug, total pressure sensors for measuring differential and injection pressures, electromagnetic pump flow meters for pump monitoring, and multiple cameras to observe pump skid functions, water discharge, and sling operations. The bucket itself carries auxiliary instrumentation, including pore pressure sensors along the skirt wall, fibre-optic strings for buckling strain measurement, and ventilation hatches to extend the operational weather window.

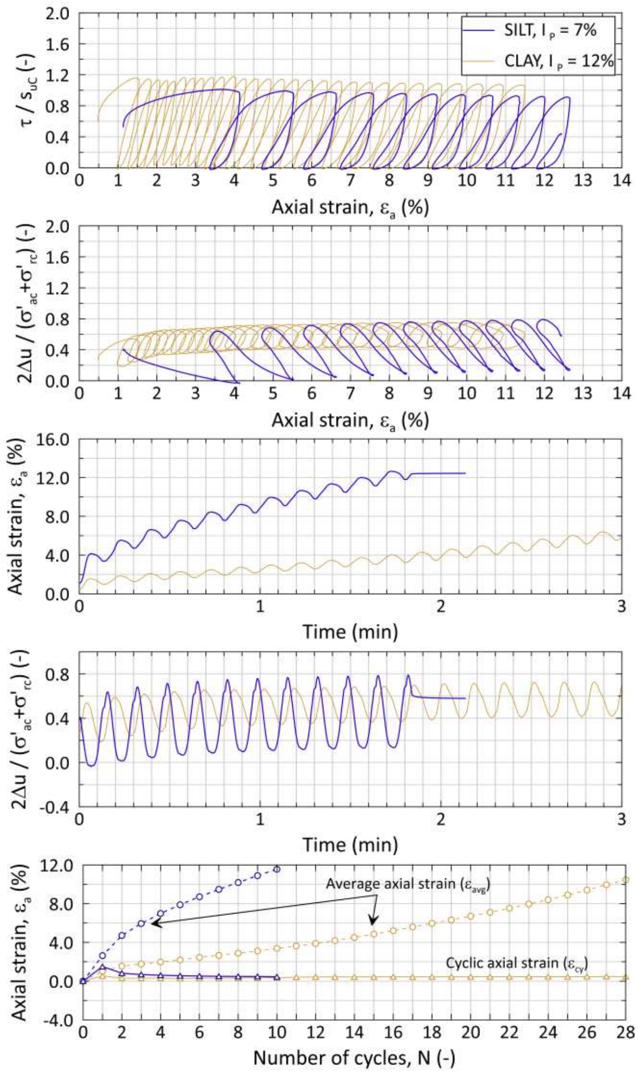

Figure 5. Example of differences in axial strain and pore pressure development in one-way undrained cyclic triaxial testing (CIUcy) on North Sea silt and clay specimens with similar normalized average and cyclic shear stress amplitudes (τ_{avg}/s_{uC}, τ_{cy}/s_{uC}).

Figure 6. Full-scale suction bucket with a skirt length of 11.0 m, an outside diameter of 9.5 m and a wall thickness of 60 mm, equipped with a comprehensive suite of instrumentation for installation assessment studies (Photo: NGI).

4.3 Offshore environment node

The fourth model scale is the instrumentation and monitoring suites provided by the Offshore environment node. It develops state-of-the-art instrumentation and monitoring equipment for offshore wind structures, marine environment and ecosystem responses. Structural retrofit instrumentation and metocean monitoring packages can include e.g. accelerometers, inclinometers, strain FBG gauges, subsea motion recorders, and wave height and direction radar. Few examples of full-scale monitoring of offshore wind structures are available and generic instrumentation packages for this purpose can avoid one-off and project specific design, reducing cost for research projects and stakeholders in need of valuable monitoring data. Example data from an instrumentation and monitoring system for offshore wind is presented by Schonberg et al. (2017) for Ørsted Wind Energy's site Borkum Riffgrund 1 (BKR1) in the German sector of the North Sea. The proof-of-concept Suction Bucket Jacket (SBJ) at the BKR1 site included a 370 ton steel jacket resting on three instrumented 8×8 m steel suction caissons installed in predominantly sand with relative density in the range of D_r = 70% - 100%. The structural monitoring system provided by NGI included: 1) wave height radar on the transition piece (TP); 2) differential pore pressure sensors under the lid and inside and outside the skirt; 3) skirt strain gauges, bucket forces in 6 degrees of freedom (DOF), inclinometers and accelerometers on the bucket lids and TP. The monitoring system and collected data demonstrated the as-installed response of the SBJ to loading, including long term behaviour of the structure, vertical stiffness response, load transfer along the bucket skirt and the variation of pore water pressures. Access to offshore wind structures is essential for collecting high-quality data, and through ProWind's partnership with the METCentre, researchers can gain access to a unique offshore test site. The METCentre, located in the North Sea west of the Norwegian island of Karmøy on the west coast of Norway, is in immediate proximity to the Norwegian Utsira Nord offshore wind lease and currently hosts two floating turbine demonstrators. The Unitech Zephyros (formerly Equinor's "Hywind demo", see Skaare et al., 2015) was the world's first offshore floating wind turbine when it was installed in 2009. The TetraSpar Demonstrator floating wind turbine (Borg et al., 2020), see Figure 7, is a demonstration project partnership between Shell, RWE, TEPCO Renewable Power, and Stiesdal Offshore, and has been operational at the site since 2021. In 2023 the MET Centre secured four additional licences, increasing its total capacity to 85 MW, and obtaining a 66 kV grid connection licence. As of May 2025, Norwegian developer Odfjell Oceanwind and American company Aikido have secured two these sites. As a national research infrastructure, ProWind can provide unique opportunities to instrument and monitor demonstrators at the METCentre or other offshore sites, strengthening offshore wind energy research.

Effective ocean management also requires integrated and sustainable ocean observing systems enabling biodiversity mapping and understanding ecosystem properties and the effects of anthropogenic intrusion. Norway's national approach to marine monitoring for offshore wind is currently being defined; and is expected to largely mirror practices in neighbouring North Sea countries. This would track a broad suite of indicators such as biodiversity, underwater noise, contaminants, and hydrography, alongside specific elements like invasive species and carbon storage impacts (See Watson et al. 2025 for a review). The scope is expected to include seabirds, pelagic biodiversity (fish, marine mammals, plankton), benthic habitats, and key oceanographic parameters with threatened species and habitats a focus while commercial and ecologically important species, groups and habitats will also require monitoring. In ProWind, an autonomous surface vehicle, vertical-profiling oceanographic mooring, and instrumented seabed landers make up a complementary and comprehensive environmental and ecosystem research infrastructure. Planned sensors and equipment include e.g. echosounder, and multi-beam, camera, CTD (temperature, salinity, pH, chl a, turbidity, visual particle sensor), environmental DNA samplers, acoustic doppler current meter (ADCP) and multidirectional hydrophone. The aim is for these tools to provide high spatiotemporal resolution and high-quality semi-autonomous marine ecosystem and biodiversity monitoring. Altogether, the Offshore Environment node importantly allows for observation of foundation system response and impact of their physiochemical intrusion to the marine environment and ecosystem at the METCentre, but will be of high relevance for other offshore wind test and development sites.

To direct effective national environmental and ecosystem monitoring, and to deepen understanding of floating offshore wind impacts and needs for mitigation, highly specialized research is required in several key areas. Priorities for research (NVE 2024; Watson et al. 2025) include understanding wake effects on primary productivity and food web dynamics, as altered flow patterns may influence nutrient transport and plankton communities (Zampollo et al. 2025). Noise impacts on fish behavior and physiology are another critical gap, particularly regarding chronic exposure during operation and cumulative effects with other stressors (Svendson et al. 2022). Additionally, seabed disturbance from turbine foundations and cable installation raises questions about long-term changes in benthic habitats, sediment stability, and consequences for blue carbon reporting (Li et al. 2023). ProWind infrastructure will be directly applicable to each of these key knowledge gaps and will provide an opportunity for in situ research that will improve engagement and education across the sector and both in national and international academia.

5 ACCESS, USE AND DATA MANAGEMENT

ProWind will operate under a structured, tiered access model to ensure utilization and broad accessibility for 1) training and educational users, 2) research users, and 3) external and industry users. Depending on user, equipment type and project, both supervised use with predefined experimental protocols, independent operation (following certification) with more custom experimental protocols, and project-based access under service or collaboration agreements will be possible. All work conducted within ProWind using RCN funding will be made publicly accessible. Data and information generated through the infrastructure‘s experimental node will be managed and stored in the ProWind platform (ProWind Cloud, available from 2027). The ProWind Cloud provides user access control and secure, FAIR-compliant (Wilkinson et al., 2016) data storage and sharing aligned with European Open Science Cloud requirements. Metadata standards enable reproducibility and data reuse. The platform is designed to facilitate dissemination and promote cohesion of high-quality geotechnical and environmental monitoring data both in Norway and internationally. To further strengthen engagement and knowledge exchange, ProWind will host annual international workshops, and public authorities, academia, research groups, contractors, consultants, and developers across the offshore wind industry are encouraged to actively use the infrastructure, improving collaboration, data and information sharing across the public, academic, and private sectors.

6 CONCLUSIONS

Offshore winds continued expansion into deeper waters, larger turbines, and more demanding environments places increasing demands on foundation performance, reliability, and cost. Geotechnical uncertainty remains one of the dominant contributors to project risk and conservatism in foundation design, while significant knowledge gaps persist in ecosystem properties and the effects of anthropogenic intrusion. ProWind addresses these challenges by establishing an integrated research infrastructure focused on advancing foundation and anchor technologies and improving understanding of environmental effects associated with offshore wind. By combining laboratory facilities, mobile field-scale testing capabilities, and advanced offshore monitoring systems, the RI strengthens national research capacity and competence, supports innovation across academia and industry, and provides high-quality open data essential for development of robust design and environmental assessment methodologies. As offshore wind deployments accelerate, ProWind will play a central role in reducing uncertainty, improving foundation behaviour understanding, and enabling sustainable growth that supports future energy and biodiversity goals.

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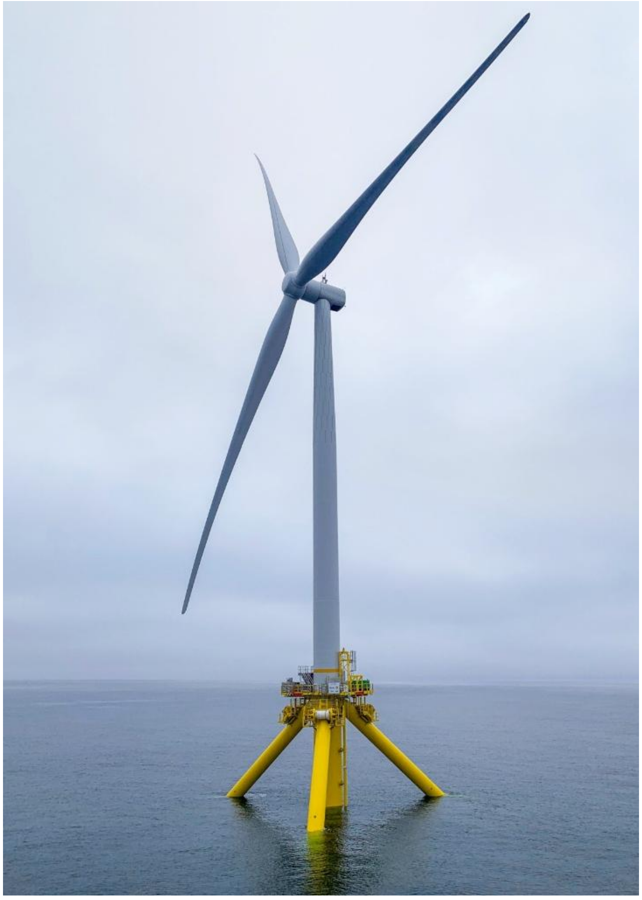

Figure 7. The TetraSpar Demonstrator, moored at the MET Centre with three anchor lines in 200 meters water depth (Photo: Stiesdal Offshore).

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