Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

First Steps towards Sustainable-by-Design Anchors for Floating Offshore Wind

Aligi Foglia*
Norwegian Geotechnical Institute NGI, Oslo, Norway

Zefeng Zhou, Yufei Wang, Oscar Polania
Norwegian Geotechnical Institute NGI, Oslo, Norway

David van den Berg, Christian Linde Olsen
Subsea7, Stavanger, Norway

Benjamin Cerfontaine, David White, Susan Gourvenec
University of Southampton, Southampton, United Kingdom

Miguel Cabrera, Ken Gavin
Delft University of Technology TUDelft, Delft, Netherlands

Athanasios Kolios
Technical University of Denmark DTU, Lyngby, Denmark

Noor Laham
Subsea7, Paris, France

**aligi.foglia@ngi.no (corresponding author)*

ABSTRACT: The Horizon Europe research project TAILWIND aims to advance station-keeping system technologies for floating offshore wind farms. This paper marks the first steps in the project putting forward economic, environmental, and technological key performance indicators to assist the selection and development of anchors. Scenarios in terms of location, soil profile, and floater are defined. Anchor loading histories are obtained through coupled load simulations and used to design typical anchors. Key performance indicators describing three sustainability aspects – economic, environmental, and technological – are proposed to assess the industrial feasibility of each anchor type. The study has two outcomes. Firstly, sustainability key performance indicators that can guide the selection of anchor technologies for future floating offshore wind development are proposed. Secondly, guidance on the most promising anchor for further development via experimental testing and numerical modelling within the TAILWIND project is provided.

Keywords: Floating offshore wind, sustainable-by-design foundations, anchors

1 INTRODUCTION

TAILWIND is a four-year research project on station-keeping systems for floating offshore wind (FOW) turbines funded by the European Union under the Horizon Europe programme. The project mandate is to advance station-keeping systems and mooring line technologies while exploring the impact of these on society and the environment to create sustainable-by-design station-keeping systems.

In the last decades, many anchors for temporary or stationary floating offshore oil and gas (O&G) structures have been deployed. FOW poses new challenges such as the requirement for many structures with multiple anchor points, as opposed to one-off O&G structures, and also the need for solutions that combine scalability, social acceptance, and low environmental impact. Recent state-of-the-art reviews on anchors for FOW highlight the need for methodological and technical innovations to meet the future market demand (Cerfontaine et al., 2023; Catapult, 2024; Xu et al., 2023).

The goal of this paper is to set out a framework that enables the selection of sustainable-by-design anchors for a given FOW scenario, accounting for societal, environmental, technological and economic impact, to guide the TAILWIND innovation activity that is further advancing anchor technology. In the following, the design loads for five scenarios are first established and typical anchors are sized using current methods. Each anchor solution is then ranked by different metrics to conduct an industrial feasibility assessment.

2 SCENARIOS

Five scenarios were selected for the anchor design assessment, which vary in reference location, floater and mooring types, and mooring line material. Simulations were undertaken to determine the design loads associated to each scenario, as outlined in the section below. Fuller details can be found in the report TAILWIND (2024a).

2.1 Reference locations and soil parameters

Reference locations define the water depth, soil profile and metocean conditions. In TAILWIND two reference locations (RLs) were selected for the load simulations: RL1 – Utsira Nord with 265 m water depth, and RL2 – Provence Grand Large with 100 m water depth (see Figure 1). The soil profiles were based on cone penetration test results of the sites found in the literature (e.g. Lunne et al., 2006) but were simplified to provide analyses that are distinct in considering only sandy or clayey soil. RL1 has three normally consolidated clay layers with soil sensitivity, S_t = 3, adhesion factor, α = 0.5, and plasticity index, I_p = 20%. The profile in terms of triaxial compression undrained shear strength, s_{uC}, and cone resistance, q_t, is given in Figure 2a). RL2 has three sand layers with interface friction angle, δ = 29°, and friction angle, ϕ = 28°, 33°, and 37° for the three layers respectively. The profile in terms of relative density, D_r, and cone resistance, q_t, is given in Figure 2b).

2.2 Load simulations

Coupled aero-hydro-servo-elastic simulations using metocean conditions of RL1 and RL2 with the software OrcaFlex were run with the IEA Wind 15 MW reference wind turbine (Evan et al., 2020). The anchor was considered as a pinned support.

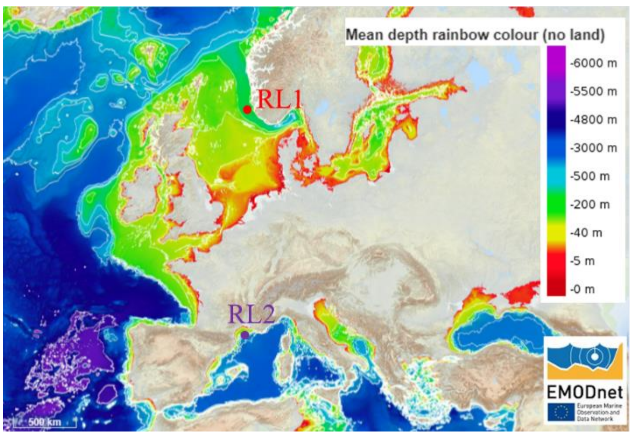


Figure 1. Mean water depth map taken from EMODnet (European Commission, 2024) with indication of Reference Location 1 (RL1) – Utsira Nord – and Reference Location 2 (RL2) – Provence Grand Large.

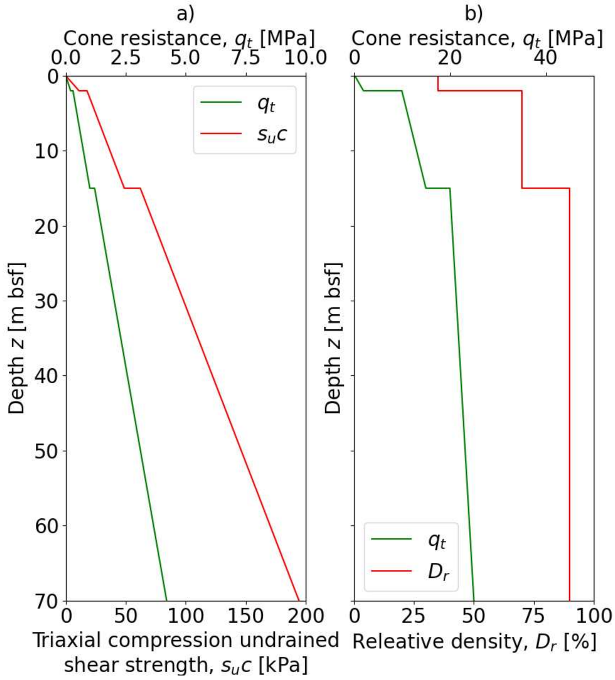


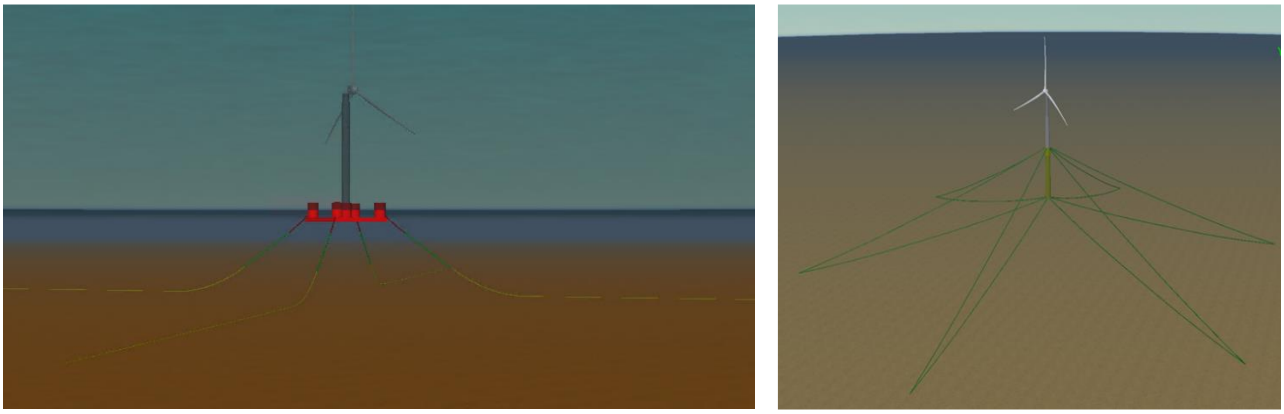
Figure 2. Principal soil properties of a) RL1; b) RL2.

Two FOW platforms and mooring systems were simulated (see Figure 3):

1. Semi-submersible (Semi-sub) of the project partner NAUTILUS featuring a semi-taut system with 4 hybrid chain and polyester mooring lines;
2. Tension Leg Buoy (TLB) of the project partner TECNALIA featuring a taut mooring system with hybrid steel and Dyneema® mooring lines and 12 anchors distributed over 6 mooring line directions;

The scenarios considered are defined in Table 1 together with their design tension, T_d, and loading angle relative to horizontal, β. Out of consistency, the labels of the scenarios follow those of the main project deliverable (TAILWIND, 2024b). The T_d of Scenario 7 is larger than that of Scenario 3, even though RL2 is in the Mediterranean, where the metocean conditions are less severe than at RL1 in the North Sea. This is the result of shallower water in RL2 that requires lower floater excursion limits (for dynamic cable integrity) and therefore stiffer moorings. Also, the wave length in RL2 nearly matches the floater's diagonal length, causing significant pitching and consequently high peak loads. The TLB loads are very large as it is a mooring stabilised system, which will be optimised in the next phases of the TAILWIND project. These results represent upper bound anchor loads for a 15 MW FOW turbine. Scenarios 3b and 10b are slight modifications of Scenarios 3 and 10 to allow for shared anchors. The load on the shared anchors was calculated vectorially after Fontana et al. (2018).

The load on shared anchors (scenarios 3b and 10b) is only slightly smaller than or even exceeds that of equivalent single anchors.



a) b)

Figure 3. Floating platforms adopted for the load simulations: a) Semi-submersible (Semi-sub) – four anchors and four mooring lines; b) Tension leg buoy (TLB) – Twelve anchors and twelve mooring lines over six directions.

Table 1. Summary of design tension T_d and loading angle relative to horizontal at touch down β for semi-submersible (Semi-sub) and Tension leg buoy (TLB).

Platform	Site / Mooring concept	Scenario	T_d [MN] / β [deg]
Semi-sub	RL1 / Semi-taut	3	12.2 / 6.0
		3b*	11.7 / 7.6
	RL2 / Semi-taut	7	20.3 / 9.6
TLB	RL1 / Taut	10	35.2 / 23.7
		10b*	38.7 / 13.6

* Shared anchors

This observation contrasts in part with previous similar studies where the loads on shared anchors were seen to decrease compared to equivalent single anchors (Fontana et al., 2018; Catapult, 2024). This discrepancy can be ascribed to:

(i) mooring type – the vertical component of taut and semi-taut systems on a shared anchor is additive (while horizontal components may cancel each other) and

(ii) mooring line layout and orientation — four mooring line directions each spaced at 90° have less load compensation potential than three mooring line directions each spaced 120°.

As shown in Section 4, and recently confirmed by Coughlan et al. (2025), the higher cost for a larger anchor is outweighed by the need of less anchors.

3 ANCHOR DESIGN ASSESSMENT

The preliminary anchor design assessment was limited to the five DNV-certifiable anchor types shown in Figure 4. Conventional design methods and ULS material factors stated in DNV (2021) were adopted. Table 2 summarises the resulting anchor dimensions for all five scenarios. It can be observed that:

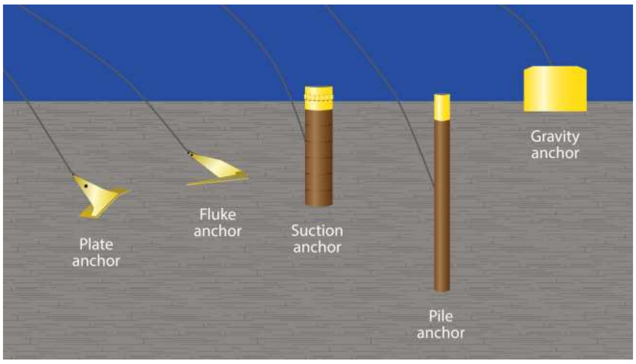


Figure 4. Anchor types considered in the assessment.

- Not all five anchors were suitable for each scenario. For instance, gravity anchors in normally consolidated clay (RL1) or fluke anchors for taut moorings (Scenario 10) were excluded;
- As expected, suction anchors are not efficient in sandy soil (RL2) due to the aspect ratio constraint – embedded length to diameter limited to slightly larger than one – in coarse grained materials;
- Given the dimensions of plate anchors – surface area exceeding 50 m^2 – and the proof loading required for fluke anchors for the large design tensions involved, installation of fluke and plate anchors may not be currently feasible;
- Gravity anchors were assumed to be iron ore filled steel boxes. Other solutions involving precast concrete or clump weights may be more efficient but were not considered as too design-specific.

The reader is referred to TAILWIND (2024b) for more detailed explanations on the design procedures.

4 INDUSTRIAL FEASIBILITY

The main TAILWIND proposition is that social, economic, environmental, and technological sustainability must be fulfilled for a given anchor to be industrially optimal.

Table 2. Overview of the anchor dimensions designed for each scenario, see TAILWIND (2024b) for full details.

Scenario	**Anchor Type**	**Diameter [m]**	**Width [m]**	**Length [m]**	**Wall thickness [m]**	**Dry Weight [t]**
3	Suction anchor	5	-	16.5	0.04	97
	Pile Anchor	3.4	-	32	0.05	132
	Plate Anchor	-	5.5	8.5	0.1	37
	Fluke Anchor (MK6)	-	8	9	-	35
3b	Suction anchor, shared	5	-	17	0.04	100
	Pile anchor, shared	3.4	-	29	0.05	120
7	Suction Anchor	12	-	11	0.06	287
	Pile anchor	3.4	-	24	0.05	99
	Gravity Anchor*	-	20	20	-	727
	Plate Anchor	-	5.2	8.1	0.1	33
	Fluke Anchor (MK6)	-	8	9	-	40
10	Suction Anchor	7.5	-	23	0.05	249
	Pile anchor	4.3	-	46	0.05	246
	Plate Anchor	-	8	12.4	0.1	79
10b	Suction Anchor, shared	8	-	23.5	0.05	273
	Pile anchor, shared	4.3	-	50	0.05	341

* Dry ballast weight 7982 t

In the following sections, key performance indicators (KPI) that express the proposed four dimensions of sustainability are described. KPI estimations are based on a floating wind development with 33 turbines. The number of anchors per turbine is reduced by 20% for Scenario 10b – 9.6 anchors per turbine for Scenario 10b instead of 12 for Scenario 10 – and by 40% for Scenario 3b – 2.4 anchors per turbine for Scenario 3b instead of 4 for Scenario 3. These are conservative estimations based on layout simulations for 33 turbines. As a mean of comparison, the only shared anchors installed so far in the FOW industry is Hywind Tampen which features an average of 1.7 anchors per turbine for a 3-line mooring system (Catapult, 2024).

4.1 Social sustainability

Local communities and supply chains must profit from the production and deployment of FOW technology to maximise the benefits of the energy transition. An analysis of regional socio-economic development including spatial organization of labour at both international and inter-regional scales allows detailed analysis of social sustainability. In this initial study, a simplified approach was used: the fabrication, logistics and installation costs of anchors for RL1 produced in three different locations - China, Norway, and Spain – were compared. Spain was selected as the best compromise of supporting the European supply chain and also limiting costs and emissions. This analysis was limited to RL1 but Spain as the production country was adopted as reasonable also for RL2. According to a global supply chain study (ERM 2024), Spain is the fabrication location with the lowest cost for a destination port in Stavanger.

4.2 Economic sustainability

The costs of all relevant project phases must be optimised to assure reliable anchor supply at the required volume scale. This is expressed by KPI_1 – Cost of fabrication, installation, and logistics – and KPI_2 – Site investigation effort. A cost model provided by the project partner Subsea 7 is used to estimate KPI_1. Logistics comprises the cost of transportation and marshalling with assumptions of type of equipment and timing for moving, loading, and offloading operations as well as storage. Installation costs are estimated by selecting realistic vessels in terms of day rates and number of vessel days considering also the necessary equipment to install the anchors. The site investigation effort is a function of the anchor depth and the number of anchor locations (adapted where required, to allow for shared anchors).

4.3 Environmental sustainability

The industrial environment during anchor fabrication and transportation, and the marine environment during anchor installation and operational lifetime must be protected. This is expressed by KPI_3 – Material sustainability – and KPI_4 – Impact on marine environment. KPI_3 is expressed as a function of material efficiency – i.e. the ratio between design tension and dry tonnage – and the decommissioning and recycling potential.

KPI_4 is a function of the disturbance to the benthic zone and the installation noise.

4.4 Technological sustainability

A given anchor must have been through enough tests and offshore deployments so that the risk of installation refusal and failure during operation is sufficiently low. KPI_5 was devised to express this principle and is a function of the general technology readiness level and the specific installation risk associated with FOW development. For instance, installation experience of plate anchors does not exist in sand, which results in a relatively small KPI_5 for such systems in Scenario 7.

4.5 Results

An evaluation matrix for each scenario is obtained by using the Weighted Sum Method, which is a formal multi-criteria decision analysis technique (Kolios et al., 2016), through the KPIs described above. To articulate and diversify the final scoring, four sets of weightings were defined:

- Set 1 – All weights are equal;
- Set 2 – Focus on economic sustainability;
- Set 3 – Focus on environmental sustainability;
- Set 4 – Focus on technological sustainability.

The evaluation matrix of Scenario 3 and 3b is shown in Table 3 as examples. It is seen that shared suction anchors have consistently the best scoring across the different weighting sets. Pile anchors score poorly, mostly for environmental reasons – installation noise and low decommissioning and recycling potential. Impact-driven piles were assumed in this analysis. The adoption of vibratory-driven piles would increase the score when the focus is on environmental sustainability. Plate and fluke anchors score poorly for Weighting Set 4. Even though these two anchors, and especially fluke anchors, have been widely used and therefore feature high technology readiness level, the current lack of experience and equipment suitable for large scale FOW developments, prevent them to excel despite their notably high geotechnical performance.

An overview of the average scoring over the four weighting sets and associated standard deviation of each anchor in all five scenarios is given in Figure 5. The bars of Scenario 3 and 3b reflect what was observed in Table 3 – i.e. the shared suction anchor scores best and consistently across the weighting sets while piles are penalised for their environmental impact. In Scenario 7, plate and fluke anchors score best but their standard deviation is high due to the technical uncertainty for installation in sand for plate anchors and lack of capable vessels for fluke anchors. Had shared piles been considered in Scenario 7, they would likely reach the score of plate and fluke anchors. Furthermore, plate anchors score best where the loads are largest (Scenario 10 and 10b) due to their high geotechnical bearing capacity performance.

Table 3. Evaluation matrix for Scenario 3 and 3b.

Anchor type	Weighting			
	Set 1	**Set 2**	**Set 3**	**Set 4**
Suction anchor	0.80	0.68	0.75	0.90
Pile anchor	0.48	0.49	0.29	0.74
Plate anchor	0.68	0.67	0.77	0.53
Fluke anchor	0.66	0.73	0.68	0.53
Shared suction anchor	0.87	0.92	0.87	0.88
Shared pile anchor	0.64	0.79	0.43	0.74

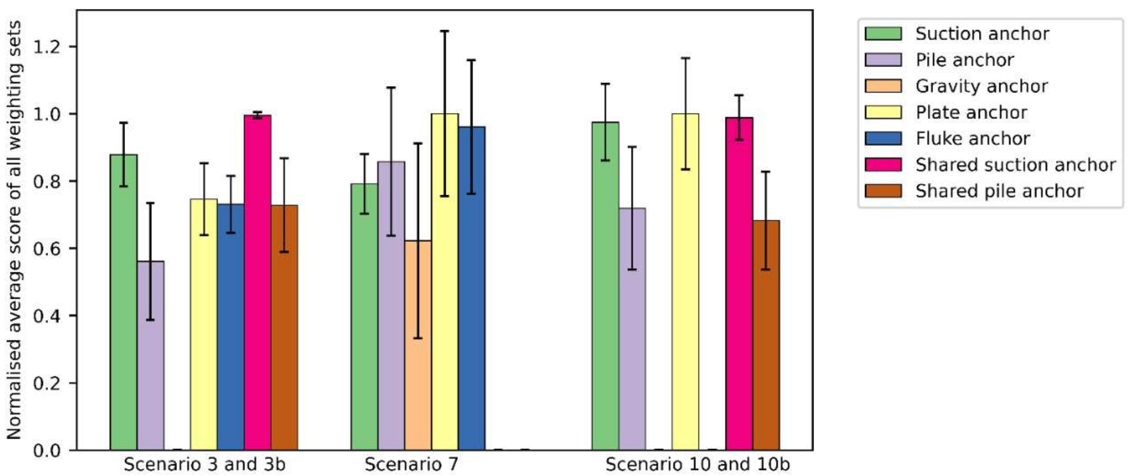


Figure 5. Industrial feasibility overview. Bars are the average scoring of all four weighting sets normalised with the highest score in each scenario. Scenario 3 and 3b are Semi-submersible at clay site, scenario 7 is Semi-submersible at sand site, and Scenario 10 and 10b are Tension leg buoy at clay site. The black error bar represents the standard deviation.

5 CONCLUSIONS

This paper proposes a first attempt to implement the sustainable-by-design principle for floating offshore wind anchor selection. Such a principle integrates the quantitative consideration of sustainability aspects along with typical design criteria such as safety and cost effectiveness towards the selection of the most suitable anchor given a scenario in terms of location, floater type, and mooring system. The paper shows how KPIs that quantify economic, environmental and technological sustainability aspects can be defined to assist the selection of anchors in five different scenarios. The TAILWIND partners are using the presented analysis to select relevant anchors for further development via both numerical and physical testing.

The main challenge encountered when creating the evaluation matrix was the quantification of KPIs for environmental sustainability. Future research activities on this topic should include: (i) improved ways to define and evaluate the KPIs, for instance by using dedicated environmental studies or probabilistic analyses and (ii) more sophisticated multi-criteria decision analysis techniques such as the order of preference by similarity to the ideal solution (Kolios et al., 2016).

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the European Commission (Grant Agreement 101136195). Pauline Suzuki is gratefully acknowledged for her essential support during the conceptualisation of the project and the proposal writing.

DISCLAMER

By presenting this work, the authors do not intend to recommend using any particular anchor type. Rather, the aim of the paper is to show a possible methodology for the selection of sustainable anchors. It should be emphasised that the final anchor selection is a function of the specifics of the given FOW development.

AUTHOR CONTRIBUTION STATEMENT

Authors from NGI, Subsea 7, University of Southampton, and DTU: Methodology, Writing Original draft, Funding Aquisition.

Other Authors: Reviewing and Editing, Funding Aquisition.

REFERENCES

Catapult (2024). Floating offshore wind anchor review. Available at: https://fowcoe.co.uk/industry-insights/reports/floating-offshore-wind-anchor-review/, accessed 19/03/2025.

Coughlan, K., Davis, M., Westgate, Z., Lee, J., Arwade, S., Martin, B., DeGroot, D. (2025). Design and analysis of shared anchor layouts for floating wind farms in deep waters. Ocean Engineering, 320, 120208. https://doi.org/10.1016/j.oceaneng.2024.120208.

DNV (2021). DNV-ST-0119 Floating wind turbine structures.

European Commission (2024). *European Marine Observation and Data Network (EMODnet)*, Available at: https://emodnet.ec.europa.eu/en, accessed: 06/12/2024.

ERM (2024). Global Supply Chain Study. Available at: https://www.norwep.com/market-intelligence/global-supply-chain-study, accessed: 15/12/2024.

Evan, G., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., and Viselli, A. (2020). Definition of the IEA 15-Megawatt Offshore Reference Wind. Golden, National Renewable Energy Laboratory. NREL/TP-5000-75698.

Fontana, C., Hallowell, S., Arwade, S., DeGroot, D., Landon, M., Aubeny, C., Diaz, B., Myers, B., Ozmutlu, S. (2018). Multiline anchor force dynamics in floating offshore wind turbines. *Wind Energy,* 21, 1177-1190. https://doi.org/10.1002/we.2222.

Lunne, T., Long, M., & Uzielli, M. (2006). Characterisation and engineering properties of Troll clay. *Proceedings of the Second International Workshop on Characterisation and Engineering Properties of Natural Soils,* Singapore. https://doi.org/10.1201/NOE0415426916.

Kolios, A., Mytilinou, V., Lozano-Minguez, E., & Salonitis, K. (2016). A Comparative Study of Multiple-Criteria Decision-Making Methods under Stochastic Inputs. Energies 9(7). https://doi.org/10.3390/en9070566.

TAILWIND (2024a). Deliverable 1.1 – Project design basis. Submitted for approval. Available on https://tailwind-project.eu/ after approval.

TAILWIND (2024b). Deliverable 3.1 – Sustainable anchor concepts. Submitted for approval. Available on https://tailwind-project.eu/ after approval.

Xu, H., Rui, S., Shen, K., Jiang, L., Zhang, H., Teng, L. (2023). Shared mooring systems for offshore floating wind farms: A review. *Energy Reviews,* 3, 100063. https://doi.org/10.1016/j.enrevrev.2023.100063