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ARTICLE

Design Basis Considerations for the Design of Floating Offshore Wind Turbines

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ABSTRACT

The wind farm owner/operator must prepare a Design Basis to facilitate the design of floating offshore wind turbines. The Design Basis is crucial to ensure that the individual elements of the wind farm are designed according to the relevant standards and the actual site conditions. In case of under-design, systematic failures can occur across the wind turbines, which can result in progressive damage to the turbines of the wind farm. This paper focuses on the safety and overall economics, including limiting potential excessive costs of heavy maintenance caused by damage due to under-design. Thus, this paper highlights critical aspects of particular importance to be implemented in the Design Basis document. Meeting all required constraints for developing offshore wind farms in deep water may result in higher costs than initially anticipated. Nonetheless, a realistic cost estimation for all phases of the project, engineering, construction, transport, and installation on site, remains essential for all engineering projects, including those involving renewable energy.

1. Introduction

Every facility development project undergoes an engineering phase and needs a Design Basis to be executed. The Design Basis document sets the framework for the project, as it contains the essential requirements and information regarding important parameters for the design, fabrication, installation, and operation phases of the facilities.

The Design Basis lists the selection of standards in every project. DNV [1] provides a comprehensible review of applicable standards, noting that the IEC 61400 series of standards [2] represents the de facto international standards for offshore wind turbines. Furthermore, standards specifically needed for the project must be listed. These requirements also include the selection of safety levels for

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the design related to safety for personnel during all phases of the project, the physical environment, and the robustness of the facilities to damage and collapse.

Furthermore, the Design Basis provides information regarding the design environmental loading in line with the selected safety level. For instance, it covers the wind, current, and wave conditions related to the selected annual exceedance probability. Additionally, the conditions of the sea floor on which the facilities are to be placed are essential information. Failing to properly assess it before commencing detailed engineering can lead to substantial cost overruns or huge damages during operations. Likewise, carefully selecting materials for the facilities is critical, as improper use of materials can quickly lead to wear and tear, corrosion, and subsequent damage. It has also recently become essential to specify all emissions from all types of facilities during their entire lifetime to gain governmental approval for the start-up of operations. The use of equipment or processes that produce toxic waste or could lead to large pollution if emitted into water or air shall be limited.

Critical design parameters for offshore wind turbines must *not be underestimated* to obtain a successful project. As the operator has to install several wind turbines in a wind farm to obtain acceptable profit from the project, a systematic failure could lead to the collapse of several wind turbines in a wind farm in a chain reaction. Selecting a Design Basis that represents an under-design could thus involve many (or all) turbines, potentially leading to irreparable damage to the wind farm.

2. The Design Basis for Floating Offshore Wind Turbines

Considerable efforts have been made to develop safe and efficient floating offshore wind turbines suitable for water depths exceeding the economic limit of fixed monopile or jacket-supported wind turbines [3,4]. Technologies applicable to such wind turbines have been developed; for example, Yang et al. [5] presented a thorough summary of commissioned floating offshore wind projects and their mooring systems, showing the versatility of the currently applied concepts. International standards [2] have been developed to ensure wind turbines are designed according to sound engineering principles.

The success of an actual wind turbine depends on its design being suitable for the *actual site conditions*. Therefore, a proper design basis must be developed by the owner and operator of all wind turbines in the entire wind farm and for the substation carrying transformers (if required).

The Design Basis for floating offshore wind turbines must cover all elements required for the fabrication, installation, and operation phases of the facilities. In recent years, the authorities have also required the Design Basis for projects to include a plan for abandonment and removal of the facilities after their intended use.

Even though authorities and operators may promote wind farm projects, a realistic attitude to costs must be the basis for decisions. The Design Basis is a document that sets the technical requirements, and the reality regarding the design conditions might disappoint the most optimistic developers. The oil and gas company Equinor announced in 2022 [6] that a wind farm is planned in the central North Sea to provide electrification of the Troll field; see Figure 1. The electricity generated was to replace the gas turbines mounted on the production platforms. One year later, Equinor announced [7] that technology was not sufficiently mature, and costs were higher than initially calculated. Therefore, the company decided to put the wind farm project at Troll on hold.

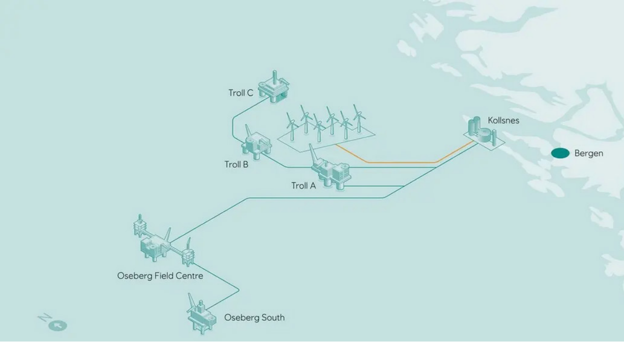

Figure 1. The planned Troll wind farm project that is put on hold, Equinor's website.

Source: Equinor Put Trollvind on Hold[7].

3. Discussion of Critical Parameters of the Design Basis

3.1 Safety Levels for the Design of Floating Offshore Wind Turbine Farms

The national authorities give the safety levels for the design of offshore wind turbines and offshore substations (transformer stations), generally building on international standards. It might be noted [8] that "for marine structures in the *offshore wind* engineering business, lower safety levels than in the oil and gas industry are specified by international standards. The set of design requirements provided by the International Electrotechnical Commission (IEC); IEC 61400 [2] ensures, however, that wind turbines are appropriately engineered against damage from hazards within the planned lifetime". One can, however, question whether the annual probability of exceedance of the environmental loading should be set to 10^{-2}, like for the oil and gas industry [9], since floating offshore wind turbines represent large investments and extreme environmental effects at present seem to occur more frequently due to ongoing climate changes. On the other hand, some authors claim that the offshore wind industry might better not adapt to the oil and gas standards, see Griffith et al. [10]. Further work is recommended to clarify the issue of how to obtain an adequate safety level in the offshore wind industry.

"It should be noted, however, that wind farms will require transformer stations, which from time to time must be manned. These substations have a considerable volume of toxic transformer oil for cooling the transformers and represent large investments. The safety level selected for the design of these substations will depend on the consequences of failure to, or loss of the stations [8]." Related to this, the actual safety level is determined by the selection of the annual probability exceedance of the environmental data and the selection of partial coefficients.

3.2 Information about the Soil Conditions at the Offshore Site

The soil conditions at the offshore site determine the design of the anchor system. For instance, in certain areas in the Norwegian Trench, the soil conditions are relatively homogeneous and consist of soft clays. In this case, an anchor system based on suction piles connected to the mooring lines can be considered. Collecting information about the soil conditions where anchors are to be placed is necessary in areas with local soil variations. In onshore projects, disputes regarding actual soil conditions often cause project cost overruns, and there should be no excuse to skip details regarding the soil conditions in the Design Basis for offshore floating wind turbines.

3.3 Data Regarding the Physical Environment

The physical environment leads to loads on built facilities. Offshore, the wind, wave, and current conditions represent large loads, and wind turbines placed offshore must be designed to resist the associated load effects. Other loads caused by snow and ice (atmospheric ice on the turbine blades and sea spray ice on the floater) must also be considered where relevant. The NORSOK N-003 standard [11] summarizes offshore actions and action effects, stating that the wind turbines must be designed to resist the loads expected for the specified annual probability of exceedance. The Design Basis must reflect the measured environmental data; however, data collection takes a long time, and available databases must be used. With the ongoing climate change, extreme weather is expected to occur more frequently than in the past. Data from databases going back in time should be considered. This should be done to consider especially extreme events adequately. Sufficient measurements of environmental conditions might be absent in areas without oil and gas developments, for example, close to the Norwegian coast. When there is a lack of sufficient measured data for environmental conditions, alternative methods should be sought to obtain physical environmental data that approximates the actual situation to reduce design risks. This may include using measurements from similar areas, simulation techniques, or other suitable methods. Additionally, it must be clear how these methods are used and referenced to effectively obtain the environmental conditions of the operating area.

Wave Conditions at the Offshore Site

The wave conditions in the North Sea and many locations worldwide are well known, and considerable databases exist. Using data about meteorological low-pressure situations and measured wave information, it should also be possible by the method of "wave hindcasting" to prepare statistics about wave conditions at most sites where offshore floating wind turbines are considered. For the Norwegian shelf, the recommendations given by NORSOK N-003 [11] for an annual probability of exceedance of 10^{-2} can be used; see Figures 2 and 3. However, the standards for offshore wind turbine design [1,2] require a design to resist environmental loading for an annual probability of exceedance of 2×10^{-2}. This means a 50-year return design wave is used for offshore wind projects rather than a 100-year return design wave that would have been applied in the oil and gas industry.

Currents at the Offshore Site

It is essential to identify the design of near-surface-current at the site where offshore wind turbines are going to be installed, as these turbines have relatively large near-surface volumes to secure sufficient buoyancy and volume for ballast (to act against tall turbines in order to secure initial stability). The forces on the anchor system might be tremendous in case of strong currents in combination with relevant wave-particle motions.

For wind turbines placed near the Norwegian coast, say within 60 to 100 km from the coast, it should be noted that The Norwegian Coastal Current (NCC) can be extremely strong. During intense northerly storms, a storm surge is created in the Southern North Sea, Skagerrak, Kattegat, and even the Baltic Sea. When the storm settles, water flows back north and can considerably enhance the NCC. Figure 4 shows coastal current whirls (eddies) on 13 April 1981 [12]. The near-surface whirls (eddies) are created as the northern flow of water becomes unstable; see also Figure 5 [13].

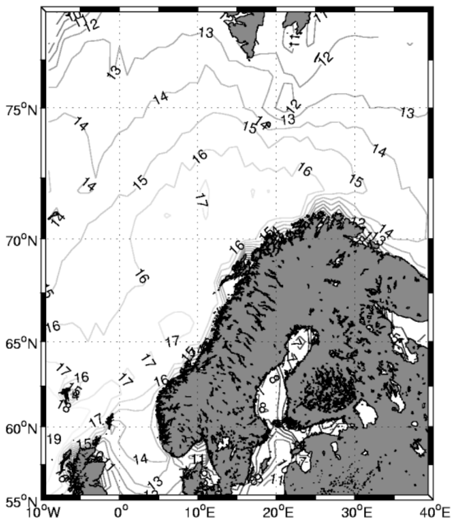

Figure 2. Significant wave height contours based on NORA10 1958-2011, corresponding to an annual exceedance probability of 10^{-2}, NORSOK.

Source: NORSOK Standard N-003 Actions and Actions Effects [11].

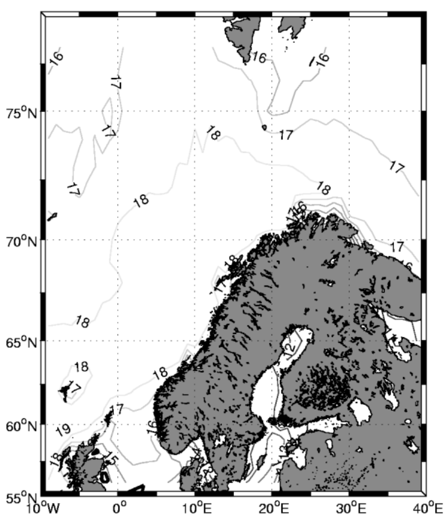

Figure 3. Spectral peak period associated with 10^{-2} annual probability significant wave height H_s: $T_p = a \cdot (1.0+H_s)^{(0.33+0.0029 \cdot HS)}$, $a = 5.8$ at N55° linear increasing to 6.6 at N78°, NORSOK.

Source: NORSOK Standard N-003 Actions and Actions Effects [11].

The Troll oil and gas field is located 65 km west of Bergen in the Northern North Sea at 60°38'44"N 3°43'35"E/60.645556°N 3.726389°E and is influenced by whirls (eddies) which expand westwards from the NCC. The water depth exceeds 300 m across the field. During the drilling of wells in the spring of 1981, there was one specific situation when very strong eddy currents occurred. The drilling rig was about to drift off location, and there were concerns that the anchor system would not hold. Supply vessels had to be linked to the rig to keep the rig in position. That was successfully done; however, an extensive research project was initiated after the event to identify the cause of the strong currents and realistic extreme values. Much of this research work was carried out at Sintef, Trondheim, under the leadership of McClimans [14,15]. The surface currents were studied in the laboratory and by numerical models to support a field measurement program. "Large bursts of coastal water with surface currents over 3 knots were observed far offshore. Laboratory studies of the dynamics of coastal currents off the west coast of Norway revealed large mesoscale eddies at an annual probability of exceedance of 10^{-2} [15]." Other locations along the Norwegian coast have also been considered by Saetre [16]. For the Troll location, the design of the current value (with an annual exceedance probability of 10^{-2}) is given in Figure 6.

One could question whether estimating this high value of the design current is correct based on one specific event and very few measurements. The argument is, however, that this value has been estimated from actual extreme data, and it is relevant to select a design basis with reference to actual events. The standard for selecting actions and action effects for oil and gas installations on the Norwegian shelf [11] requires measurements at the site to use lower values for the current; see Figure 7. For the design of offshore wind turbines, careful selection of design current values must be carried out to ensure that the mooring system can keep the wind turbines on location. It should be noted that the extreme value of the current may not be combined with the maximum waves, as extreme currents occur after a storm event, following the backflow of water after the storm surge.

Furthermore, the design value of the current will influence the design of the electric cables between the individual wind turbines [17,18] and the transformer station [19], where the electricity generated by the wind turbines is transformed from alternating current (AC) to direct current (DC) to limit energy loss during transport to shore. Functioning cables are crucial for the profit of a wind farm, and the risk of damage must be minimized. That is important to consider in the design, as repair works on cables can often only be carried out in small weather windows, meaning the wind turbines might be disconnected from the electricity grid over several months [20].

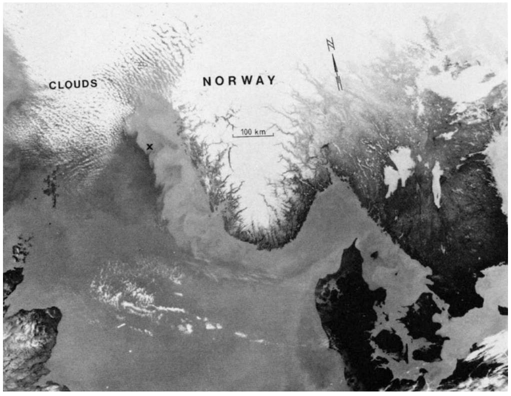

Figure 4. Satellite thermal image of coastal whirls (eddies) on 13 April 1981, McClimans and Lønseth.

Source: McClimans, T.A., Lønseth, L. [12].

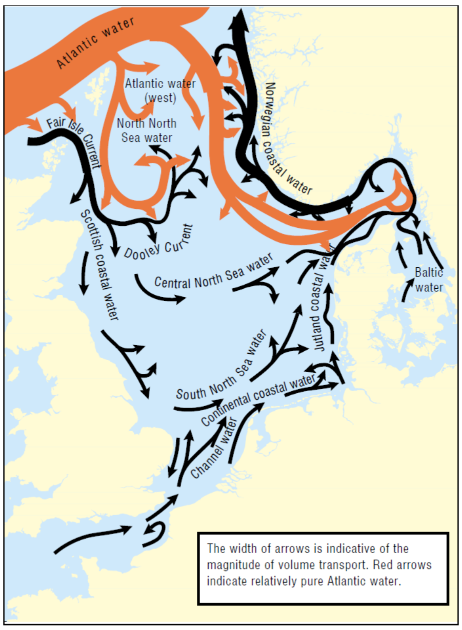

Figure 5. The general current circulation system of the North Sea, OSPAR.

Source: Quality Status Report 2000 Region II Greater North Sea [13].

Wind Conditions at the Offshore Site

In the actual marine environment, wind loads mainly come from the cyclic loads of the turbine. The economic viability of different wind fields needs to be demonstrated. The unbalanced wind load on the upper part of the tower poses a challenge to the control of the nacelle. Furthermore, there is a fire and mechanical failure risk, which requires additional analysis and description.

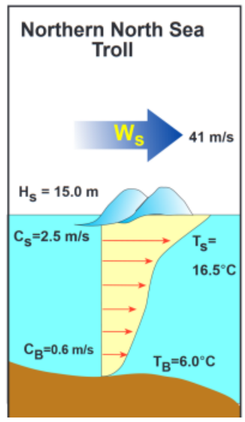

Figure 6. Design current suggested for the Troll field; C_S = surface current, C_B = bottom current, T represents the max. temperatures in the water column; note that the water depth is 300 m, Saetre.

Source: Saetre, H.J. [16].

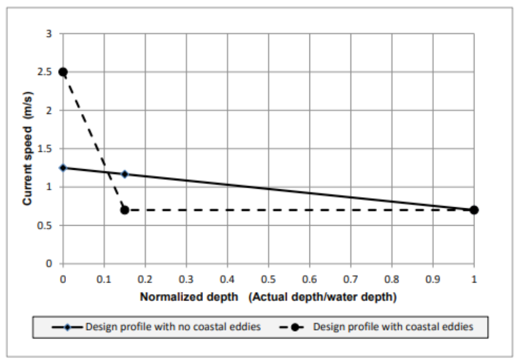

Figure 7. Preliminary total current profiles for cases when no current data is available, NORSOK.

Source: NORSOK Standard N-003 Actions and Actions Effects [11].

Ice Conditions at the Offshore Site

The presence of ice and ice sheets represents special consideration for certain areas. The floating wind turbine structures can fail under compression from the ice [21]. In some areas (e.g., in the Baltic Sea and Bohai Bay), the bottom fixed wind turbines are designed to resist these loads, and the reference is usually ISO 19906 [22]. For floating wind turbines, the potential presence of ice can represent a "no-go" whereby no floating wind turbines should be installed in the area. Ice management can be considered in the case of light ice conditions. It should be noted that vessels in ice are designed to turn up against the ice drift; this might not be possible for floating wind turbines.

Conditions of the Physical Environment at the Fabrication Site

When the fabrication site has been selected for the wind turbines, it is of utmost importance that the environmental conditions at the fabrication site are known to ensure that the design for fabrication considers the soil conditions as well as the wind, wave, current, and bathymetry at the site. While it is expected that most of the needed data is easily available, strong winds occurring during the fabrication period may cause damage and even lead to fatalities. Furthermore, the wind turbines may be moored near the fabrication dock before the float-out to the offshore site. The mooring system during fabrication must be designed for the actual conditions. The selection of safety level includes the selection of the return period for wind and wave conditions at the fabrication site and is critical. With changing climatic conditions, extreme weather is occurring more frequently, and safety during fabrication must be considered appropriately.

It should be noted that all countries will endeavour to fabricate wind turbines at local fabrication sites [23]. This can be seen as the biggest risk in the supply chain [24]. Concepts requiring wide fabrication yards will be excluded from most shipyards. The bathymetry at the construction site and along the tow-out channel to the offshore site will largely influence the concept selection. Restrictions will favor concepts that do not need a deep draft. Due to this, the deep-draft Hywind will not be given priority when operators are selecting a wind turbine concept that can be partly fabricated in drydocks and be finalized inshore in shallow waters, ready to be towed to the site with tower, nacelle, and turbine blades installed.

3.4 Use of Toxic Fluids in Wind Farm Transformers

A wind farm consisting of many individual wind turbines will generate large quantities of electricity. In order to efficiently transport the electric current to the users, the (AC) generated must be transferred to the (DC). Separate transformer stations must be installed. The wind turbines are connected to a transformer station by electric cables hanging between the wind turbines. The cables are made buoyant using buoyancy elements or routed along the seafloor. These cables will severely restrict fishing activities in the area; note that the mooring system will also do so. The transformer stations contain a significant volume of oil, up to 50 m^3 [25], for cooling the transformer. As transformer oil is generally very toxic, the pollution from the collapse of a transformer station is non-negligible. The design basis for the transformer stations must consider this fact [19]. A requirement that the mooring system shall be redundant is relevant. It is also suggested that efforts must focus on using less toxic transformer fluid or developing transformers that can better handle the heat generated through the electricity transformation from AC to DC [26].

4. Need for Adequate Insurance Cover

As wind farm operators are not necessarily organizations with large funds and may struggle to repair their assets, there is a need for proper insurance to protect the public from having to take over a malfunctioning offshore wind farm project. For onshore wind farms, the numerous failures can generally be classified as individual failures rather than systematic failures. However, there is a tendency for the gear systems to be weak, and the blades of offshore wind turbines deteriorate faster than expected [27].

For offshore wind turbines, a failure in the grouting system between the foundation and the tower has been of much concern and has caused much repair work [28]. The floating wind turbines are individually more expensive than fixed wind turbines, and a systematic error or under-design for a complete wind farm may lead to bankruptcy of the farm. Such an error can easily be caused by the collision of a drifting ship with a floating wind turbine resulting in progressive drifts throughout the entire farm [29]. For a discussion of using shared or four mooring lines to provide redundancy see Hall et al. [30].

It is, therefore, suggested that the authorities require offshore floating wind farm projects to have proper insurance to handle situations with major damage to wind turbines in the wind farm. Such a requirement will lead to the need for external verification by a warranty surveying company in all project phases to ensure that the facilities are built, installed, and operated according to specifications, the established Design Basis, and sound engineering and operational principles, like in the offshore oil and gas industry. For a full review of North Sea environmental conditions see Quante et al. [31]. The costs of insurance coverage throughout the lifetime of the floating offshore wind parks will be noticeable. However, if a company cannot afford safety, the company might have to face the costs of accidents. In civil society, insurance is required when the potential economic loss exceeds the funds of the owner. All cars must, for example, have third-party damage insurance coverage referring to their license plates, as the costs of collisions with potential personnel injury can be exceptionally high, outside the range where individuals can pay the compensation set by the juridical system.

5. Safety for Personnel Involved in the Fabrication, Installation, and Operation of Floating Offshore Wind Turbines

In addition to the structure itself, personnel safety and risks involved in the construction process are critical factors to consider for the overall operational cost of floating wind turbines. Ensuring personnel safety should be reflected throughout the entire construction and operation processes. The safety risk during the construction period should follow industry standards that are set in the offshore construction industry.

The safety of everyone involved in the operations of floating offshore wind turbines, including access for maintenance and repair, must be ensured [32,33]. The theme is highly relevant as the activities involve transfer from the ship to the wind turbine, a transfer between two moving objects often in conditions where the personnel transport vessel has considerable movements in waves [34]. A complete Design Basis will have to ensure that personnel safety is incorporated in the design of all wind farm facilities.

6. Construction Management and Installation Risk

Efficient construction management is key to the success of all construction projects. The process for a well-planned project emphasizes a detailed FEED (Front End Engineering Design) document, rigorous cost control, relevant standards and clear contracts, and company attendance at the construction site. Following the COVID-19 pandemic, some construction material has come in high demand that cannot be supplied as quickly as before, causing project delays and cost overrun. In the long term, construction and operational experience are expected to contribute significantly to reducing the levelized cost of energy (LCOE) of floating offshore wind farms [24].

Insurance companies and warranty surveyors must be involved to ensure acceptable risks during towing and installation. The consequence of carefully planned and executed installation activities might be “waiting on the weather” to carry out the marine operations. The probability of waiting for adequate weather will influence the towing and installation costs, and the marine operations must be carefully designed and planned to avoid excessive cost escalations during towing and installation.

7. Discussion and Conclusions

A discussion on the necessity to prepare a proper Design Basis for floating offshore wind turbines has been presented. The focus has been on selecting relevant standards and values of the environmental data to be used for the design. Unless safe values are selected, there is a high probability that wind turbines can be damaged during extreme weather events. Furthermore, it is emphasized that soil data for mooring system design must be available.

The findings imply that developing offshore wind farms in deep waters might increase costs. At the same time, the probabilities of damages or failures can be reduced.

The principal findings of the paper can be summarized as follows:

• The selection of data for environmental loading should be reviewed with a discussion of whether data with an annual probability of exceedance of 10^{-2} should be used, as for the oil and gas industry. The argument is that the costs of floating offshore wind turbines are very high, and under-design might involve the failure of many or all turbines in a wind farm.

• The current at the site is a major unknown, and efforts must be made to identify the value of the design current. The statistical database for selecting extreme current values may not be sufficient, and separate data collection or laboratory modeling may be necessary. The problem is, however, that extreme design currents occur very infrequently. It might be necessary to consult data archives to identify realistic values. Selecting the combination of extremely strong currents and large waves can also be necessary to design the mooring and electrical cable systems.

• The central electricity transformer station of a wind farm represents a non-negligible environmental pollution risk. Efforts should be made to reduce this risk, either by designing the transformer station to a high safety standard to reduce the probability of pollution or to reduce the volume of toxic transformer oil to minimize the consequences of an oil spill. Offshore wind farms should be prepared for oil spill clean-up operations.

• The repair costs of damaged wind turbines in a wind farm might exceed the financial capabilities of the owner of the facilities. It is suggested that insurance coverage should be mandatory to ensure that the authorities do not have to take over the responsibility to repair or remove the damaged turbines.

• The wind turbine operators shall be prepared to bear the costs of abandoning the wind farm and removing all facilities at the location.

• Given the above findings and conclusions, research efforts are recommended concerning the following:

• A review of the selection of safety levels for offshore floating wind turbines and all equipment installed in a wind farm should be conducted. That will also include robust mooring design and selection of mooring line redundancy requirements.

• Data evaluation projects related to identifying realistic values for the current are recommended for all areas opened by authorities for the development of floating offshore wind farms.

• A project should be carried out to ensure the safety of all involved in the operations of floating offshore wind turbines, including access for maintenance and repair.

Author Contributions

The first author prepared the first draft of the paper. The second author contributed with discussions of the topics and a thorough document review.

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Conflict of Interest

The authors declare no conflict of interest.

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