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Safety Indicators for the Marine Operations in the Installation and Operating Phase of an Offshore Wind Farm

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Abstract

As a measure of performance, safety indicators are already used for many types of operations, such as in the offshore oil and gas industry. The indicators are used by operators to enhance the safety and performance of the individual plants or vessels and total productivity of the system.

This paper reviews existing safety analyses of the offshore wind industry, the onshore wind industry and offshore oil and gas industries. An offshore wind farm is divided into subsystems and operational phases. Safety indicators are developed for the phases and subsystems by reviewing existing safety indicators from related industries and adapting them to the offshore wind industry. The indicators for the individual subsystems and phases are then combined to provide safety indicators for the whole wind farm over the lifetime. Finally, the indicators are matched against incident data from the offshore wind industry and an outlook for further research and indicator validation is given.

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Keywords: Safety Indicators, Marine Operations, Offshore, Wind Energy, Maintenance, Performance

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1. Introduction

Safety indicators as a measure of performance are already in place for many types of operations. Øien et al. present the theoretical background of safety indicators in [1] and their application in [2]. Safety indicators are widely used in the offshore oil and gas industry as presented e.g. by Skogdalen et al. [3] and Utne et al. [4]. Safety indicators are used to enhance the safety and performance of the individual plants and total productivity of the system. This can be achieved through proactive work preventing losses that becomes possible thanks to the indicators as stated by Pasman et al. in [5]. The indicators are also used in political discussions to have a common framework when discussing worker safety with unions. According to [6], indicators should be "complete, consistent, effective, traceable, minimal, continually improving and unbiased". When looking at safety indicators the question is not about the probability of an accident, but whether it can happen at all. Until now, indicators are used in the offshore oil and gas industry, however

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no such indicators exist for the offshore wind industry (OWI). According to Hopkins [7], safety indicators are only worth developing if they can drive improvement. A large amount of the energy costs is caused by downtime and maintenance as described by Feng et al. [8] and Scheu et al. [9]. When enhancing the performance of an OWF, it is important not to compromise safety of the maintenance personnel. Therefore safety indicators can in fact help drive the improvement of the performance of an offshore wind farm and are hence worth developing.

In this paper, we define a safety indicator as a measurable representation of a risk influencing factor [1], where the risk influencing factor is defined as an aspect of a system or an activity that affects the risk level of this system or activity, as defined by Øien [10]. The aim of this paper is to identify safety indicators for the offshore wind industry and establish a common framework for the installation and operational phase of an offshore wind park. This is done by taking a holistic approach and considering an offshore wind farm (OWF) from the beginning of installation until the decommissioning. The wind farm is divided into subsystems, according to the phase (installation, operation), technical subsystems (substations, vessels, turbines and turbine subsystems) and operations (transport of material and workers, turbine access, execution of maintenance actions). Existing analysis of the individual subsystems is reviewed, taking into account analysis from other offshore industries and onshore wind energy. Based on this review, safety indicators are developed for all the subsystems. The indicators are combined to provide safety indicators for the whole wind farm. The indicators are validated with incident data and presented in the conclusions of the paper.

The paper is structured as follows. Section 2 gives an overview over the methodology used. The OWF with all the subsystems is presented in Section 3. Section 4 reviews the existing analysis and presents the safety indicators for the different subsystems. The indicators are related to reported incident data in section 5. Finally in section 6, the paper concludes with a presentation of the developed safety indicators and gives ideas for further research.

2. Methodology

In this paper, an OWF is analysed by dividing it into different phases and subsystems. This is done by reviewing existing literature on OWFs and adapting the subsystems. Subsystems of offshore wind turbines are presented e.g. by Arabian-Hoseynabadi et al. [11] and Faulstich et al. [12].

This paper further presents a review of existing analysis in the field of health and safety in relation with the OWI. Since few publications exists specifically on the OWI, analysis from related fields namely the offshore oil and gas industry and onshore wind industry are reviewed to cover additional perspectives on the topic.

The SINTEF report on health and safety by Tveiten et al. [13], investigates among others hazards and accident scenarios for OWFs. The report on Worker Health and Safety by the Transportation Research Board [14] also investigates hazards of working on an OWF. Two reports by the G9 Offshore wind health and safety association [15,16] give an overview of incidents and accidents on OWF and provide a breakdown of the accidents according to incident areas and work processes.

Aneziris et al. [17] investigate hazards for onshore wind farms, reviewing also the database of the Caithness Windfarm Information Forum [18]. This database is regularly updated, the authors used the first 1142 reported accidents, accessing the database in 2012. Arabian-Hoseynabadi et al. [11] present annual failure rates and risk priority numbers (RPN) for the individual subsystems. Faulstich et al. [12] also give annual failure rates and consider downtime per failure for the subsystems discussed in their paper. We present the failure rates from both papers and give a comparison and discussion of the values.

For the analysis of offshore structures in the offshore oil and gas industry, we chose a paper by Skogdalen et al. [3] focusing on safety indicators for deep water drilling blowouts and a paper by Utne et al. [4] on shutdown preparedness. To cover the external factors that influence the performance and safety of an OWF, we review the work of Dai et al. [19] on the risk of collision between vessels and offshore wind turbines. Dai et al. also identify risk reducing measures which we present and discuss as well.

3. Description of the wind farm and its subsystems

When considering an OWF, the main stakeholder involved is the WF operator. The operator of a wind farm (WF) is interested in maximizing the performance of the WF in order to maximize the profits. Both downtime and

Table 1. Turbine subsystems in the two papers and their equivalences

Faulstich et al.	Arabian-Hoseynabadi et al.
generator	generator
gearbox	gearbox
mechanical break	mechanical break
yaw system	yaw system
hydraulic system	hydraulics
rotor hub	rotor and blade assembly
rotor blades	
electronic control	electrical control
electrical system	grid and electrical system
drive train	main shaft
support and housing	tower, foundation and nacelle
sensors	
	pitch control system

maintenance are expensive, so improving the performance is vital to maximizing profits. The main performance requirement for the OWF is power production. The production of power depends on the availability and operation of the WF subsystems like the turbine itself, substations and power cables. To monitor the performance, key performance indicators like the energy-based availability can be used. We do not investigate the monitoring of performance in this work. Rather we want to focus on safety indicators that enable the operator and other stakeholders (worker unions, maintenance providers) to monitor the system and worker safety, while maximizing profits with the help of key performance indicators. The analysis of the main stakeholder and subsystems corresponds to the first steps in a system engineering process [20] and our analysis could be further extended using this approach. Since we want to see the OWF through all the phases of operation, we begin with identifying the operational phases we want to investigate. Aneziris et al. describe three different operational phases in their paper [17]. These are “installation”, “commission” and “maintenance/operations”. In the SINTEF report [13], Tveiten et al. chose “installation and commissioning”, “operations”, and “maintenance” as their operational phases. To compare input from both papers, we combine the categories “installation” and “commissioning” into one phase and choose “maintenance and operations” as second phase.

The next part of our analysis will be the individual turbines as parts of the whole OWF. In their paper, Arabian-Hoseynabadi et al. [11] focus on one individual turbine and identify eleven turbine subsystems, listed in Table 1. The authors further investigate these subsystems and divide them until they reach a total of 107 parts in a wind turbine. However, the individual parts are not reported and can hence not be used here. Still, considering the eleven subsystems is already enough, when combined with the two different operational phases and additional subsystems outside the turbine. Faulstich et al. [12] identify twelve turbine subsystems as presented in Table 1. They do not divide the system into more parts and look at failure rates for these turbine subsystems. Combining the two turbine subsystems “rotor hub” and “rotor blades” discussed by Faulstich et al. makes it possible to compare the failure rates to those presented by Arabian-Hoseynabadi et al.

For the analysis of the support structure of the wind turbine, we only consider general reviews of the oil and gas industry and do not consider OWF specific structures apart from the tower mentioned above. Since offshore structures in the oil and gas industry are usually larger and have different properties than turbine structures, these analyses will not match the OWI exactly and review of different OWI specific support structures, such as monopiles, jackets and floaters should be considered for further work. Subsystems of the OWF outside the turbine include vessels, access systems, substations, cables and organizational structures. In this paper, we focus on the collisions between vessels and wind turbines, as considered by Dai et al. [19].

4. Safety indicators

In this section we present the safety indicators as described in existing literature. First we discuss hazards during the life time of an OWF, separately for each operational phase. These hazards can be translated into safety indicators by e.g. monitoring the number of incidents due to the hazards. Next, possible failures for a single turbine and its subsystems and indicators from related industries are reviewed. The failures in a turbine can be related to safety indicators, since a higher failure probability will lead to more frequent repair, which in turn enhances the likelihood of other risk factors. Finally, indicators for the risk of collision with a vessel are presented.

4.1. Hazards according to phases

The hazards according to operational phases, identified by Tveiten et al. [13] and Aneziris et al. [17] are presented for the installation and commissioning phase in Table 2. In both phases Tveiten et al. focus mainly on properties of the system, such as slippery surfaces, dangerous substances and failures in the organizational structure. Aneziris et al. however, focus their hazards on the work tasks that are carried out, like mechanical or electrical work. This difference in approach makes it difficult to compare the results. However, some hazards are being identified in both publications and named differently. Both lists recognize the danger due to the height of the turbine. This can be measured by a safety indicator measuring the number of incidents due to the identified hazards. These are "falling structure/load/object", "kinetic energy" and "potential energy" in Tveiten et al. and "contact with falling, hanging or moving objects" by Aneziris et al. The hazards concerned with marine and helicopter operations can be referenced to the hazards concerned with moving vehicles by Aneziris et al. Safety indicators can measure again the number of occurring incidents due to these hazards. External factors such as weather, are only considered by Tveiten et al. and not included in the analysis by Aneziris et al. In general the analysis by Aneziris et al. is narrower than the analysis by Tveiten et al. However, having many different indicators about dangerous working environment or distinguishing between different classes of dangerous substances as in the analysis by Tveiten at al. is not practical to monitor. A solution to this would be to group the hazards by dangerous substances together and not report the details. This leads to one safety indicator presenting the number of incidents due to contact with (hazardous) substances. The same could be done for external factors, like wind speed and direction, wave height and persistence or possibility of earthquakes. It is possible to define certain thresholds for these factors, as done by Scheu et al. [9] for wave height and wind speeds, and then only report violations of the thresholds as part of the safety analysis.

4.2. Failures in a single turbine

Reviewing the analysis of Faulstich et al. [12] and Arabian-Hoseynabadi et al. [11], we analyze a single turbine as part of an OWF. As described, the authors consider different subsystems for a turbine. They evaluate different data on the annual failure rates of turbines and conclude that the subsystems with the highest failure rates are "electrical systems", "electronic control" and "rotor and blade assembly". While both papers agree on the three subsystems with the highest failure rates, analysis differs for the subsystems with lower failure rates. Since high failure rates result in more frequent maintenance and repair actions, high failure rates increase the risk of accidents for the maintenance personnel. In a safety analysis, the stakeholder aims to monitor and consequently improve the workers safety. Since an improvement in the failure rates will lead to fewer repair actions and therefore increase the workers' safety, we suggest monitoring the failure rates as part of a safety analysis. An improvement in the turbine is most likely in the subsystems with the highest failure rates, so for a first safety analysis considering those three subsystems will be sufficient. In further development of the safety indicators, new analyses and comparison between the existing data should be considered to specify failure rates for all turbine subsystems and further validate the already existing failure rates.

4.3. Safety indicators from oil and gas industry

Skogdalen et al. [3] develop safety indicators for offshore oil and gas drilling. The indicators are summarized in Figure 3 in their paper. The indicators for operational aspects, schedule and costs can be used for the OWI just as they are for the oil and gas industries. The drilling phase in oil and gas industry can be compared with the installation phase of the WF. When looking at the "well incidents" the indicators can no longer be used and have to be adapted to the specific incidents that can occur in the OWI as presented in the G9 reports [15,16]. The indicators for the "operator well response" can again be used for the OWI, by simply changing "well incident" to "turbine incident" and "well response action" to "incident response action". The indicators concerned with the technical condition of the safety critical equipment need to be adjusted to the wind farm as well. Utne et al. [4] develop twelve indicators for shutdown preparedness in oil and gas industry. Shutdown preparedness means to schedule maintenance tasks ahead of time to fulfill them during unexpected or planned shutdown of the system. This relates to the OWI such that the maintenance has to be planned ahead and performed during weather windows that allow access to the OWF. Utne et al. consider five qualitative indicators. The number of work orders (WO) with a low man hour estimate is an indicator for poorly planned WOs. The same holds for the number of WOs missing location codes or short descriptions. The indicator measuring if the needed material and spare parts are in stock also judges how well a WO is prepared. Assessing the work scope is necessary to decide whether a maintenance job needs a shutdown to be performed. This indicator will not be useful in the OWI, since weather windows are used instead of shutdowns and maintenance is not possible without accessing the turbine. The indicators concerned with volume as presented in Table 1 in their paper can again be used in the OWI. The two indicators on utilization can also be used in the OWI. They can help to see how well the weather windows are used to perform maintenance tasks and how this impacts the future turnaround.

4.4. Collisions between vessels and turbines

Dai et al. investigate the risk of collisions between vessels and offshore wind turbines [19]. They consider four different vessel types and seven different collision scenarios in their analysis. The overall conclusion of the paper is that collisions may cause structural damage to the turbines. Therefore it is important to include the risk of collisions in any safety analysis and we take a closer look on the risk mitigating aspects presented by Dai et al. They can be monitored and the violation of rules, crossing of thresholds or lack of monitoring can be used as safety indicators. Dai et al. group their risk mitigating aspects into six groups. Considerations about the energy that can be absorbed during a collision without damaging the structure are usually made during the design phase. Depending on the location of the turbine these energies can be very low (only maintenance vessels are expected to interact) or very high (risk of being hit by oil tankers). The presence or absence of a specific boat landing structure can also be monitored as a safety indicator. If a structure is present, the damage to the turbine while landing a maintenance vessel is lower. “Vessel capability” and “crew competence” are important for mitigating risk and ensuring safe operations according to Dai et al. The capability of the crew can be measured by hours of experience or training hours. Reliability of the navigation, propulsion and control system should be high. The safety indicators should reflect the risk of a possible failure. As already stated above, the environmental conditions like sea state and wind speed need to be monitored and threshold levels established. The number of their violations can give an additional safety indicator. In the organizational part of the system, procedures and maintenance strategies are developed as well as contingency plans. Follow up analysis is conducted based on the incidents reported. For monitoring this, multiple indicators can be monitored. Procedures can be used to set the course of the vessel not directly against the turbine structure but slightly off, to avoid collision or to establish safety zones around OWFs to prevent external vessels from crashing. The violation of these procedures can be measured, either in absolute numbers of vessels entering the safety zone or in terms of the number of turbine accesses per passing vessel. Even though all these indicators have the goal to prevent collisions, Dai et al. suggest that emergency procedures should be established in order to ensure safety. The existence or the lack of such emergency procedures and evacuation facilities should also be monitored by safety indicators. Since the concept of safety indicators depends heavily on the reporting of incidents and accidents it is necessary to establish a suitable reporting system for the OWF. The compliance with the system can again be measured by indicators, when reporting the lack of incidents is requested. Dai et al. focus on turbines with monopile structures, additional analysis of collisions between vessels and other structure types like jackets or floating turbines should be considered in future work.

5. Indicators and incident data

This section reviews the incident data reports from the G9 Offshore wind health and safety association [15,16] and matches them to the indicators and hazards discussed before. In 2013 a total of 616 incidents was reported. This number rose in 2014 to 994 reported incidents. However, the lost time injuries frequency, comprised of the percentage of fatalities and lost work days in the total number of reported incidents, decreased by 34%. Therefore the authors suggest that the reporting system has improved leading to a higher number of reported incidents. This higher number

Table 2. Hazards during installation and commissioning

Type of hazard	Tveiten et al.	Aneziris et al.
Uncontrolled movement of object	Falling structure/load/object Kinetic energy Potential energy	Contact with falling objects from crane or load Contact with falling objects from other Contact with hanging or swinging objects Contact with flying object machine or tool Contact with moving parts of a machine
Transportation	Marine operations (ship collision, man overboard) Helicopter operations	Struck by moving vehicle In or on moving vehicle with loss of control
Miscellaneous	Vibration (during testing)	
Electrical dangers	Short circuit Overcharge Electrostatic phenomena (shock, spark)	Contact with electricity - tool Contact with electricity - electrical work Contact with electricity
Exposure to dangerous work environment	Fire and/or explosion Radiation Noise	Fire - working near flammables or combustibles
Indirect effects on worker health	Physiological effects due to heavy lifting, repeated movements, uncomfortable positions Psychological effects	
Uncontrolled movement of person	Work at height Slippery surfaces Base/ground failure	Fall from height - fixed ladder Fall from height - other situation Fall on same level
Exposure to dangerous material	Flammable materials Poisonous materials Harmful material Oxidizing/corrosive material Battery acid	Fire - working near flammables or combustibles
Organizational malfunctions	Insufficient/missing safety equipment Incorrect use of machinery/tools Lack of relevant expertise Several actors/companies involved in same operation Time pressure	Trapped between Contact with hand held tool by self
External factors	Wind Waves and currents Lightening Earthquake Sabotage Terrorism	

however does not automatically imply a decrease in worker safety. Following the same structure as for the indicators, we first analyze the general incidents before looking at the turbine specific incidents.

In 2013, 26% of recorded incidents were due to lifting operations including 9 incidents that lead to lost work days. In 2014 this number decreased to 14% of the total incidents, including three lost work day incidents. Lifting operations were not considered as an individual hazard in any of the reviewed analyses. The closest presented hazards were those concerned with "work at height" and "falling structure/load/object" in Tveiten et al. [13] and "contact with falling objects from crane or load/from other" and "contact with hanging or swinging objects" by Aneziris et al. [17]. In both incident data reports, incidents that occurred while working at height are listed. For 2013 a total of 45 incidents have been reported and for 2014 the number of reported incidents is 77. Working at heights contributes hence to just over 7% of the reported incidents in both years. Monitoring this risk with an individual indicator thus seems practical. Incidents due to dropping objects are listed separately in the 2014 incident data report, with a total of 93 incidents due to dropped objects, of which none cause lost work days. However, the largest part of those dropped object incidents occurred during lifting operations or working at heights. This supports the intuition, that during lifting parts or working at heights is the time when dropping occurs most frequently. Having indicators in place for those cases, as suggested by the literature, is considered to be reasonable by us. Distinguishing between different sources of falling objects as suggested by Aneziris et al., however, seems to be unnecessary. A distinction between work processes during which the dropping occurs, as done in the 2014 incident data report seems more desirable. Marine operations, with 131 reported incidents in 2013 and 237 in 2014 are accounting for more than 20% of all reported incidents in both years. This includes maritime operations, transfer by vessels, vessel mobilization and vessel operations. Out of these 106 and 167 incidents occurred on vessels, causing 7 lost work days in 2013 and 12 in 2014. In other words 10% of the lost work days in 2013 were caused on vessels during marine operations. This percentage rose in 2014 to over 25%. Monitoring the health and safety of workers on vessels during marine operations therefore seems to be an integral part of any safety analysis.

For the incidents related to specific turbine subsystems, the nacelle region accounts for 40 reported incident in 2013 and 83 in 2014. These are 6% of the reported incidents in 2013 and 8% in 2014. The nacelle region hosts most of the subsystems of a wind turbine other than the rotor. Therefore work on any of the subsystems could lead to an incident in the nacelle region. In 2013 four work days were lost in the nacelle region, one of them caused by manual handling, one by operating plant and machinery and two work days by "other" work. In 2014, four work days were lost, of which three were lost due to manual handling and one due to operating plant and machinery in the nacelle. This analysis does not give information on the subsystem that was involved in the incident. Knowing during which activity the incident occurred, gives information on how to prevent it. In other words, knowing the activity that causes incidents give an operator the chance to train workers for these situations to prevent incidents from happening. In the hub and blade area 24 incidents were reported in 2013 and 20 in 2014. These account for 4% and 2% of the reports. In both years, one work day was lost in the hub and blade area. Even though these number are not high, we suggest to survey the hub and blade assembly as an individual subsystem, due to its unique function within the turbine and the resultant unique work tasks.

The incident data report from 2013 mentions a total of 15 incidents with chemicals and hazardous substances, comprising under 3% of all incidents. In 2014 this number went down to 10 incidents (1%). This supports the previously mentioned idea to monitor several hazard categories mentioned by Tveiten et al. with one common safety indicator. These are "flammable materials", "poisonous materials", "harmful material", "oxidizing material", "corrosive material", "carcinogenic material", "material harmful to genes" and "battery acid". A suggested name for the new indicator is "contact with hazardous substances".

Categories for organizational problems or collisions are not included in the G9 incident data reports. Hence the indicators for these cannot be validated. System safety theory advises to include human error in the analysis. Therefore the authors suggest to keep the indicators for organizational failures in place. No collisions happened during the incident data recording interval and therefore no such incidents are recorded. Since a collision of a ship and a turbine has extensive consequences, monitoring the risk and possibility of such a collision seems sensible.

Two incident areas are mentioned in the data reports, where no indicators were considered in our previous analysis. The transition piece area accounts for 32 and 53 reported yearly incidents in 2013 and 2014 respectively. These are just over 5% of incidents, accounting for 2 lost work days in both years. Since this is the area where maintenance personal accesses the turbine and vessels could collide with the structure, detailed monitoring of the type of work

Table 3. List of Proposed Safety Indicators

Category	Subcategory	Indicator (*Description*)	Measure
Organizational	*For organizational safety indicators, please see Utne et al. [4], Table 1, indicators Q1, Q2, Q3, Q4, U1, U2, U3, U4, U5, V1, V2 and Skogdalen et al. [3], Figure 3, indicators for "schedule and costs", "operational aspects" and "Operator well response". For the indicators concerned with the well response, note that "Time from first indication of well incident to first response" is substituted by "Time from first indication of subsystem failure to first response" and "Evaluation of well response action" is replaced by "Evaluation of repair action/failure response action".*		
Technical failure	All turbine subsystems	Annual failure rates for turbine subsystems (*The mean number of failures per year for each turbine subsystem gives a probability of failure*).	Probability
Work Environment and Training	Lifting	The number of incidents during lifting operations (*This indicator is measured as a percentage of the total number of lifting operations performed. Incidents caused by falling objects are monitored separately and are therefore excluded.*)	Percentage
	Work at heights	The number of incidents during work at heights. (*The indicator is measured as a percentage of the total number of work actions performed at heights. Incidents due to falling objects are excluded and monitored by a separate indicator.*)	Percentage
	Falling objects	The number of incidents due to the falling of an object during any operation in the WF (*measured as a percentage of the total work actions performed*).	Percentage
	Hub and Blade	Number of incidents occurring in the Hub and Blade area of the rotor of a turbine during work actions. (*The number is given as a percentage of the total work actions in the hub and blade area and give the percentage of work at the rotor that results in incidents.*)	Percentage
	Nacelle electrical	Number of incidents caused by electrical work in the nacelle (*measured as a percentage of all electrical work actions undertaken*).	Percentage
	Nacelle mechanical	Number of incidents caused by mechanical work in the nacelle (*measured as a percentage of all mechanical work actions undertaken*).	Percentage
	Contact with Substances	Number of incidents where a worker was exposed to a hazardous substance (*measured as a percentage of total number of work actions performed in a place with possible exposure*).	Percentage
	Substation	Number of incidents occurring in the substation (*measured as percentage of the total number of work actions performed in the substation*).	Percentage
Transport and Traffic	Helicopter incidents	Number of incidents happening during transportation with a helicopter. (*This includes material and worker transportation to and from the wind farm. Given as a percentage of total transportation actions with helicopters.*)	Percentage
	Vessel incidents	Number of incidents happening during transportation with a vessel. (*This includes worker and material transportation both to and from the wind farm and is given as a percentage of total (vessel) transportation actions.*)	Percentage
	Transition piece incidents	Number of incidents during turbine access in the transition piece area (*given as a percentage of total turbines accesses in the TP area*).	Percentage
	Collisions internal	Number of vessel accesses complying with the safety procedure. (*Measures the risk of vessels, part of the WF, colliding with the turbine structure or substation by measuring the number of vessel accesses complying with a procedure, like setting the vessel course not directly at the turbine, as percentage of the total accesses to the WF.*)	Percentage
	Collisions external	Number of safety zone violations. (*The number of wind farm accesses per violation of the safety zone measures the risk of an external vessel colliding with the turbine structure or substation.*)	Percentage
	Boat landing structure	Presence of a boat landing structure. (*A landing structure improves the energy absorbed by the structure.*)	Binary
External Factors	Wind	Number of vessel/helicopter operation in violation of wind speed thresholds (*as a percentage of total number of operations*).	Percentage
	Wave	Number of vessel operations in violation of wave height restrictions (*as a percentage of total number of vessel operations*).	Percentage
	Seismic risk	Peak ground acceleration factor. (*This is a factor of standard gravity g providing information about the risk of earthquakes. It can be obtained from seismic hazard maps.*)	Factor

carried out when an incident happens is suggested. Substations, both onshore and offshore, including high voltage areas and cable work caused 18 and 25 incidents, respectively. This is approximately 3% of the total reported incidents each year. In 2013 substation work and cable areas accounted for one lost work day. In 2014 no work day was lost in the substation area. The number of incidents is not exceptionally high in the substation area. However, due to the unique function and properties of it, having an indicator in place for the substations is recommended. Further, due to its unique properties, monitoring of this indicator is relatively easy.

6. Conclusion and Further Research

In this paper, we presented a review of existing literature on system and worker safety specific to the field of offshore and onshore wind industry including some related analyses from the offshore oil and gas industries. The analysis includes both the installation and operational phase of the OWF as well as individual turbines, turbine subsystems and the interaction with vessels. Finally, the incident data reported by G9 [15,16] was connected to the hazards described in other publications like Tveiten et al. [13] and Aneziris at al. [17]. Most of the indicators were found to be relevant, when compared to reported incident data. However, grouping together different indicators concerned with hazardous substances can facilitate the recording process and will most likely enhance the utility of the indicators. Additional indicators for the access to the turbine and substations are recommended as well as indicators monitoring the organizational structure and reporting system. The full list of the proposed safety indicators for the wind farm can be found in Table 3. The table includes the categories and names of indicators, a short description and a suggestion for measuring. For future research, additional review of other structures than monopiles is highly recommended. In a next step, face validation by industrial partners namely WF operators should be considered. Finally, the safety indicators have to be used in operations, data needs to be collected and the indicators need to be revised based on the collected data. A continuous loop of adjusting the indicators based on available incident data will help improve the indicators and can eventually lead to an improvement of the worker health and safety in an offshore wind farm.

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References

[1] Øien K, Utne IB and Herrera IA. Building Safety indicators: Part 1 - Theoretical foundation. *Safety Science* 2011;49:148–161. doi:10.1016/j.ssci.2010.05.012.

[2] Øien K, Utne IB, Tinmannsvik RK and Massaiu S. Building Safety indicators: Part 2 - Application, practices and results. *Safety Science* 2011;49:162–171. doi:10.1016/j.ssci.2010.05.015.

[3] Skogdalen JE, Utne IB and Vinnem JE. Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts. *Safety Science* 2011;49:1187–1199. doi:10.1016/j.ssci.2011.03.012.

[4] Utne I, Thuestad L, Finbak K and Thorstensen TA. Shutdown preparedness in oil and gas production. *Quality in Maintenance Engineering* 2012;18:154–170. doi:10.1108/13552511211244193.

[5] Pasman HJ and Rogers WJ. How can we use the information provided by process safety performance indicators? Possibilities and limitations. *Loss Prevention in the Process Industries* 2013;30:197–206. doi:10.1016/j.jlp.2013.06.001.

[6] Leveson N. A systems approach to risk management through leading safety indicators. *Reliability Engineering & System Safety* 2015;136:17–34. doi:10.1016/j.ress.2014.10.008.

[7] Hopkins A. Thinking About Process Safety Indicators. *Safety Science* 2009;47:460–465. doi:10.1016/j.ssci.2007.12.006.

[8] Feng Y, Tavner P and Long H. Early experience with UK round 1 offshore wind farms. *Proceedings of the Institution of Civil Engineers - Energy* 2010;163:167–181. doi:10.1680/ener.2010.163.4.167.

[9] Scheu M, Matha D, Hofmann M and Muskulus, M. Maintenance strategies for large offshore wind farms. *Energy Procedia* 2012;24:281–288. doi:10.1016/j.egypro.2012.06.110.

[10] Øien K. Risk indicators as a tool for risk control. *Reliability Engineering & System Safety* 2001;74:129–145. doi:10.1016/S0951-8320(01)00067-9.

[11] Arabian-Hoseynabadi H, Oraee H and Tavner P. Failure Modes and Effects Analysis (FMEA) for wind turbines. *Electrical Power and Energy Systems* 2010;32:817–824. doi:10.1016/j.ijepes.2010.01.019.

[12] Faulstich S, Hahn B and Tavner PJ. Wind turbine downtime and its importance for offshore deployment. *Wind Energy* 2011;14:327–337. doi:10.1002/we.421.

[13] Tveiten CK, Albrechtsen E, Hofmann M, Jersin E, Leira B and Norddal PK. *Report, HSE challenges related to offshore renewable energy*. Trondheim: SINTEF Technology and Society; 2011.

[14] Committee on Offshore Wind Farm Worker Safety. *Special Report, Worker Health and Safety on Offshore Wind Farms*. Washington DC: Transportation Research Board of the National Academies; 2013.

[15] G9 Offshore wind health and safety association. *Report, 2013 annual incident data report*. Energy Institute; 2014.

[16] G9 Offshore wind health and safety association. *Report, 2014 incident data report*. Energy Institute; 2015.

[17] Aneziris ON, Papazoglou IA and Psinias A. Occupational risk for wind farms. In: Steenbergen RDJM, van Gelder PHAJM, Miraglia S, Vrouwenvelder ACWM, editors. *Safety, Reliability and Risk Analysis: Beyond the Horizon*; London: Taylor and Francis Group; 2014:1489–1496.

[18] Caithness Windfarm Information Forum. Summary of Wind Turbine Accidents. 2012. URL: www.caithnesswindfarms.co.uk [Accessed 30-11-2015].

[19] Dai L, Ehlers S, Rausand M and Utne IB. Risk of collision between service vessels and offshore wind turbines. *Reliability Engineering & System Safety* 2013;109:18–31. doi:10.1016/j.ress.2012.07.008.

[20] Utne IB. Systems engineering principles in fisheries management. *Marine Policy* 2006;30:624–634. doi:10.1016/j.marpol.2006.04.005.