Navigating Towards Safe and Secure Offshore Wind Farms: An Indicator-Based Approach in the German North and Baltic Sea

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ABSTRACT

Offshore wind farms (OWFs) have become an increasingly relevant form of renewable energy in recent years, with the German North Sea being one of the most active regions in the world. However, the safety and security of OWF have become increasingly important due to the potential threats and risks associated with their growing share in the security of energy supply. This paper aims to present a comprehensive and systematic indicator-based approach to assess the safety and security status of OWFs in the German North Sea. The approach is based on the results of a survey of people working in the offshore industry and draws on the work published by Gabriel et al. (2022). The results of the study suggest that the indicator-based approach is a useful tool for end users to assess the security status of offshore wind farms and can be used for further research and development.

Keywords

Offshore, Risk assessment, Threat assessment, Indicator, Wind energy

INTRODUCTION

Wind farms play a key role in the energy transition to renewable energy sources. Since the potential for onshore expansion is limited, especially in densely populated environments, offshore wind energy will have to make a significant contribution. In the light of the ambitious expansion targets pursued by numerous European countries (cf. WindSeeG, BGBl. I p. 1325 et sqq.) and the integration of offshore wind energy into the European interconnected power grid, offshore wind energy, with a forecasted share of 15.9 to 19.3 percent of the total energy produced in Europe in 2040 (IEA 2019), will play a crucial role in ensuring the security of energy supply for Europe's societies and countries in the medium and long term. The relevance of offshore wind energy is also expected to increase significantly outside Europe. For example, the IEA expects between 2.9 and 5.3 percent of total electricity demand in the United States and between 1.1 and 6.7 percent in Japan to be generated from offshore wind energy (IEA 2019). In the same study, the IEA concludes in the positive scenario of a continued shift to renewables that by mid-century, offshore wind will be the largest source of electrical energy in Europe (Birol 2019). Consequently, there is an increased need for protection of the OWFs as maritime critical infrastructures (MCI) and the corresponding systems for energy generation as well as energy transformation, energy transport and for grid connection to land-based systems and onshore power grids against both man-made and natural threats or hazards.

The high relevance of OWFs for the security of energy supply and the success of the energy transition is contrasted by the particular vulnerability of MCI to anthropogenic threats of symmetric and hybrid origin, as well as to accidental events due to their exposed geographical location. A study by Gabriel et al. (2022) provided insights into which threat scenarios are of particular relevance for MCI and OWFs in particular. The same paper also indicated that employees' and managers' perceived preparedness for critical incidents in OWF shows at least a divergent picture (Gabriel et al. 2022). It also identified particularly relevant or vulnerable components of OWFs, which are primarily located on the major high-voltage transformer platforms (Gabriel et al. 2022). Two aspects are of particular relevance here: On the one hand, the corresponding data collection for the publication was performed before the escalation of the conflict in Ukraine. Accordingly, it can be assumed - also against the background of the attacks launched against the pipelines in the Baltic Sea on September 26, 2022 near Bornholm/Denmark - that the threat situation has intensified since then. On the other hand, the transmission capacity of the high-voltage direct current transformer platforms currently in operation in the German North Sea and Baltic Sea is in the range of around 900 megawatt (MW), while planned projects at the end of the 2020s will transmit power of 2000 MW - comparable to that of a nuclear power plant (Bundesamt für Seeschifffahrt und Hydrographie 2023). Thus, the security and safety requirements are becoming even more critical due to the focus on some singular systems.

In this respect, the safety and security status of OWFs has to be understood and assessed as being a multi-dimensional issue (airspace, surface, subsea, seabed). This paper therefore contributes to the assessment of risks and threats arising from accidental events and intentional attacks on OWFs. For this purpose, the paper briefly outlines the basic infrastructure design and relevant threat scenarios for OWFs in the first section. In the second section, a discussion of existing risk and security assessment approaches for MCI and OWFs in particular is provided based on the results of a literature review. On this basis, a specific indicator-based assessment framework is then developed and introduced in the third section and the corresponding subsections. The paper concludes with an exemplary application of the proposed assessment framework on two OWFs located in the German North Sea and Baltic Sea, followed by a discussion of the findings as well as further research and development opportunities.

INFRASTRUCTURE COMPONENTS AND STRUCTURE OF OWFS AND THREAT SCENARIOS

OWFs essentially consist of the wind turbine generators (WTGs) for power generation, the corresponding cable connection to the offshore substation based on a platform and the power export cable to the coast. The individual components of OWFs are subject to different threats in this regard.

Components and layout of OWFs

The wind turbines available on the market have since reached considerable dimensions and power outputs. Performances of up to 15 MW per individual wind turbine at rotor diameters of more than 220 meters and tower heights of around 250 meters are available and are increasingly being installed. However, due to the rapid pace of development in recent years, many wind farms already in commercial operation still have much smaller and less powerful turbines (< 10 MW in the German exclusive economic zone) in service, which will remain in operation for several more years. Figure 1 illustrates the current status of WTGs in operation and planned projects in the German EEZ and a forecast projection of the number of WTGs required to achieve the policy goals for the expansion of German offshore wind energy. It was assumed by the author for the calculations in the optimistic scenario (lowest number of turbines required) that only 16 MW turbines will be installed from 2022 onwards. The pessimistic scenario is based on the assumption that only turbines with a capacity of 12 MW will be installed from 2022 onwards. This does not take into account any initiatives that may be launched to repower turbines that have already been installed. The results of this analysis thus indicate that the number of wind turbines in the German North Sea and Baltic Sea alone will increase by a factor of 3.7 to 4.5 until 2045 compared to the reference year 2021.

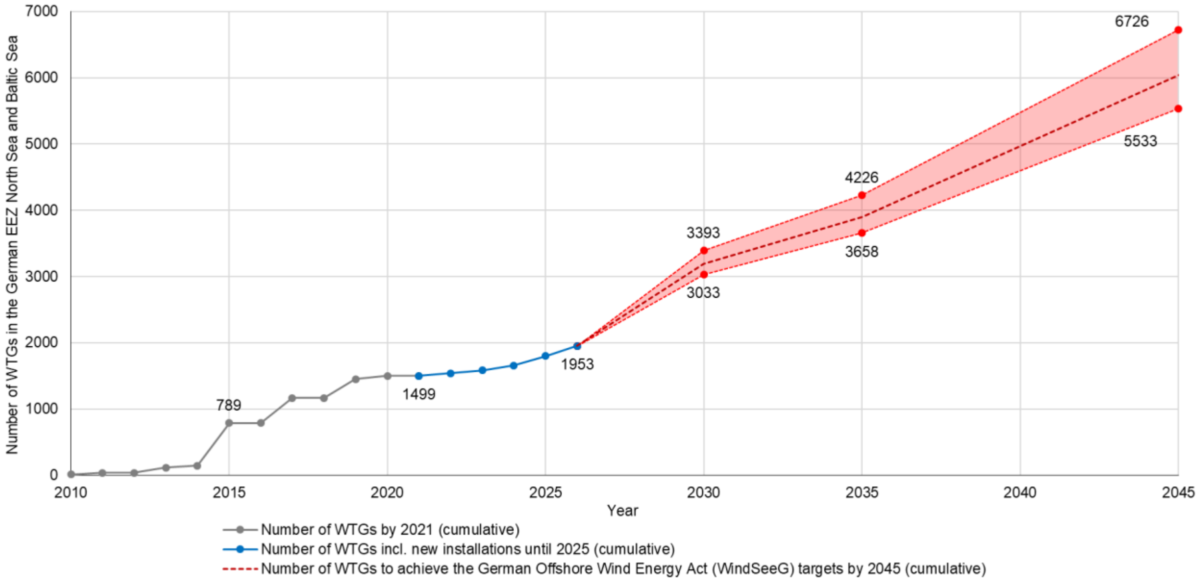

Figure 1. Number of currently installed and planned WTGs in the German EEZ and projection of the future number until 2045

The individual WTGs are connected to offshore substations via cables buried on the seabed. The WTGs can be connected to the platform either individually or via a ring connection. Particularly at farshore offshore wind farms, the wind farms and offshore substations themselves are not connected to the onshore power grid via individual export cables. Instead, the individual offshore substations of each OWP are being connected to a high-voltage converter platform. This type of connection is called a cluster connection and uses high-voltage direct current transmission technology to route the generated power via an export cable to the shore for delivery to the power grid. In this case, the export cables are composed of several conductor bundles as well as fiber optic cables for controlling facilities and are equipped with multi-layer shielding. The cables are usually embedded or buried in the seabed so that they can be protected from external influences.

Offshore substations and high voltage direct current converter platforms are quite similar in design. Typically, in the shallow water zones of the North and Baltic Seas, they consist of supporting structures embedded in the seabed, namely the foundation and the substructure. Mounted on top of these are topside structures, the actual platform structure consisting of several decks. The larger platforms usually have a main deck with social, housing and workshop quarters, a cable or transformer deck containing the actual switchgear and transformers and a submarine cable entry and exit point on the bottom side of the platform (Robak and Raczkowski 2018).

Threat and risk scenarios

Threat scenarios for OWFs have been a topic that has received little attention in academia. In a survey of 31 employees in the offshore wind energy industry, Gabriel et al. (2022) were able to identify the scenarios subjectively perceived as most relevant (cf. Table 1).

Table 1. Qualitative analysis on the perception of currently most relevant threats and risks for offshore wind farms (Gabriel et al. 2022)

Risk or threat scenario	Number of mentions
Cyberattack	9
Technical failure/Poor maintenance	6
Natural hazards/Extreme weather	7
Terrorism	10
Sabotage	6
Human error/Organizational shortcomings	6
Collision with ships	9
Helicopter incidents/Fire on platform	4

It should be noted that a shift in the results due to recent events in the field of maritime security can be assumed to be likely. Nevertheless, the results allow concluding that mainly terrorist and cyber-attacks as well as collisions with ships can be seen as the main scenarios. This is also in line with an analysis of OWF stakeholder safety and security goals by Ramírez-Agudelo et al. (2021). Accordingly, an indicator-based assessment framework usable by end users would need to consider these scenarios, as well as the particularly vulnerable components of OWFs.

EXISTING APPROACHES TO SECURITY AND THREAT ASSESSMENT

To identify already existing security or threat analysis approaches in the context of MCI, a structured literature analysis was conducted in three databases. In each case, the same search terms were used in the combination "offshore AND security AND assessment". The selection of the search terms was intentionally restricted to security, since numerous publications exist, especially in the field of risk management for offshore wind turbines. However, most of these refer to the operation and maintenance of wind turbines and are therefore of little relevance to the research in this paper, which focuses on anthropogenic risks and threats. From the articles identified the relevant ones were extracted based on a review of title and abstract, which contained thematic relevance and subsequently the duplicates were removed from the articles retrieved from the different databases. Based on this, the remaining articles were evaluated with regard to the criteria listed in Figure 2 and included accordingly in the further research and as a basis for the development of an evaluation approach.

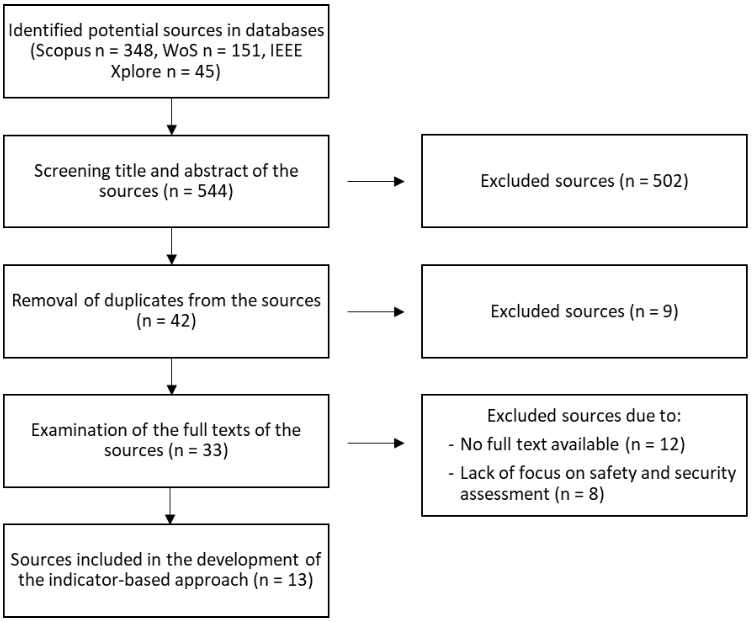

Figure 2. Methodological approach and steps of the literature analysis

The results of the literature review reveal that the field of MCI and especially OWF security assessment is still selectively under-researched or not fully explored. The existing approaches often focus on specific aspects and only rarely on safety and security or the resilience of the infrastructure and the people working there, as well as on the impacts and interactions with society as a whole. It is also noticeable that complex simulation models have to be developed or a considerable amount of data has to be available for many approaches

In their paper, Hermansyah et al. (2020) for example, state that the success of methods for quantitative risk analysis depends primarily on the availability of data and the use of highly specific models for different risks. If no data are available, quantitative risk analysis is not possible, as well as if the user does not have extensive mathematical and technical skills to interpret the results. For this reason, they suggest using semi-quantitative risk assessment methods, as these place lower demands on both the users and the availability of data. A comparable argumentation is used by Kumaraningrum et al. (2019), who further state that semi-quantitative risk analysis offers a compromise between purely qualitative description of risks and their numerical simulation. Thus, they argue, the approach provides a sufficient basis for decision making for risk mitigation measures. Other approaches, such as that of Ramírez-Agudelo et al. (2021) use FRAM-based probabilistic approaches to estimate the safety and security situation in OWFs. However, the approach remains high-level and cannot identify specific risks or threats, but rather generic ones. An approach specifically designed for attacks and less for accident events is presented by Harbour (2002).

In their paper, Köpke et al. (2023) develop a risk analysis for the destruction of a cable of an OWF. For this purpose, they use finite element methods as an approach of numerical simulations. Accordingly, accurate data are required on the nature of cables and means of attack. On this basis, they derive a risk assessment and corresponding possible safety measures. A mathematically more complex approach to maritime risk modeling is developed by Yang and Qu (2016) to assess port security.

The required amount and accuracy of data or the required advanced mathematical knowledge severely limits the applicability by end users on the side of authorities or industry. The indicator-based approach in the presented paper is intended to fill exactly this gap in order to enable a comparatively low threshold for security status assessment for MCI respectively OWFs in the concrete case by the end user himself.

However, the literature found provides relevant information in some places on indicators used or at least characteristics for the security and threats of MCI (cf. Ariany et al. 2022; Kumaraningrum et al. 2019). These can be used for the following development of the indicator-based assessment approach.

INDICATOR-BASED APPROACH ON OWF SECURITY AND THREAT ASSESSMENT

Its comparatively straightforward applicability by practitioners on the part of authorities and OWF operators distinguishes a semi-quantitative approach from purely quantitative methods. The high robustness against limited or insufficiently available data is a particular advantage of the indicator-based approach. Especially in the maritime environment, the data situation is often insufficient (underwater situation picture factually not available) or of uncertain quality (AIS data not verifiable or rather easily manipulated). Therefore, and due to the complex models required, the corresponding approaches discussed in science respectively developed so far are of extremely limited use in practice at sea. This gap between practical application and science is to be closed by means of an indicator-based assessment approach. The indicator-based approach will use reliable quantitative data for threat and risk assessment as far as possible and combine them - where missing - with the semi-quantitative assessment by domain experts. The following section introduces and explains the development of the indicator framework as well as the assessment scheme and the resulting risk categories.

Development of indicators for security assessment in OWFs

The indicator-based approach to assessing the security status of OWFs is a systematic and comprehensive approach that takes into account different factors affecting the security of the facilities. In this context, the development of the assessment approach and corresponding set of indicators is carried out in several essential steps:

- Identification of the most important factors affecting the security of OWFs, taking into account the most relevant threat and security scenarios (Terrorism/Collision with ships)
- Development of indicators to assess the level of security and threats in the OWFs as holistically as possible, drawing on the results of the literature review
- Development of assessment categories and to the extent possible, delineation semi-quantitative categories
- Evaluation of the indicators and giving recommendations to improve the security status in OWFs

Key factors affecting the security of offshore wind farms in the German North Sea and Baltic Sea include the design and construction of the facilities, the location and environment of the operating sites, the human factors involved in the operation and maintenance of the facilities, and the interactions between these various factors. Accordingly, the indicators that are developed to assess the security level of the OWFs should be able to reflect these aspects. From this, the following four groups with their respective indicators were derived:

Composition and layout

- Number of WTGs: Indicator for recording the number of wind turbines located in the wind farm, which can be easily quantified. The classification is based on the quartiles of wind farms currently in operation in the North Sea and Baltic Sea.
- Output of installed WTGs per WTG: Output of the individual turbines in the wind farm, to capture farms with few, but powerful turbines. The classification is also based on the quartiles of WTGs currently in operation in the North Sea and Baltic Sea.
- Number of OSS connected: Indicator can only be meaningfully evaluated for high-voltage platforms; these are of particular interest due to their prominent relevance.
- Security zone established: Has a security zone or general no-shipping zone been established around the wind farm and entered in the relevant nautical charts.
- Geographic peculiarities (River mouth, near harbor, island, ...): OWFs located near harbors or estuaries or islands usually heavily frequented by other vessels are subject to greater risk.
- Distance from the coastline: As distance from the coastline increases, accessibility to the OWF is more difficult, making attacks by third parties much more complex and costly.
- Number of export cables available: Redundancy in the existing export cables makes it possible to maintain the provision of the core service - energy production - as far as possible even if one cable is damaged.

Operation and maintenance

- Number of workers on platform/WTG/transferred (per day): The number of workers assigned to the wind farm each day increases the risk of sabotage or attack, so the indicator is intended to capture this qualitatively.
- Routine sole work/sole workplaces without third persons: Sole workplaces allow unsupervised manipulation of sensitive equipment or its compromise with the aim of later attacks.
- Number of CTVs in service in OWF: A high number of vessel movements in the wind farm increases collision risks and places increased demands on traffic and permit management.
- Monitoring of the direct environment by means of AIS/radar: Monitoring of the surrounding sea and air space enables early detection of unauthorized or unannounced approaches. The indicator differentiates between continuous/automated monitoring and monitoring only at certain operating times or not at all.
- Security guards available in OWFs: The long intervention times of security or assistance forces are a

particular security challenge in OWFs. This can be mitigated by providing towing/intervention capacities; the indicator also distinguishes whether these are provided continuously or only partially or not at all.

Position and environment

- Distance from the nearest shipping lane: The indicator in this case represents the distance from the OWF to the nearest point of a permanent or buoyed shipping lane in the vicinity of the wind farm.
- Average number of passing ships < 2 nm p.a.: The number of passing ships within a short distance is considered in the scoring, since a large number of ship movements increases the risk of intentional and especially unintentional collisions.
- Type/Risk classification of passing ships < 2 nm: The risk class of passing ships is crucial for the safety situation of the OWF. The risk class can either be formed on the basis of ship types (derived from AIS data) or determined using the ship risk profile of the Paris Memorandum of Understanding on Port State Control ("Paris Memorandum of Understanding on Port State Control").
- Anchorage around the OWF: Like shipping lanes in close proximity to the wind farm, designated anchorages are relevant to the risk posed to the OWF. Anchored vessels may begin to drift, particularly during severe weather conditions, and thus become hazardous to wind farms.
- Intensity of fishing activity in the sea area: Intensive fishing activities may result in an increased risk of unauthorized approaches, as wind farm protection zones in particular sometimes include attractive fishing grounds.
- Intensity of flight activities in the sea area: A high number of aerial movements in the wind farm increases collision risks and places increased demands on traffic and permit management.
- Intensity of submarine activities in the sea area: A high number of subsurface movements in the wind farm increases collision risks and places increased demands on traffic and permit management.
- Sea areas with special relevance in the surrounding area (shooting area, diving area, low-flying zone, ...): Proximity to naval training areas increases the risk to the wind farm partly due to the activities themselves, and partly due to possible actions by other actors to gather information about operations in the training areas.
- Weather conditions: heavy weather is one of the main risk factors in maritime transport, therefore bad weather in terms of storm or hurricane indirectly contributes to the threat to the wind farm.

Other

- Local attack relevance (official warnings, naval equipment): The installation of equipment for civil-military co-use leads to an increased military relevance of OWFs and thus higher threat levels.
- Intervention forces available: The availability of professional intervention forces - deployable by air or sea - significantly strengthens the response capability in the event of a crisis and thus reduces the risk to OWFs.

Evaluation scheme and determination of a threat or security index

The indicators are rated on the basis of semi-quantitative classes with corresponding risk or threat scores. The classes are formed and defined on the basis of either a qualitative or quantitative description.

	Threat indicator	Score		
		1	2	3
Composition and layout	Number of WTGs	< 30	30-80	> 80
	Output of the installed WTGs per WTG	< 4.5 MW	4.5-8 MW	> 8 MW
	Number of OSS connected	not applicable	one	more than one
	Security zone established	applicable	-	not applicable
	Geographic peculiarities (River mouth, near harbor, island, ...)	not applicable	-	applicable
	Distance from the coastline	< 5 nm	5-12 nm	> 12 nm
	Number of export cables available	more than one	-	one
Operation and maintenance	Number of workers on platform/WTG/transferred (per day)	low	medium	high
	Routine sole work/sole workplaces without third persons	low	medium	high
	Number of CTVs in service in OWF	none	one	more than one
	Monitoring of the direct environment by means of AIS/radar	applicable	partially	not applicable
	Security guards available in OWF	applicable	partially	not applicable
Position and environment	Distance from the nearest shipping lane	< 1 nm	1-2 nm	> 2 nm
	Average number of passing ships < 2 nm p.a.	< 1000	1000-10.000	> 10.000
	Type/Risk classification of passing ships < 2 nm	low risk	standard risk	high risk
	Anchorage around the OWF	< 2 nm	2-5 nm	> 5 nm
	Intensity of fishing activity in the sea area	low	-	high
	Intensity of flight activities in the sea area	low	-	high
	Intensity of submarine activities in the sea area	none	low	high
	Sea areas with special relevance in the surrounding area (shooting area, diving area, low-flying zone, ...)	not applicable	-	applicable
	Weather conditions	normal	-	severe weather
Other	Local attack relevance (official warnings, naval equipment)	none	low	high
	Intervention forces available	applicable	-	not applicable

Figure 3. Indicator framework and evaluation categories and their description

A purely qualitative class formation is primarily required if no quantitative data are available or if these cannot be evaluated by the end user in a meaningful way and with limited effort. In this case, indicators can either be evaluated with the linguistic descriptions "low", "medium" and "high", or they can be evaluated on two levels "available/applicable" and "not available/not applicable". The formation of quantitative or quantifiably separable classes is particularly suitable for the indicators that can be technically measured or are geographical in nature, since a clear demarcation is possible here and the data situation is generally sufficient or even good.

The risk or threat scoring results from the weighted, aggregated score in all four categories respectively the total sum of the indicator scores. The weighting is based on a logarithmic weighting according to formula 1. The weighting makes it possible to give special consideration to indicators rated as critical or particularly risky.

$$f(x) = \log_4(x + 1) \quad \textbf{(1)}$$

In order to allow end users to give greater weighting to risk factors that are particularly relevant to them, and thus to take sufficient account of local peculiarities, an additional individual weighting factor (custom weight) was introduced. This overwrites the weighting factor defined by the weighting function. The individual weighting can be done with the factor 0.5, 0.79 or 1 corresponding to the weighting function and thereby directly influences the weighted score of the respective indicator.

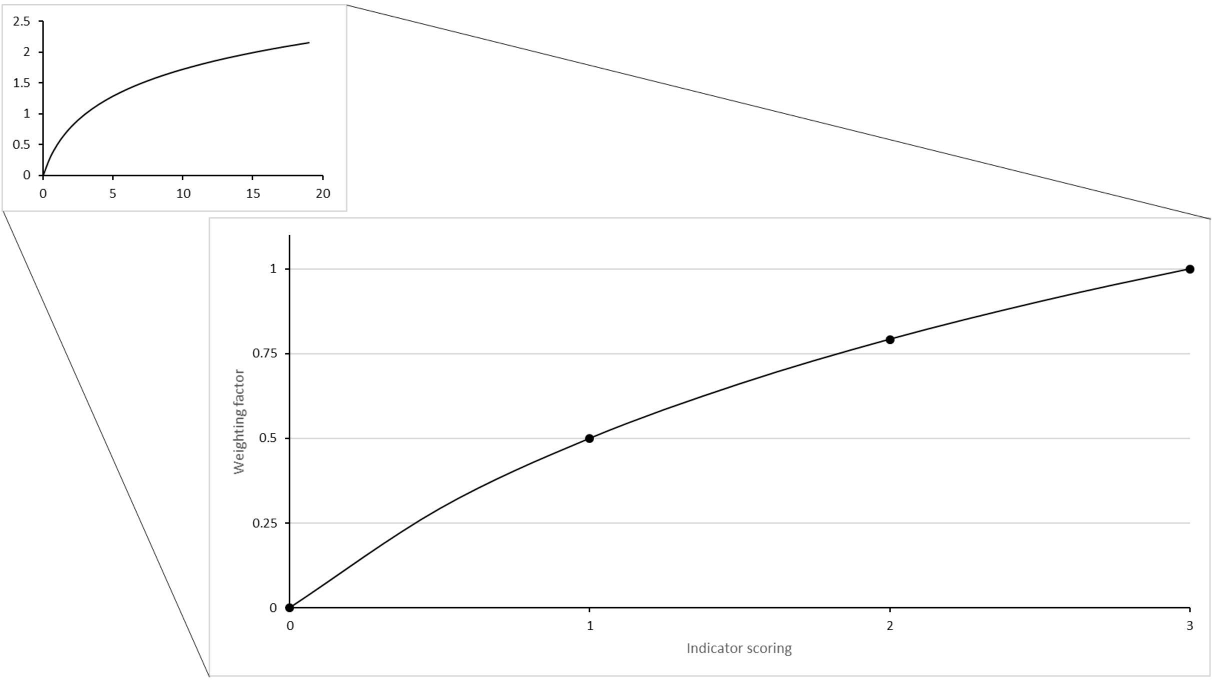

Figure 4. Graphical representation of the weighting function in the interval from 0 to 3 or 0 to 20 (small figure)

A high overall score is equivalent to a high risk or threat level, while a low score indicates a good security status or a low threat profile for the OWF. The classification into one of five risk classes is made linearly on the basis of the sum of the weighted threat scores, with a global maximum of 69 points and a global minimum of 11.5 points.

Table 2. Risk or threat classes and threshold values

Risk/Threat category	Lower boundary	Upper boundary	Significance
1	11.5	23	Low threat/risk
2	23	34.5	Medium threat/risk
3	34.5	46	Increased threat/risk
4	46	57.5	High threat/risk
5	57.5	69	Severe threat/risk

CASE STUDYS IN NORTH AND BALTIC SEA

The feasibility and practicality of the proposed assessment tool is to be demonstrated in two case studies and thus subjected to a plausibility test. The wind farm Nordergruende, located in the North Sea, and the wind farm Borkum Riffgrund 2, also located in the North Sea, were selected as application examples.

Application to OWF Nordergruende

The OWF Nordergruende is located between the estuaries of the Jade and Weser rivers in the middle of the Outer Weser and Outer Jade in a zone of relatively shallow water. The wind farm has 18 WTGs with a total capacity of 110 MW and is connected to the grid via its own OSS. The evaluation results in a comparatively low risk index for the Nordergruende wind farm. This is in line with expectations, as it is an older and more coastal located wind farm with lower-power wind turbines. However, the location in the estuary of the Weser or Jade rivers and the resulting high traffic density in the immediate vicinity of the wind farm are particular risk factors.

Threat indicator		Score 1	Score 2	Score 3	Scoring	Weight	Custom Weight	Weighted Score
Composition and layout	Number of WTGs	< 30	30-80	> 80	1	0.50		0.50
	Output of the installed WTGs per WTG	< 4.5 MW	4.5-8 MW	> 8 MW	2	0.79		1.58
	Number of OSS connected	not applicable	one	more than one	1	0.50		0.50
	Security zone established	applicable	-	not applicable	1	0.50		0.50
	Geographic peculiarities (River mouth, near harbor, island, ...)	not applicable	-	applicable	3	1.00	1.00	3.00
	Distance from the coastline	> 12 nm	5-12 nm	< 5 nm	2	0.79	1.00	2.00
	Number of export cables available	more than one	-	one	3	1.00		3.00
Operation and maintenance	Number of workers on platform/WTG/transferred (per day)	low	medium	high	2	0.79		1.58
	Routine sole work/sole workplaces without third persons	low	medium	high	2	0.79		1.58
	Number of CTVs in service in OWF	none	one	more than one	1	0.50		0.50
	Monitoring of the direct environment by means of AIS/radar	applicable	partially	not applicable	2	0.79		1.58
	Security guards available in OWF	applicable	partially	not applicable	3	1.00		3.00
Position and environment	Distance from the nearest shipping lane	> 2 nm	1-2 nm	< 1 nm	2	0.79		1.58
	Average number of passing ships < 2 nm p.a.	< 1000	1000-10.000	> 10.000	3	1.00		3.00
	Type/Risk classification of passing ships < 2 nm	low risk	standard risk	high risk	3	1.00		3.00
	Anchorage around the OWF	> 5 nm	2-5 nm	< 2 nm	1	0.50		0.50
	Intensity of fishing activity in the sea area	low	-	high	3	1.00		3.00
	Intensity of flight activities in the sea area	low	-	high	1	0.50		0.50
	Intensity of submarine activities in the sea area	none	low	high	1	0.50		0.50
	Sea areas with special relevance in the surrounding area (shooting area, diving area, low-flying zone, ...)	not applicable	-	applicable	1	0.50		0.50
	Weather conditions	normal	-	severe weather	1	0.50		0.50
Other	Local attack relevance (official warnings, naval equipment)	none	low	high	1	0.50		0.50
	Intervention forces available	applicable	-	not applicable	1	0.50		0.50
			OFW Nordergruende		Risk/Threat Score			33.42

Figure 5. Exemplary application for the case study OWF Nordergruende

Application to OWF Borkum Riffgrund 2

The OWF Borkum Riffgrund 2 is located in the North Sea about twenty nautical miles off the island of Borkum. The wind farm has 56 WTGs installed, which can produce a total output of 448 MW. Due to the long distance to the coast, the connection is made by HVDC converter platform via submarine cable. The Borkum Riffgrund wind farm has an increased risk and threat potential, which also corresponds to expectations. It is a wind farm in relative proximity to major shipping routes in the German Bight, which are highly frequented. In addition, there are German Navy training areas not too far away from the wind farm.

Threat indicator		Score 1	Score 2	Score 3	Scoring	Weight	Custom Weight	Weighted Score
Composition and layout	Number of WTGs	< 30	30-80	> 80	2	0.79	1.00	2.00
	Output of the installed WTGs per WTG	< 4.5 MW	4.5-8 MW	> 8 MW	3	1.00		3.00
	Number of OSS connected	not applicable	one	more than one	2	0.79		1.58
	Security zone established	applicable	-	not applicable	1	0.50		0.50
	Geographic peculiarities (River mouth, near harbor, island, ...)	not applicable	-	applicable	1	0.50		0.50
	Distance from the coastline	> 12 nm	5-12 nm	< 5 nm	3	1.00		3.00
	Number of export cables available	more than one	-	one	1	0.50		0.50
Operation and maintenance	Number of workers on platform/WTG/transferred (per day)	low	medium	high	3	1.00		3.00
	Routine sole work/sole workplaces without third persons	low	medium	high	2	0.79		1.58
	Number of CTVs in service in OWF	none	one	more than one	3	1.00		3.00
	Monitoring of the direct environment by means of AIS/radar	applicable	partially	not applicable	2	0.79		1.58
	Security guards available in OWF	applicable	partially	not applicable	3	1.00		3.00
Position and environment	Distance from the nearest shipping lane	> 2 nm	1-2 nm	< 1 nm	2	0.79	1.00	2.00
	Average number of passing ships < 2 nm p.a.	< 1000	1000-10.000	> 10.000	3	1.00	1.00	3.00
	Type/Risk classification of passing ships < 2 nm	low risk	standard risk	high risk	3	1.00	1.00	3.00
	Anchorage around the OWF	> 5 nm	2-5 nm	< 2 nm	1	0.50		0.50
	Intensity of fishing activity in the sea area	low	-	high	3	1.00		3.00
	Intensity of flight activities in the sea area	low	-	high	3	1.00		3.00
	Intensity of submarine activities in the sea area	none	low	high	2	0.79		1.58
	Sea areas with special relevance in the surrounding area (shooting area, diving area, low-flying zone, ...)	not applicable	-	applicable	3	1.00	1.00	3.00
	Weather conditions	normal	-	severe weather	1	0.50		0.50
Other	Local attack relevance (official warnings, naval equipment)	none	low	high	2	0.79		1.58
	Intervention forces available	applicable	-	not applicable	3	1.00		3.00
			OFW Borkum Riffgrund 2		Risk/Threat Score			47.42

Figure 6. Exemplary application for the case study OWF Borkum Riffgrund 2

CONCLUSION AND OUTLOOK

Both case studies show that the evaluation approach is in principle implementable. The developed indicators need to be verified in an evaluation process with the users, primarily operators of OWFs and government agencies. In particular, a calibration of the individual classes respectively their delimitations in the assessment framework seems to be necessary in this context. It is planned to evaluate and calibrate the risk and threat assessment approach presented in this paper in close cooperation with wind farm operators and the operators of the major sub-station and transformer platforms in the North Sea in a number of pilot case studies. The main objective will be the verification of the meaningfulness of the results and the demonstration of the validity of the developed approach. An initial exchange with operators and authorities confirmed the strong interest in an approach that is easy to implement. In particular, the implementability without additional effort of extensive data collection is a relevant criterion for the operators, especially against the background of the so far missing regulatory requirements for a dedicated security management. In this respect, the developed approach can, after a successful evaluation and implementation, make a first contribution to security management by the stakeholders themselves in OWFs.

It is particularly relevant that the approach allows for an overall assessment using an aggregated risk or threat index. At the same time, the approach also allows for an assessment of particular risk factors and their comparison across different OFWs in the North and Baltic Sea. Thus, the indicator-based approach offers a first step towards harmonizing and comparing the level of security or threat for different OWFs or offshore clusters (a grouping of several OWFs) for operators and, in particular, regulatory authorities. The operators themselves are enabled for the first time by the assessment framework to coordinate their safety and security measures across different OWFs and to organize cross-farm measures for a cluster collectively if necessary. A possible further development towards a standardized security assessment tool in connection with the threat assessment approach presented in Gabriel et al. (2021) using Bayesian networks remains to be discussed.

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