Received: 30 January 2023 | Revised: 4 July 2023 | Accepted: 27 August 2023

DOI: 10.1002/we.2871

RESEARCH ARTICLE

WILEY

# Norwegian offshore wind power—Spatial planning using multi-criteria decision analysis

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**Funding information**
University of Bergen; Research Council of Norway, Grant/Award Number: 309562

## Abstract

The Norwegian government recently agreed on the goal *30by40*, which involves opening Norwegian offshore areas to host 30 GW of installed wind power by 2040. We address this goal by presenting a first mapping of wind power suitability scores (WPSS) for the entire Norwegian economic zone (NEZ) using a multi-criteria decision analysis framework (MCDA), namely, the analytical hierarchical process (AHP) approach. We obtain WPSS considering relevant criteria like wind resources, techno-economic aspects, social acceptance, environmental considerations, and met-ocean constraints such as wind and wave conditions. The results starts with a baseline scenario, where the criterion importance is pairwise compared in the context of balancing economic incentives and conflicting interests. Additionally, to reveal regions that are robust to changes in criterion importance, we carry out a sensitivity analysis by introducing three additional scenarios. These scenarios represent stereotypical actors with distinct preferences for siting of wind farms: *the investor*, *the environmentalist*, and *the fisherman*. The results show that the southern part of the NEZ is the most suitable and robust region for offshore wind power deployment. This region receives the highest suitability category ("very high" suitability for wind power application) throughout all the scenarios. Areas in the Norwegian part of the Barents Sea and the near-coastal areas outside mid-Norway are also well suited regions, but these are more sensitive to the choice of criterion importance. The use of AHP within the framework of MCDA is shown to be a promising tool for pinpointing the best Norwegian offshore areas for wind power application.

**KEYWORDS**
analytical hierarchy process, multi-criteria decision analysis, optimal offshore wind farm siting, wind farm spatial planning

## 1 | INTRODUCTION

The wind power potential in Norwegian offshore areas is outstanding. A study by Soares et al[1] based on the state-of-the art reanalysis product (ERA5) from the European Centre for Medium-Range Weather Forecast (ECMWF) found the Norwegian offshore wind power potential to be between 800 and 1200 W/m$^2$. Bosch et al[2] state that Norway has one of the world's best offshore wind resources with a potential to produce almost 16,000 TWh/year with wind turbine spacing of 1 km, including wake losses. For comparison, the wind power potential of 16,000

TWh/year is 114 times the Norwegian yearly electricity consumption (140 TWh/year). Based on the NORA3-WP dataset,[3] a simple estimate of the yearly offshore power potential within the Norwegian economic zone (NEZ) is 14,000 TWh/year (excluding wake losses), assuming the IEA 15 MW reference turbine,[4] and with a turbines spacing of approximately 2 km (corresponding to eight turbine diameters).

Despite the excellent wind power potential, and the fact that Norway has Europe's longest coastline, no wind farm is operating in Norway's marine areas. However, in 2020, the Norwegian Government opened two offshore areas for large-scale offshore wind application, "Utsira Nord" and "Sørlige Nordsjøen 2."[5] As an advancement, in February 2022, the government sets new national goals for the Norwegian offshore wind development: *30by40*.[6] By 2040, the government will open offshore areas to host 30 GW of installed wind power capacity. In the preparatory work, there is a need to identify new potential areas for large-scale offshore wind power application.

The Norwegian offshore areas are already used for many purposes, like commercial fishing activity, shipping, military activity, and so forth. In addition, ecologically valuable areas such as spawning grounds and bird nesting sites, as well as protected areas, pose limitations on the space available for offshore wind power. Thus, the identification of potential areas for wind power applications requires consideration of numerous criteria to identify and reduce potential conflicts.

Complex decision-making like wind power spatial planning requires methods that can handle numerous of conflicting criteria. Multi-criteria decision analysis (MCDA) is a formal and structured decision-making methodology that can be used for comparing different alternatives and exploring decisions in the case of situations with multiple and conflicting criteria. Analytical hierarchy process (AHP) is a commonly used method within the MCDA framework.[7–10] The role of the AHP is to split the overarching goal into subcriteria, creating a hierarchy of goal-affecting components. The AHP has been used numerous times in previous research within wind power spatial planning, both onshore and offshore.[10–13] Chaouachi et al[11] studied optimal wind farm siting in the Baltic States by applying the AHP framework. For each of the Baltic countries, optimal wind farm locations were assessed under different scenarios by applying different magnitudes of importance to different criteria. Different scenarios represent different characteristics such as market design, regulatory aspects, or renewable integration targets. The authors also considered foreseen upgrades and network reinforcements. The work done by Stefanakou et al[12] presents a decision support model for optimal offshore wind farm siting using MCDA, AHP, and a geographic information system (GIS).[*] A four-step procedure was implemented for the Aegan Sea, and a sensitivity analysis was carried out to test the robustness of the result. The authors found that only a small percentage of the study region could be characterized as appropriate for floating wind power facilities. Díaz and Soares[13] have presented a method for optimal offshore wind farm siting in the Canary Islands. First, they identify problematic areas using a GIS. Second, the available maritime areas were analyzed and ranked using the AHP technique. The authors obtained a realistic and objective overview of areas suitable for floating offshore wind farm sites while minimizing the possible environmental impacts and social conflicts. A recent study by Díaz and Guedes Soares[10] developed a decision tool for spatial planning of offshore wind farms, using both a GIS and MCDA. They considered relevant criteria like technological, environmental, social, and economic criteria for evaluating and identifying potential locations for offshore wind farm deployment using AHP for the coastal areas of Portugal, Spain, and France. The authors conclude that their tool has potential to support decision-makers in the early phase of wind power spatial planning in the area of concern. In contrast to the previous studies, we use the AHP framework to determine optimal wind farm siting and to develop unprecedented wind power suitability scores for the entire Norwegian economic zone. In this offshore area, the wind power development is in its infancy and will be further developed in the years to come.[6] No peer-reviewed research has been published evaluating the prospect of offshore wind farms in Norwegian waters. The overall objective of this study is to detect offshore regions with a desirable combination of good wind resources, favorable techno-economic parameters, social acceptance, low potential for environmental conflicts, and mild met-ocean conditions for wind farm siting within the Norwegian offshore areas. Stress testing these results by introducing stereotypical characters with distinct preferences will reveal areas that are robust to changes in criterion importance, and hence will be optimal for wind power installation. In addition, we give a clear and transparent description of the framework and procedure to obtain such a suitability assessment. This is relevant for other researchers, policymakers, and so forth.

The backbone of this study is the new high-resolution ($3 \times 3$ km) wind resource and wind power mapping described and validated in Solbrekke and Sorteberg[3] and Solbrekke et al.[14] By using the decision support system provided by MCDA and AHP together with a relevant datasets, we are able to calculate the wind farm suitability of each grid point in the entire Norwegian economic zone (NEZ). A unique ensemble of spatial datasets is utilized to detect optimal areas for offshore wind production, considering well-known parameters such as wind power production, ocean-depth, distance to shore, potential environmental conflicts, and possible military and commercial conflicts of interest. In addition, we incorporate important parameters not used in previous research such as wind power intermittency over different timescales, distance to oil and gas platforms, turbine visibility, and accumulated met-ocean waiting time for maintenance and operation, among others. As the criterion importance is subjectively determined and depends on the preference of the decision-makers, no single optimal solution exists in MCDA. To cope with this, we first establish a baseline scenario, where the wind power suitability scores (WPSS) are calculated based on the preferences of a decision maker that sought a balance between economic incentives and potential conflicts of interests. To test the robustness of these WPSS, we introduce three additional actors: the investor, the environmentalist, and the fisherman, each putting distinct weighting on power production and cost related issues, as well as possible environmental and commercial conflicts. Recent political engagement with energy self-sufficiency within the EU,

*A GIS is a comprehensive computer system for capturing, storing, checking and displaying data related to positions on the Earth's surface.

**TABLE 1** Data sets used in the analysis.

| Variable in this study | Retrieved variable | Host |
|---|---|---|
| Capacity factor | Monthly capacity factor | NORA3-WP[3] |
| Hourly wind power var. | Monthly avg. abs. wind power ramp rate | NORA3-WP[3] |
| Inter-annual wind power var. | Monthly capacity factor | NORA3-WP[3] |
| Ocean depth | Gridded Bathymetry | GEBCO[15] |
| Distance to central el. network | Power voltage transformers | Geonorge[16] |
| Oil and gas platforms | Oilfields | Geonorge[17] |
| Protected areas | Coral reefs | Geonorge[18] |
| Protected areas | Marine protection plan (A-list) | Geonorge[19] |
| Military areas | Areas for military practice | Geonorge[20] |
| Fishing activity | Report of ship position (VMS) | NDF[21] |
| Shipping activity | AIS shipping density | Geonorge[22] |
| Turbine visibility | Norway's maritime boarders | Geonorge[23] |
| Valuable areas | Particular valuable offshore areas | Geonorge[24] |
| AWT light O&M 1 | Hourly wind speed | NORA3-WP[3] |
| AWT light O&M 2 | Hourly hs | WAM[25] |
| AWT heavy O&M | Hourly wind speed and hourly hs | NORA3-WP[3] & WAM[25] |
| Distance to major port | ISPS port facilities | Geonorge[26] |
| Average yearly maximum u | Monthly wind speed | NORA3-WP[3] |
| Average yearly maximum hs | Hourly hs | WAM[25] |

*Note*: "Variable in this study" corresponds to the name of the variables used in this study; "Retrieved variable" refers to the variable(s) downloaded from the "host" dataset, used to calculate the variables in this study. "geonorge" is the Norwegian online database for maps and other data repository for spatial information.

Abbreviations: el. network, electricity network; hs, significant wave height; NCA, Norwegian Coastal Authority; NDEA, The Norwegian Defence Estates Agency; NDF, The Norwegian Directorate of Fisheries; NEA, Norwegian Environment Agency; NMA, The Norwegian Mapping Authority; NVE, The Norwegian Water Resource and Energy Directorate.

the Norwegian potential for offshore wind generation, and political pressure for a new national energy program that builds on the competence of existing oil industry all underline the importance of this study.

The paper is composed in the following way: In Section 2, we present the datasets. Section 3 deals with methodology, giving a brief description of the MCDA and AHP, a detailed step-by-step procedure for finding the optimal Norwegian offshore wind power sites (Section 3.1), how to obtain and calculate comparison matrices, criterion weights, and the suitability scores (Section 3.2), as well as introducing the four scenarios (Sections 3.3 and 3.4). Last part of Section 3 deals with an exemplification of the AHP framework (Section 3.5). Section 4 shows the results on the optimal wind power siting, discussing the WPSS obtained from the baseline scenario and the sensitivity analysis. The choice of method, implications of the findings, and limitations of the study are briefly discussed in Section 5. Lastly, Section 6 summarizes and concludes the paper and discusses the policy implications of the findings. The Appendix contains descriptions of all the criteria considered and the post-processing of the corresponding data (Appendix A), in addition to all the comparison matrices (Appendix B).

## 2 | DATA

A unique assembly of datasets has been put together and analyzed, using the framework of MCDA and AHP, to derive wind power suitability scores (WPSS) for the Norwegian economic zone (NEZ). The NEZ usually refers to the offshore area from 12 to 200 NM from the Norwegian baseline.[†] In our study, we include the territorial waters (0–12 NM) in the term NEZ. Table 1 contains information on the datasets and the corresponding variables used in this study. All the datasets are freely available. The backbone of this study relies on two newly generated high-resolution reanalysis NORA3-WP and WAM. These two datasets are briefly described below.

[†]The Norwegian baseline refers to the outer boundary of Norway's sovereignty area.

### 2.1 | High-resolution wind power estimates: NORA3-WP

Spatial planning of offshore wind power in the NEZ requires wind power related data covering the entire Norwegian offshore area. A couple of high-resolution wind resource data sets do exist, like the New European Wind Atlas (NEWA)[27] and the Global Wind Atlas (GWA).[28] Both NEWA and GWA are downscalings of the new reanalysis product from the European Centre of Medium-Range Weather Forecasts (ECMWF); ERA5,[29] using the Weather Research and Forecasting model (WRF). NEWA covers the European countries and parts of the surrounding offshore areas, while GWA has global onshore and near-coastal coverage. However, neither of these datasets fully covers NEZ. "NORA3-WP: A high-resolution wind power dataset for the Baltic, North, Norwegian, and Barents Seas" is a data repository for wind resources and wind power related data created by Solbrekke and Sorteberg,[3] providing data for the whole NEZ. NORA3-WP was generated to ease the access of relevant wind power data for stakeholders, decision-makers, researchers, students, politicians, and so forth. NORA3-WP is based on the 3 km Norwegian Reanalysis (NORA3) generated by the Norwegian Meteorological Institute.[30] NORA3 is a retrospective climate dataset with high spatial ($3 \times 3$ km) and temporal (1 h) resolution. NORA3 outperforms its host dataset (ERA5) for all wind-speed percentiles.[14] See Haakenstad et al[30] for more details regarding the generation and validation of NORA3. For a detailed validation of NORA3 towards offshore wind power, see Solbrekke et al.[14] More information and details on the generation of NORA3-WP can be found in Solbrekke and Sorteberg.[3]

Wind speed data used in this study are valid at 150 m, corresponding to the hub height of the IEA's 15 MW reference turbine,[4] used to calculate the wind power related variables. Key turbine-specific information is found in Table 2.

### 2.2 | Ocean wave dataset (WAM)

The wave model data used in this study are taken from a hindcast, also known as back-testing, covering the period 1996–2019 using a recent, modified version of the WAM wave model, Cycle 4.7.[31–33] The WAM hindcast has hourly output on a $3 \times 3$ km grid. The revised parameterization of the Charnock coefficient, a non-dimensional parameter used to express the sea state roughness, yields a reduced wind stress on the waves during high-wind events.[33,34] A validation of the wave hindcast against a control run without a high-wind reduction of the Charnock coefficient, covering the period 2011–2012, shows that the wave-height bias is dramatically reduced in high-wind events (particulary above 30 m/s). For more details, see Breivik et al.[35]

## 3 | METHODOLOGY

Detecting the most optimal locations for offshore wind farms is complex. MCDA is often used to solve a decision-problem that consists of complex and conflicting criteria (Mardani et al[36] and references therein) and can involve social, political, environmental, and economic aspects. Such an intricate process can be approached in different ways using different MCDA-methods, like multi-attribute utility or value theory (MAUT/MAVT), stochastic multi-criteria acceptability analysis (SMAA), and analytical hierarchical process (AHP), among others. In this study, we use the AHP.

### 3.1 | The analytical hierarchy process (AHP)

The analytical hierarchical process (AHP) was established by Thomas L. Saaty[37,38] and is by far the most utilized MCDA method.[7,9] It is especially widespread among studies involving energy, natural resources, sustainable manufacturing/engineering, spatial and strategic planning, and environmental assessments.[7] Huang et al[7] looked at trends in the application of MCDA in the period 2000–2009. The authors found that out of 312 MCDA studies, the AHP method was the preferred application in 48% of the cases. According to Munier and Hontoria,[9] the world-wide usage of the AHP method is likely to be linked to its user-friendliness; it is easy to learn and understand and is not mathematically complex, and the user can directly affect the outcome through their own perceptions—determining which criteria that are important and which that are not.

**TABLE 2** Turbine information for the 15 MW reference turbine from IEA.[4]

| Rated P | Hub height | Diameter | Specific rated P | Cut-in | Rated | Cut-out |
|---|---|---|---|---|---|---|
| 15 MW | 150 m | 240 m | 165.8 W/m$^2$ | 3 m/s | 10.59 m/s | 25 m/s |

*Note*: "Rated P" is rated wind power, "specific rated P" is the rated power divided by the rotor disk area; "cut-in," "rated," and "cut-out" correspond to the turbine-specific cut-in, rated, and cut-out wind speed limits, respectively.

### 3.1.1 | AHP limitations

Despite being the most commonly used MCDA method, AHP also has its drawbacks and limitations, like any other method. Three of these are discussed in detail by Brunelli[8]; we mention two. The first is the "rank reversal" phenomenon. This axiom states that if an alternative is added or excluded from the analysis, the order of the alternatives is not allowed to change. Second, we have the "different scales" issue. This includes the difficulty of assigning numbers to linguistic terms of preferences. For example, why should "I *strongly* prefer salad over pasta" be equal to 5 and not some other number? And why should the numerical priority scale be linear? The usage of numerical scales is an ongoing debate, and researchers have tried to come up with scales that are more appropriate than the priority scale from Saaty (See Table 3).

### 3.1.2 | How AHP works

The AHP splits the study-goal into main criteria and subcriteria affecting the goal. The relative importance of each criterion is evaluated against another criterion according to Saaty's priority scale[39] (see Table 3). If two criteria are of equal importance, a value of 1 is given in the comparison matrix. By contrast, a value of 9 would indicate the absolute importance of one criterion over the other. As a hierarchy consists of several hierarchy levels the starting-point is to perform pairwise comparisons of the subcriteria within each hierarchy-branch, followed by pairwise comparisons of the criteria in the parent-criterion level, always at the same hierarchy level.

The WPSS are obtained following the six steps outlined below:

1. Finding the overarching goal: obtaining relative wind power suitability scores for the entire Norwegian economic zone, and pinpointing optimal regions.
2. Deciding on the goal-influencing criteria and subcriteria (hierarchy).
3. Obtaining comparison matrices through pairwise comparisons of the criteria (see Figure 1) using Saaty's priority scale (see Table 3).
4. Determining the weightings of the criteria by calculating the geometric mean of the comparison matrices using Equation (2).
5. Normalizing the criterion fields and the criterion weightings using a maximum–minimum normalization method (see Equation (1)).
6. Multiplying the criterion fields with their corresponding weighting and sum up using Equation (7), resulting in one WPSS for each grid point.

## 3.2 | Calculation of comparison matrices, criterion weights, and suitability scores

Finding optimal wind power production sites is influenced by many and often conflicting criteria. Figure 1 displays a simplified diagram with the hierarchical study-setup. In addition, all study-criteria with a short description are listed in Table 4. One aspect that cause problems to the detection of optimal wind farm sites is that the criteria are measured in different scales: CF in percentage, ocean depth in meters, waiting times in hours, and so forth. And some criteria are only an indicator of yes or no (military activity, particular valuables areas, etc.). One solution could be to express the criteria in EUR/MWh. However, these measures are constantly changing. Therefore, to ensure that criterion fields and weights are given within equal scales, the criterion ($X$) in each grid point are scaled according to spatial maximum-minimum normalization:

$$X^n = \frac{X - \min X}{\max X - \min X}, \tag{1}$$

where $\max X$ and $\min X$ refer to the maximum and minimum value of $X$, respectively.

**TABLE 3** Saaty's priority scale used to rank the criteria in the pairwise comparisons.

| IoI | Description |
|---|---|
| 1 | Equal importance |
| 3 | Moderate importance |
| 5 | Strong importance |
| 7 | Very strong importance |
| 9 | Extreme importance |
| 2, 4, 6, 8 | Can be used to express intermediate values |

Abbreviation: IoI, intensity of importance.

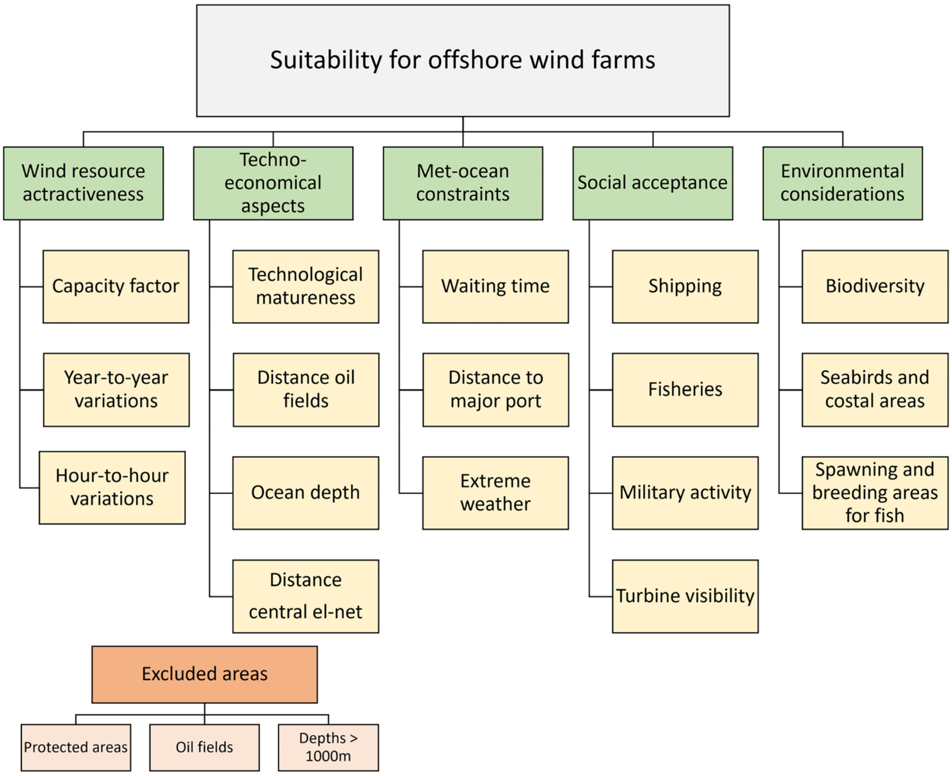


**FIGURE 1** The hierarchical diagram of the study, showing the goal (light gray), and two layers of criteria: the main criteria (green) and the subcriteria (light yellow), in addition to the excluded grid points (orange).

The comparison matrices are derived performing step 3 in the procedure described in Section 3.1.2. The criterion weightings ($\omega$) are obtained by calculating the geometric mean for each of these matrices. This follows the procedure in Brunelli[8]:

$$\omega_i = \left[\prod_{i,j=1}^{k} a_{i,j}\right]^{\frac{1}{k}}, \quad i,j \in [1,k] \tag{2}$$

where $a_{i,j}$ are the entries in the comparison matrix **A** and k is the total number of criteria. For example, the weightings for the capacity factor compared to the other criteria in the WRA category will be

$$\omega_{CF} = [1 \times 7 \times 9]^{\frac{1}{3}} \tag{3}$$

where CF is ranked as 7 (very strong importance) over HARR and 9 (extreme importance) over YARR, according to Saaty's scale (see Table 3). As a next step, the criterion weightings within the same criterion branch and hierarchy level are normalized by the sum of the criterion-weightings:

$$\omega_i^n = \frac{\omega_i}{\sum_{i=1}^{k} \omega_i}, \quad i \in [1,k] \tag{4}$$

In the case of perfect rationality in the pairwise criterion comparisons, that is, where all the pairwise comparison weights reflect the overall importance of a criterion across all the criteria, we then have $a_{ij} = \omega_i/\omega_j$ for all $i,j$, and the goal is to minimize the distance between the comparison matrix **A** and the weighting relationship matrix $\left(\omega_i^n/\omega_j^n\right)_{k \times k}$:

$$\min \sum_{i=1}^{k}\sum_{j=1}^{k}\left(a_{i,j} - \frac{\omega_i^n}{\omega_j^n}\right)^2, \tag{5}$$

**TABLE 4** A list of the criteria considered in this study (with abbreviations in parenthesis), and a short description and objective of each criterion.

| Criteria | Short description | Objective |
|---|---|---|
| **Wind resource attractiveness (WRA)** | Wind power production characteristics | maximize |
| └ Capacity factor (CF) | Wind power production capacity | maximize |
| └ Hourly power ramp rate (HARR) | Hourly wind power production stability | minimize |
| └ Yearly CF change (YARR) | Yearly wind power production reliability | minimize |
| **Techno-economic aspects (TEA)** | The technological potential and economical aspects | minimize |
| └ Ocean-depth function (ODF) | Indicator for relative installation costs due to ocean depth | minimize |
| └ Distance to central el-network (DCEN) | Indicator for cable costs for power transmission | minimize. |
| └ Distance to oil- and gas platforms (DOP) | Distance to the closest oil- and gas installation | minimize. |
| └ Technical risk (TR) | Technology risk tied to the technology | minimize |
| **Social acceptance (SA)** | Competing offshore activities and human acceptance | minimize |
| └ Shipping activity (SH) | Shipping activities and offshore transportation | minimize |
| └ Military area (MA) | Areas of military practice | 0 or 1 |
| └ Fishing activity (FA) | Commercial fishing activity | minimize |
| └ Turbine visibility (TV) | Related to wind turbines visual and auditory noise | minimize |
| **Environmental considerations (EC)** | Valuable areas for biodiversity, birds and fish | minimize |
| └ Biological diversity (BD) | Areas important for retaining a rich marine biodiversity | 0 or 1 |
| └ Bird nesting and coastal zones (BC) | Important areas for bird nesting and rich coastal areas | 0 or 1 |
| └ Fish and spawning grounds (FS) | Grounds for spawning and growth of fish | 0 or 1 |
| **Met-ocean constraints (MO)** | Wind farm constraints related to the met-ocean conditions | minimize |
| └ Inaccessibility (IACC) | Reduced accessibility of potential offshore wind farms | minimize |
| └└ Accumulated waiting time (AWT) | Accumulated waiting time (AWT) when O&M is impossible | minimize |
| └└└ Light O&M 1 (L1) | AWT for light O&M by helicopter | minimize |
| └└└ Light O&M 2 (L2) | AWT for light O&M by light boat (catamaran) | minimize |
| └└└ Heavy O&M (H1) | AWT for heavy O&M by crane vessel | minimize |
| └└ Distance to major port (DMP) | Distance to major port for O&M vessels | minimize |
| └ Extreme conditions (EXT) | Design requirements in harsh met-ocean conditions | minimize |
| └└ Average yearly maximum u (max u) | Average yearly maximum of hourly wind speed | minimize |
| └└ Average yearly maximum hs (max hs) | Average yearly maximum of hourly significant wave height | minimize |

*Note*: See Appendix A for more detailed description of all the criteria.
Abbreviations: el-network, electricity network; O&M, operation and maintenance.

Equation (5) represents an optimization problem minimizing the distance between the comparison matrix **A** and the weighting relationship matrix. However, the solution to the equation is not straightforward. Nevertheless, by applying the characteristics of the monotonic increasing natural logarithm ($ln(x)$), the approximated analytic solution to the optimization problem (Equation (5)) is the geometric mean, and the optimization problem (minimizing the distance between **A** and $\left(\omega_i^n/\omega_j^n\right)_{k\times k}$) can be expressed in the following way:

$$\min \sum_{i=1}^{k}\sum_{j=1}^{k}\left(lna_{i,j}+ln\omega_j^n-ln\omega_i^n\right)^2,\ \text{subject to}\quad \sum_{i=1}^{k}\omega_i^n=1,\quad w_i^n>0\forall i \tag{6}$$

The optimal weighting vector is associated with the minimization problem in Equation (6), that is, obtaining the closest consistent approximation of the comparison matrix A to $(\omega_i/\omega_j)_{kxk}$.

After deriving the criterion weights, the wind power suitability score (WPSS) for each grid point is calculated using the following equation:

$$\text{WPSS}=\sum_{n=1}^{N}\left(\left[\prod_{m=1}^{M}\omega_n^m\right]X_n\right) \tag{7}$$

where M is the number of hierarchy levels, $N$ is the number of criteria in current hierarchy level, $\omega_n^m$ is the normalized criterion weight (between 0 and 1), and $X_i^n$ is the current normalized criterion field (between 0 and 1). For example, $\omega_1^2$ will be the weight of “techno-economic aspects” in relation to the other main criteria (e.g., wind resource attractiveness etc.), while $\omega_2^2$ will be the weight of, for example, “ocean depth function” over the other criteria in the “techno-economic aspects”-criterion. WPSS will take on values from 0 to 1, with large WPSS values representing the most suitable locations. See Appendix A for a detailed description of the criteria taken into consideration in this MCDA-study.

**TABLE 5** Pairwise comparison values for the five main criteria (WRA, TEA, SA, EC, and MO) using Saaty's priority scale (Table 3) for the four scenarios: "baseline," "investor," "environmentalist," and "fisherman."

| | Saaty's priority scale value | | | |
|---|---|---|---|---|
| Pairwise criterion comparisons | Baseline | Investor | Environmentalist | Fisherman |
| WRA vs. TEA | 2 | 2 | 4 | 4 |
| WRA vs. SA | 3 | 4 | 3 | 1 |
| WRA vs. EC | 3 | 4 | 1 | 2 |
| WRA vs. MO | 3 | 3 | 4 | 4 |
| TEA vs. SA | 2 | 3 | 1/2 | 1/4 |
| TEA vs. EC | 2 | 3 | 1/4 | 1/3 |
| TEA vs. MO | 2 | 2 | 1 | 1 |
| SA vs.EC | 1 | 1 | 1/3 | 2 |
| SA vs. MO | 1 | 1/3 | 2 | 4 |
| EC vs. MO | 1 | 1/3 | 4 | 3 |

*Note*: Fractional comparison values mean that the first criterion is less important than the second criterion. For example, SH versus TV = 2 (1/2), meaning that SH is more (less) important than TV.
Abbreviations: EC, environmental considerations; MO, met-ocean constraints; SA, social acceptance; TEA, techno-economic aspects; WRA, wind resource attractiveness.

Note that AHP uses an outranking method[‡] where the objective is to provide a set of preference relations between the alternatives. The method makes no judgment on whether an alternative is good or bad in general or compared to other alternatives outside the study (in this case other offshore areas), but rather assesses if a grid point in NEZ is better or worse compared to other grid points in NEZ. Thus, a low score does not mean that the grid point is unsuited for wind power; it means that this grid point is less suited compared to other sites within NEZ. We also provide categorical wind power suitability scores (CWPSS), where we define the relative suitability as being very high (10% grid points with the highest score), high (the highest 10%–35%), average (35%–65%), low (65%–90%), and very low (10% grid points with the lowest score).

## 3.3 | The baseline scenario

As the pairwise comparisons of the criteria is a subjective procedure, we start with a baseline scenario. The baseline scenario reflects a decision maker that does not prioritize one set of criteria strongly but realizes the importance of selecting areas that are economically attractive and that have a low risk of potential conflict of interests. The column "Baseline" in Table 5 lists the pairwise criterion comparisons for the five main criteria (WRA, TEA, SA, EC, and MO) for the baseline scenario. See Table A3 for the reasoning of the comparison values. Table A4 holds the pairwise comparison values for the subcriteria.

Calculating the geometric mean of the comparison matrices using Equations (2) and (4), we obtain the baseline criterion weightings, illustrated by the donut diagram in Figure 2. The normalized criterion weightings give information on how much (in percentage) each criterion will contribute to the basline WPSS. The WRA criteria is most important, accounting for 39% of the WPSS. Within WRA, the most important subcriterion is power production (CF), making up 72% of the parent criterion and 28% of the total WPSS. TEA is also very important and accounts for 23% of the WPSS, with the subcriteria ODF and DCEN being equally important (9% of the WPSS). The three criteria SA, EC, and MO are equally important, where each constitutes 12% of the WPSS. After obtaining all the criterion weightings, the WPSS is calculated using Equation (7).

## 3.4 | Sensitivity analysis: the investor, the environmentalist, and the fisherman

To investigate to what degree the pairwise subjective criterion importance influences the weightings from Section 3.3, we perform a sensitivity analysis by introducing three additional actors: the investor, the environmentalist, and the fisherman. The new scenarios reflect actors having distinct preferences when it comes to offshore wind farm spatial planning. Unlike the baseline scenario, the three actors have more polarized preferences to the prioritization of the goal-affecting criteria. In addition to the pairwise comparisons between the five main criteria for the baseline scenario, Table 5 also contains the comparison values for the three additional actors. Table A5 holds the details for the pairwise comparisons of

[‡]Outranking method compares pairs of alternatives and assign them a degree of preference, dominance, or indifference, reflecting the degree of influence on the overarching goal.

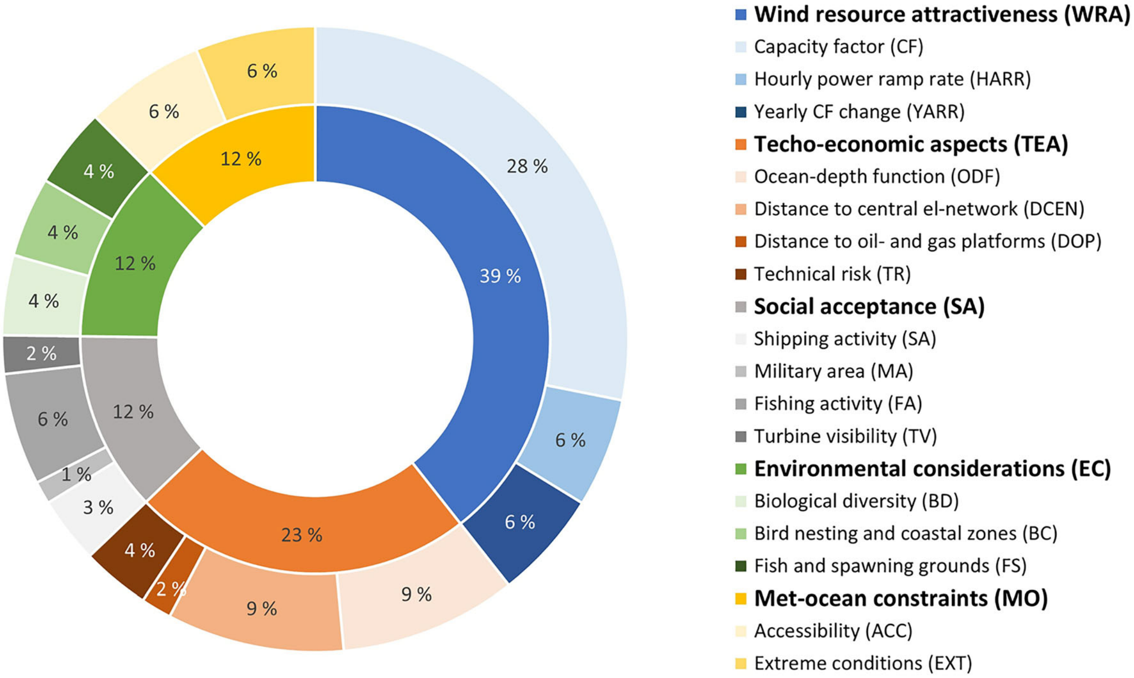


**FIGURE 2** The normalized criterion weighting ($\omega_i^n$) as a percentage for each criterion in the baseline scenario.

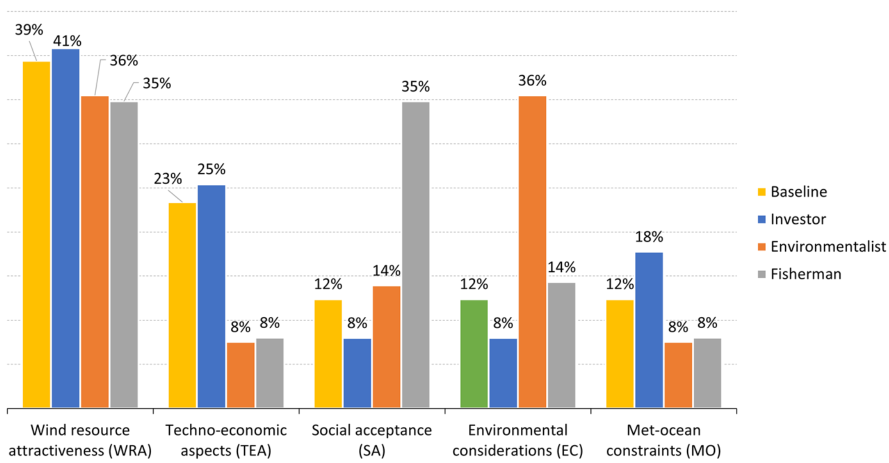


**FIGURE 3** The criterion weightings in percentages for the baseline (yellow bars) and the three actors in the sensitivity analysis: "the investor" (blue bars); "the environmentalist" (orange bars); "the fisherman" (gray bars).

the subcriteria. Whenever a pairwise comparison value is below one (e.g., one half or one third), it implies that the criterion listed first is less important than the second criterion. Table 5 and Figure 3 summarize the primary focus areas for all the narratives.

Compared with the baseline, the investor puts more emphasize on revenue (WRA) and cost (TEA + MO) and less on social acceptance (SA) and environmental considerations (EC). These preferences are shown by lowering the relative importance of SA and EC over WRA, TEA, and MO. Within the WRA criterion, the investor weighs up the importance of the subcriterion CF (reflecting the wind farm's income) compared with the subcriteria on power variability (HARR/YARR). Since ocean depth (ODF) and distance to shore (DCEN) are reflecting up-front costs of a new wind farm, these are more important than technological risk (TR) and distance to oil and gas activity (DOP) for the investor character compared with the baseline scenario.

The environmentalist is naturally more focused on EC than TEA and MO but still emphasizes good WRA, due to area-efficient wind power production. Unlike the baseline scenario, the environmentalist puts a higher priority on CF than on HARR/YARR. In addition, the importance of the opportunity to provide local wind power to the oil and gas industry is heavily weighted against (ODF/DCEN vs DOP = 9). The environmentalist would rather see the end of the oil and gas era than supporting a greener oil industry.

The fisherman weighs up the SA and prioritizes the subcriterion fishing activity (FA) and to some extent also shipping activity (SH) at the expense of the other subcriteria in SA. Like the other actors, WRA is also important to the fisherman, reflecting the benefit of area-efficient wind power production. Other cost-related criteria such as TEA and MO receive low importance.

## 3.5 | Application of the AHP framework

This section exemplifies the AHP framework using the six-step procedure from section 3.1.2 using three example-sites, considering only the criteria in the WRA-category (see Table 4):

1. Settling the goal: Find the most optimal wind power site using three example-sites.
2. Gather the criteria that influences the goal: Capacity factor (CF), hourly absolute wind power ramp rate (HARR), and yearly CF change (YARR).
3. Obtain the comparison matrix for the criteria by conducting a pairwise comparison between CF, HARR, and YARR using Saaty's priority scale (see Table 3). See Table 6.
   Table 6 illustrates that HARR and YARR have equal importance, while CF have "strong importance" (5) compared to HARR and YARR.
4. Calculating the geometric mean of each row in Table 6 using Equation (2) results in Table 7.
5. The entries in Table 7 are normalized (using Equation (4)) by the sum of the weights. The resulting criterion weights ($\omega$) are listed in Table 8. The sum of the criterion weightings in Table 8 is equal 1. The normalization by the sum of the weightings ensures that the criteria (CF, HARR, and YARR) are not influencing the weighting of their parent-criterion (WRA).
   Table 9 includes the grid-point-specific criterion-values and the max-min normalized version of the criterion-values for the example-sites. The

**TABLE 6** The comparison matrix for the criteria in the "wind-resource attractiveness" category.

| Comparison matrix | | | |
|---|---|---|---|
| | CF | HARR | YARR |
| CF | 1 | 5 | 5 |
| HARR | 1/5 | 1 | 1 |
| YARR | 1/5 | 1 | 1 |

**TABLE 7** The geometric mean for the criteria in the "wind-resource attractiveness" category.

| CF | HARR | YARR |
|---|---|---|
| 2.92 | 0.59 | 0.59 |

**TABLE 8** The normalized weightings ($\omega$) for the subcriteria in the "wind resource attractiveness" category.

| $\omega$ | | |
|---|---|---|
| CF | HARR | YARR |
| 0.71 | 0.14 | 0.14 |

**TABLE 9** The criterion values and the normalized criterion values for CF, HARR, and YARR and for the three example sites.

| | Criterion values | | | Normalized criterion values | | |
|---|---|---|---|---|---|---|
| Sites | CF | HARR | YARR | $CF^n$ | $HARR^n$ | $YARR^n$ |
| Site 1 | 54 | 1.2 | 3 | 0.4 | 0.5 | 0.5 |
| Site 2 | 58 | 1.3 | 4 | 0.8 | 0.75 | 0.75 |
| Site 3 | 56 | 1.1 | 5 | 0.6 | 0.25 | 1 |

*Note*: The *n*-superscript represents the normalized variable values.

max-min normalization is done using Equation (1) with the following max-min values: max(CF) = 60, min(CF) = 50; max(HARR) = 1.4, min(HARR) = 1.0; max(YARR) = 5, min(YARR) = 1.

6. After the max–min normalization, the normalized criterion values in Table 9 are multiplied with their respective normalized criterionweightings from Table 8 and summed up (according to Equation (7)) obtaining the total score (WPSS) for each site:

$$\mathrm{WPSS} = \omega_1^n CF^n + \omega_2^n (1 - HARR^n) + \omega_3^n (1 - YARR^n), \tag{8}$$

where large values of S represents the most suitable site for a wind farm. However, large values of HARR and YARR are undesirable, hence the usage of (1 − HARR) and (1 − YARR) in Equation (8). The n-superscript represents the min–max normalized variable-values.

The WPSS seen in Table 10 show that example-site 2 is the most suitable location for a wind farm considering only the criteria in the WRA category.

## 4 | RESULTS

Finalizing the application of the AHP framework carrying out the six-step procedure in 3.1.2 using all the criteria in Table 4 provides one WPSS for each grid point in NEZ. The scores, between 0 and 1, reflect the grid-point-specific relative suitability for wind power application; high values correspond to high suitability, while lower values indicate lower suitability. The WPSS emerges from the sum of normalized criterion weightings multiplied by their normalized criterion-fields (Equation (7)).

### 4.1 | Wind power suitability scores: baseline

Figure 4 displays the WPSS and the CWPSS for the baseline scenario. According to the "excluded areas" (Section A.1.5), a large area in the western part of the NEZ is excluded due to the water depth (>1000 m), in addition to grid points with oil and gas activity and protected marine areas.

**TABLE 10** The total suitability score (WPSS) for the three example sites.

| WPSS | | |
|---|---|---|
| Site 1 | Site 2 | Site 3 |
| 0.43 | 0.64 | 0.54 |

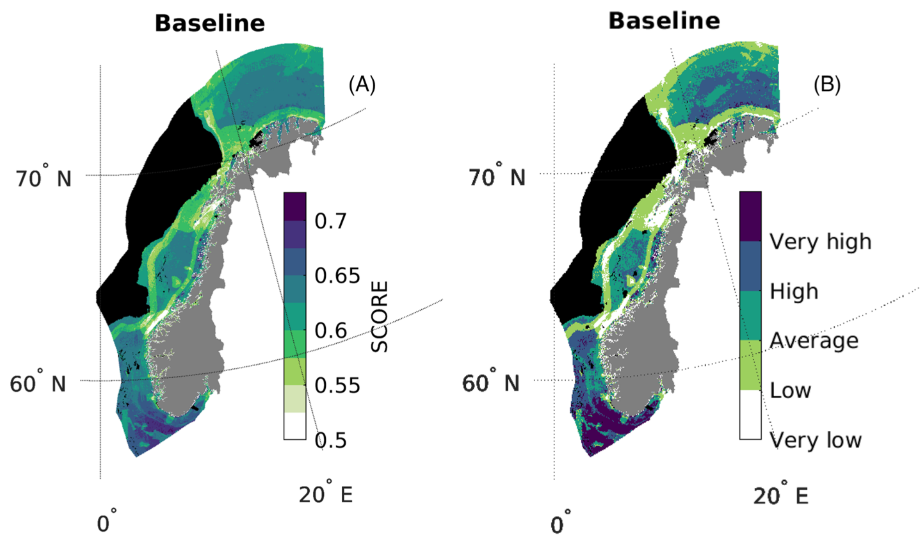


**FIGURE 4** Wind power suitability scores (WPSS) for the baseline scenario (A). Categorized WPSS according to the suitability of an offshore wind farm being the following percentile values: very high (10% grid points with the highest score), high (the highest 10%–35%), average (35%–65%), low (65%–90%), and very low (10% grid points with the lowest score) (B). The black areas are excluded grid points (see Section A6).

In general, grid points close to the Norwegian coast receive low WPSS. The relative unsuitability of these points is tied to low capacity factors, high wind power variability, and several conflicting interests. Regions with environmental considerations receive low suitability scores, especially areas with multiple conflicts of interests, such as the regions in northern Norway around Lofoten and Vesterålen, which have relatively harsh met-ocean conditions and high fishing and shipping activity. Along the Norwegian northwest coast and at the Norwegian continental shelf slope, environmental issues (high biodiversity, Figure A2D) and significant shipping activity (Figure A3A) in addition to relatively harsh met-ocean conditions (Figure A4) contribute to low WPSS. The most suitable area for wind power is located in the southern part of the NEZ. Almost the entire Norwegian part of the North Sea and Skagerak are ranked "average" to "very high" CWPSS (see Figure 4B). This region has the best combination of wind resources, techno-economic aspects, low potential for conflict of interests, and a relatively favorable met-ocean environment using the baseline criteria preferences (see Table 5). One of the two Norwegian offshore areas opened for large-scale offshore wind power development, "Sørlige Nordsjø," is located in the area receiving the highest WPSS in the baseline scenario.[5]

Despite considerable fishing activity, parts of the NEZ located in the Barents Sea are also suitable for wind power production (note that possible icing risks are not included among the criteria). Scattered grid points offshore the coast of mid-Norway also receive CWPSS values ranging form "average" to "very high." This area has good wind resources, low hourly variability despite the proximity to the shore, low fishing and shipping activity, no major environmental considerations, and relatively mild met-ocean conditions.

### 4.1.1 | Wind power suitability scores: the investor, the environmentalist, and the fisherman

The WPSS for the narratives are derived by multiplying the new criterion weightings for the three actors with the corresponding criterion fields and summed up (Equation (7)). Figure 5A–C shows the CWPSS for the three scenarios investor, environmentalist, and fisherman, respectively. In addition, the figure contains the differences in CWPSS between the baseline and the three scenarios (D–F).

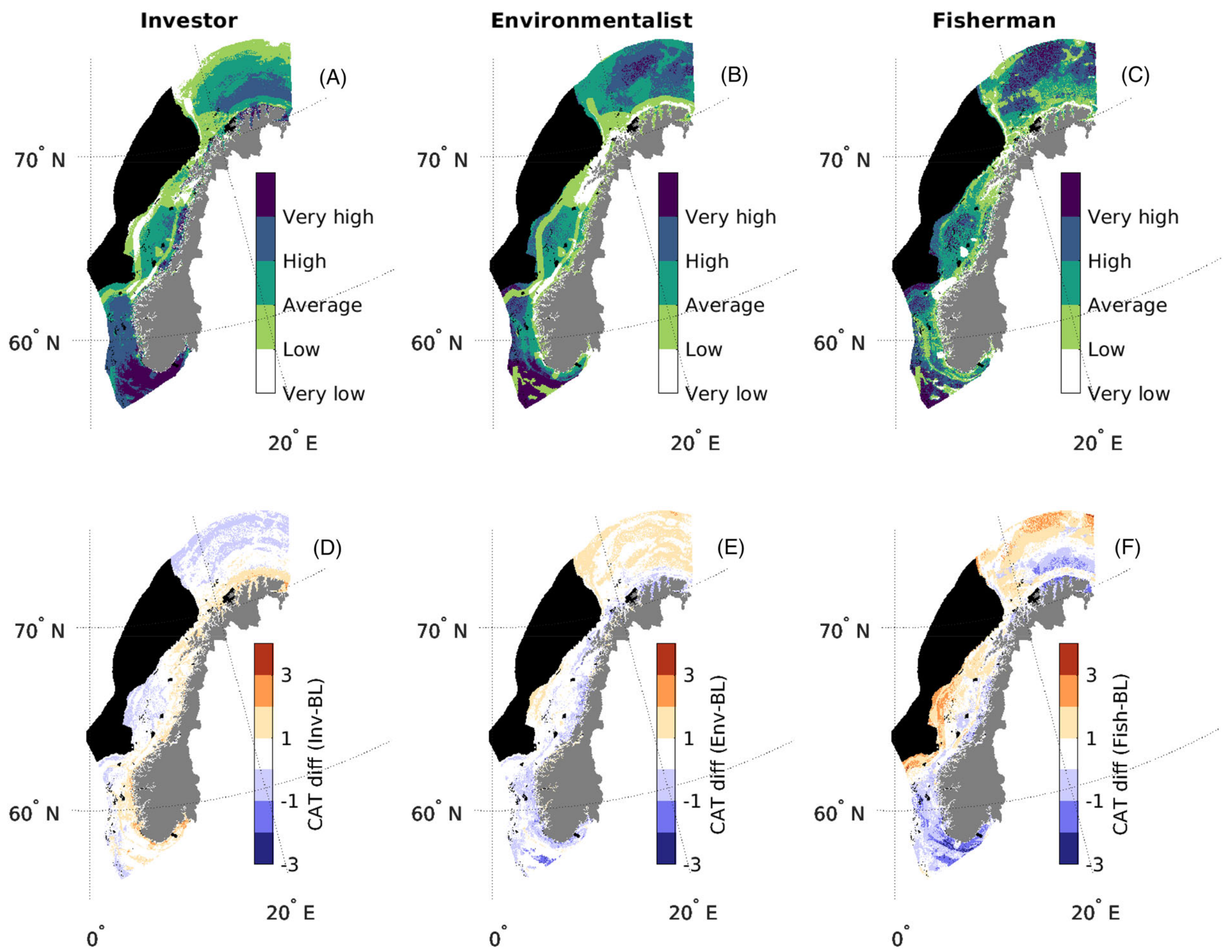


**FIGURE 5** Results from the sensitivity analysis, including (A–C) categorical suitability scores for the three scenarios: (A) Investor (Inv); (B) Environmentalist (Env); (C) Fisherman (Fish). (D)–(F) correspond to the difference in categorical suitability scores (CAT diff) between the baseline (BL) and the other scenarios.

The differences in CWPSS between the baseline scenario and the investor can be seen in Figure 5D. In general, the areas close to shore receive higher CWPSS in the investor narrative than in the baseline scenario, while those further from land receive a correspondingly lower score. This occurs as a result of the investor's focus on cost and revenue related variables such as wind power production, ocean depth, distance to shore, and met-ocean constraints (WRA, TEA, and MO), in addition to a reduced focus on environmental considerations (EC) and social acceptance (SA). Many of these aspects favor wind farms closer to shore, resulting in a higher CWPSS for these sites. As in the baseline scenario, the most suitable offshore areas for wind power applications are still in the southern part of NEZ, in the Norwegian part of Skagerak, and in the near-coastal areas off mid-Norway.

In the environmentalist-scenario (Figure 5B and 5E), the significance of "valuable areas" (see Figure A2D) is prominent in the score-map. Grid points outside the valuable areas receive higher scores than those within. However, regions to the south and north of Norway are still the most optimal areas for offshore wind farms. In general, grid points close to shore receive a lower CWPSS in the environmentalist's scenario than in the baseline scenario due to many potential social conflicts and environmental considerations.

Of the three actors, the fisherman's narrative is the one with the largest difference in CWPSS compared with the baseline scenario (Figure 5C and 5F). Almost the entire Norwegian part of the North Sea has its categorical wind power suitability score reduced by one to three categories due to the fishing and shipping activity in this region. Deeper regions further away from the mainland gain one to two categories and are hence considered more suitable for wind power development in this narrative than under the baseline scenario.

## 4.2 | Where are the optimal wind farm sites?

The results of the sensitivity analysis demonstrate the ability of the chosen method to provide insights into how different criterion preferences affect suitability scores. In our case, some of the optimal regions obtained through the four scenarios (basline, investor, environmentalist, and fisherman) are rather robust to moderate changes in the criterion preferences.

Figure 6 shows the robustness of WPSS to variations in criterion importance. Panel (A) displays the areas that are among the 35% of the grid points with the highest suitability score (points receiving the highest or the second highest CWPSS) for all the four scenarios and hence are the most resistant regions to changes in criterion importance. The figure shows that large areas in the southern part of the NEZ are highly robust and suitable for wind power. In addition, parts of the Barents Sea and scattered grid points outside mid-Norway are also robust and highly suitable for wind power. The regions that exclusively receive the highest categorical score ("very high" suitability) for all the scenarios are shown in panel (B). The optimal Norwegian offshore regions are here pin-pointed, and the southern part of NEZ stands out as the optimal and most resistant choice for siting of future wind farms.

Figure 6 also shows the two offshore areas opened for large-scale wind power installation in the Norwegian waters, "Utsira Nord" (UN, northern blue square) and "Sørlige Nordsjøen 2" (SN2, southern blue square). From our analysis, there are large differences regarding how suitable these areas are. Almost the entire SN2-area has a very high suitability score (the highest category) throughout all the four scenarios. Comparing

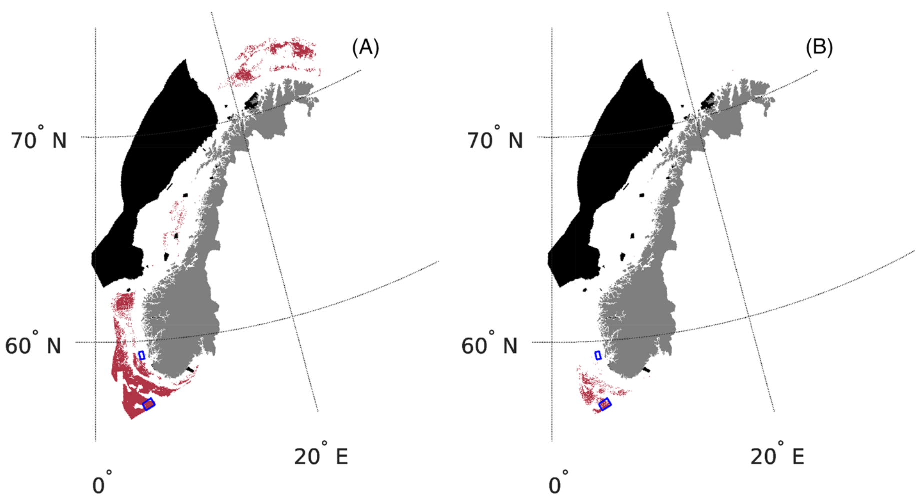


**FIGURE 6** Areas (red) that are resistant to changes in criterion-importance. (A) Areas receiving "high" or "very high" suitability score along all four scenarios. (B) Areas that exclusively receive "very high" suitability score for all scenarios. Black areas are excluded grid points due to either protected areas, oil and gas activity, or ocean depth (see Appendix A.6 for more maps and information). The blue squares corresponds to "Utsira Nord" and "Sørlige Nordsjø 2," the two areas opened for wind power application in Norwegian waters. "Very high" suitability score: 10% grid points with the highest score. "High" suitability score: the highest 10%–35% of the grid points.

that to the suitability of UN, not even parts of that area receive high or very high (second highest or highest category) suitability. This means that UN is less robust to changes in the criterion importance compared to SN2.

## 5 | DISCUSSION OF LIMITATIONS

Dealing with optimal offshore wind farm siting is an issue in a multidisciplinary research field. The criteria used to determine an ideal location, as considered in previous research on the issue are numerous and span a range of various disciplines. Some of these criteria are specific to certain regions (Díaz and Guedes Soares[10] and the references therein).

Choosing relevant criteria for an MCDA and AHP analysis can be challenging. The criteria directly related to the study's aims must be included for the analysis to have a realistic outcome. After gathering all possible goal-influencing criteria, one has to settle with the idea that only the most important criteria are considered and others have to be excluded from the analysis. During this work, we discovered a lack of certain key datasets that could further distinguish suitability of sites.

Due to the lack of an extensive dataset on Norwegian offshore sea bed conditions, we could not consider any geological information in this study. Sea bed conditions influence the anchoring used for the substructure of a wind farm, and permanent anchors have different designs depending on ground and rock types.

An improved interconnected European electricity grid is important for a future electricity mix with a large share of renewable energy sources. A direct connection from an offshore wind farm to the European electricity system through a hybrid electricity cable is a realistic prospect in the future. However, in February 2022, the Norwegian government decided that the first part of Sørlige Nordsjøen 2 will not be connected to the European grid.[6] Therefore, we have excluded direct European electricity connections in this study and did only use the distance to electricity infrastructure on the Norwegian mainland.

Icing on maritime structures and vessels can also be a problem, caused by sea spray and freezing rain. Icing can cause gravitational problems as the structures gain irregular mass (ice) and thus change the center of gravity, resulting in a reduced wind farm operational time. We have excluded icing due to the lack of proper open-source national maps on such conditions.

The Norwegian offshore wind power industry is in its infancy, and its regulatory regime is also under development. While there are basic rules concerning the selection of areas to be licensed (§2-2 of the Lov om fornybar energiproduksjon til havs (Havenergiloven) LOV-2010-06-04-21; see also: Forskrift til havenergilova FOR-2020-06-12-1192), the particularities of these rules and the related methodologies to be adopted are under revision. In June 2021, the Norwegian government presented a draft for a "Guidance Note on Opening of Areas, Concession Process and Application" that is currently being revised after accounting for comments by stakeholders.[40] Due to the scope and nature of this paper and the ongoing legal developments, these legal issues are excluded from this study. We do, however, exclude already protected areas, but include marine areas used for military training, though they may be excluded when a new regulative framework is in place.

The socio-economic benefits can be huge for a community in terms of wind-farm related value creation and employment.[41] This goes beyond revenue and cost and would incorporate the notion of new wind farms as strategic decisions and a long-term socio-economic investment in a new national industry important for national employment and tax income. This possible criteria connected to national strategic decision-making is not covered in this paper. Our analysis also leaves out wind farm size and design and number of turbines. These are important factors to determine the economy of offshore wind power but they are less important for the comparison between regions.

Like all MCDA-based studies, the results obtained here are to some extent constrained by the choice of method (i.e., AHP), the quality of the data used, and the selection of criteria and their subjective pairwise comparisons. The results should therefore be treated with caution and not as absolute truth regarding optimal Norwegian offshore areas for wind power deployment. That said, the results obtained in this study demonstrate that large parts of the Norwegian sector of the North Sea are highly suitable for offshore wind power, especially the southern areas. This result is robust to moderate changes in criterion importance as investigated through the sensitivity analysis. Several offshore wind farms are already operating (e.g., Dudgeon, Sheringham Shoal, Hornsea 1, Alpha Ventus, etc.) or are under construction or under development (Hornsea 2, Dogger bank A, B, C, Sofia, etc.) in other parts of the North Sea. A wind farm in the Norwegian sector of the North Sea will have a relatively short distance to the Norwegian mainland, but will also be close to the European continent and to a larger interconnected electricity system (not taken into account in our analysis).

## 6 | SUMMARY AND CONCLUDING REMARKS

Using the framework of MCDA and AHP, we provide unprecedented wind power suitability scores (WPSS) and optimal areas for offshore wind power application for the entire Norwegian offshore region. Calculating WPSS and finding optimal offshore wind sites were achieved by splitting the decision-making process into five main goal-affecting criteria: wind resource attractiveness, techno-economic aspects, social acceptance, environmental considerations, and met-ocean constraints. These five main criteria were further divided into 17 subcriteria.

Furthermore, the WPSS were derived for a baseline scenario, where the importance of criteria was pairwised compared through a decision maker that sees the value of balancing economic incentives and potential conflicts of interests. The results show that regions in the southern part of the Norwegian economic zone (NEZ) received the highest WPSS, together with areas in the Norwegian part of the Barents Sea and along the coast of mid-Norway.

To test the robustness of the results obtained in the baseline scenario, we carried out a sensitivity analysis by introducing three additional scenarios, each representing a decision maker with distinct preferences for wind farm spatial planning, differing from the baseline-preferences. These are *the investor*, *the environmentalist*, and *the fisherman*. Tuning of criterion importance to reflect the priorities of the investor, environmentalist, and fisherman demonstrated that the main results were robust to changes in the priority of criteria; The southern part of NEZ received the highest WPSS for all four scenarios. However, certain geographical areas were more sensitive to the tuning of criterion importance than others, like the Norwegian part of the Barents Sea and along the coast of mid-Norway. There was a general increase in the WPSS for far-offshore regions when either environmental or social-acceptance criteria were prioritized over cost-related criteria. This reflects that near-coastal regions already have considerable human activities and/or are important in terms off marine ecosystems, favoring far-offshore regions over areas close to shore. Regions with numerous conflict of interests, such as those along the northwest coast of Norway, received low scores for all scenarios. Since wind farm revenue is proportional to the power production and area efficient use of the ocean space is important, wind power production was prioritized in all scenarios, generally resulting in low suitability scores for areas with low generation capacity.

For the two areas opened for offshore wind application, Utsira Nord (UN) and Sørlige Nordsjø 2 (SN2), the robustness test discovered that only SN2 receives very high suitability scores throughout all the four scenarios, while UN was more sensitive to changes in the criterion importance. The fact that UN and SN2 receives so different WPSS and robustness undermines the importance of studies like this that questions and challenges the governmental decisions forming the basis for the development of the Norwegian offshore wind industry.

The use of MCDA with the application of the AHP method is shown to be a promising tool for separating areas with high offshore wind power suitability from areas with low suitability. We have exemplified the usage of AHP and thorougly described the process for transparency and reproducibility. This way of doing spatial planning, with relative wind power suitably scores, is shown here as a powerful framework for assisting future discussions on optimal offshore wind farm siting.

## AUTHOR CONTRIBUTIONS

Ida Marie Solbrekke and Asgeir Sorteberg conceptualized the overarching research goals of the study, in addition to conducting formal analysis regarding statistical and mathematical techniques and methods. Ida Marie Solbrekke was responsible for the data curation and creation of software code, visualization of data, and preparation of the original draft, with contribution from Asgeir Sorteberg. In addition, Asgeir Sorteberg was responsible for the supervision. Both authors contributed to the revision and editing process of the paper.

## ACKNOWLEDGEMENTS

This work was part of a PhD-project funded by the University of Bergen and was partly funded by the Research Council of Norway through the Climate Futures initiative (grant 309562).

## CONFLICT OF INTEREST STATEMENT

No competing interests to declare.

## PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/we.2871.

## DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

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**How to cite this article:** Solbrekke IM, Sorteberg A. Norwegian offshore wind power—Spatial planning using multi-criteria decision analysis. *Wind Energy*. 2023;1-28. doi:10.1002/we.2871

## APPENDIX A: CRITERIA

When dealing with MCDA and AHP, an important step is to obtain all relevant criteria affecting the study goal. Below are descriptions of the criteria considered.

### A.1 | Wind resource attractiveness

The category of wind resource attractiveness includes wind power production characteristics such as capacity factor (CF), hourly wind power variability, and inter-annual fluctuations in the capacity factor.

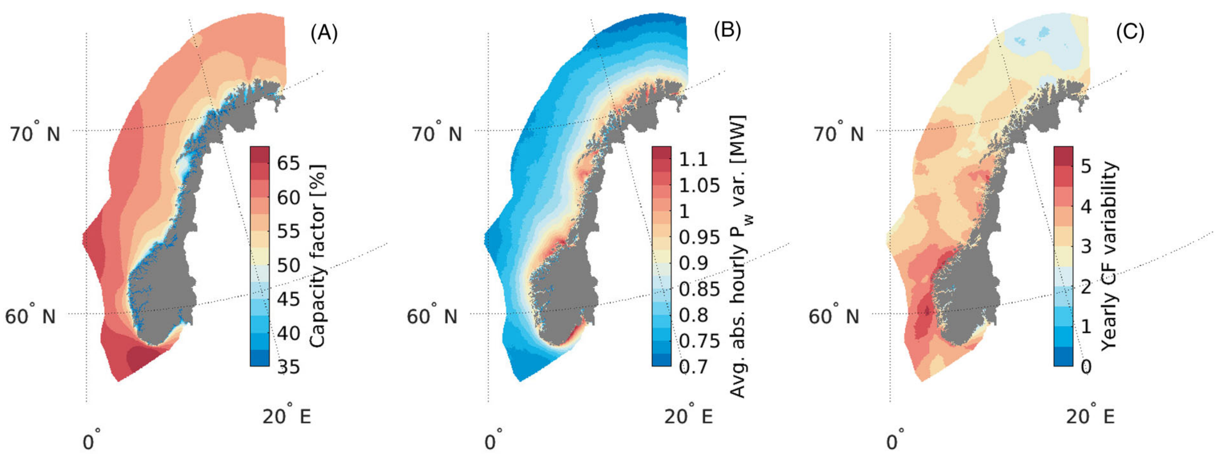


**FIGURE A1** The wind power production characteristics from the wind resource attractiveness category for the year 1996–2019, including (A) climatological capacity factor in percentage (CF); (B) average absolute hourly change in wind power production in MW (HARR); (C) average absolute inter-annual variation in the capacity factor in percentage points (YARR).

#### A.1.1 | Capacity factor

Wind conditions and potential wind power production are important when evaluating new sites for wind power installation. We use the average monthly capacity factor (CF) from 1996 to 2019 for a single turbine as a measure of wind power production. CF is the fraction between the produced wind power and the installed wind power capacity. Sites with a high CF will be attractive for wind power installation due to the inverse relationship between wind power production and the levelized cost of energy (LCoE). For details on the calculations of CF, see Solbrekke and Sorteberg.[3] Wind power wake loss is a important factor when calculating CF. However, since the most important factor in this study is the difference in CF between sites A and B, the effect of wake losses is excluded.

If the optimal spot for wind power production was solely based on CF, the area with the highest WPSS would coincide with the area of highest CF values. Figure A1A displays the monthly average CF (1996–2019). The area that generates most wind power and hence is the most suitable region for wind power application is located south of Norway, along the border of the Danish economic zone. This area has single-turbine CF values exceeding 65% (not accounting for any wind farm wake loss), which is outstanding in terms of wind power production. For comparison, onshore CFs are typically between 20% and 40%, though higher values are also reported.[42,43]

For context, one turbine with CF $=$ 65% has the ability to produce $0.65 \times 15\text{MW} \times 8760\text{h/year} = 85.4\text{GWh/year}$. The Norwegian hydro power is 140TWh/year. Then, we would need $140\text{TWh}/85.4\text{GW} = 1639$ turbines. Assuming one turbine per 2 km (spacing of 8 turbine diameter), these turbines would require $2\text{km}^2 \times 1639 = 3278\text{km}^2$. This correspond to a square with sides of 57 km. Comparing that to the less suitable areas with CF $=$ 50%, producing the yearly hydro power production would require a square with sides equal 65 km.

#### A.1.2 | Wind power variability

Wind power variability pose challenges for system operations and increases the need for a flexible power system.[44] As a measure of short-term wind power variability, we use the hourly wind power absolute ramp rate (HARR). HARR states how much the wind power production changes between two time increment. For calculations, see Solbrekke and Sorteberg.[3] Figure A1B displays the hourly wind power variability and reveals that the most suitable regions for low hourly wind power variability are located far away from the Norwegian mainland. The coast of Norway with its fjords and mountains creates turbulence in the air stream resulting in a highly variable hourly wind power production.

In addition to hourly wind power variability, the inter-annual variability is highly important indicating long-term power fluctuations. We calculate the average absolute yearly variations in CF (YARR) for each grid point, reflecting how much the wind power production varies on an yearly basis. See Solbrekke and Sorteberg[3] for the calculations. Figure A1C illustrates the inter-annual wind power variability (YARR). Areas along the western and northwestern coasts have highly fluctuating yearly CF-values of 4–5 percentage points, whereas the sites in the northernmost areas have considerably more stable year-to-year production. This is tied to the more frequent passage of strong low-pressure systems in southern Norway, as the low-pressure systems usually weaken as they move northwards along the Norwegian coast.

### A.2 | Techno-economic attractiveness

Techno-economic aspects include criteria that reflect the cost and economic risks related to offshore wind power technology. We choose four factors to reflect the main techno-economical drivers: a cost-related ocean-depth function; the minimum distance to the Norwegian central electricity network; the minimum distance to oil and gas activity; and the risk of the desired technology (bottom-fixed or floating wind turbines). See Figure A2 for the four criteria.

#### A.2.1 | Ocean-depth function

Ocean depth is an important factor when it comes to cost and technological solutions for offshore wind farms. Several publications[2,45] illustrate the nonlinear relationship between cost and ocean depth. Our starting point is the Myhr et al.'s[45] LCoE estimates (Euro/MWh) for three different turbine foundations (monopile, jacket, and the spar-Buoy Hywind II). We fit the LCoE estimates of Myhr et al[45] to linear and quadratic regression lines in order to estimate LCoE for all ocean depths:

$$\begin{aligned} LCoE_{Mono} &= -0.01h^2 + 0.749h + 139.1, \quad 0 < h \leq 30 \\ LCoE_{Jacket} &= 0.0016h^2 + 0.02h + 159.0, \quad 30 < h \leq 50 \\ LCoE_{Spar} &= 0.0062h + 163.2, \quad 50 < h \leq 1000 \end{aligned} \tag{A1}$$

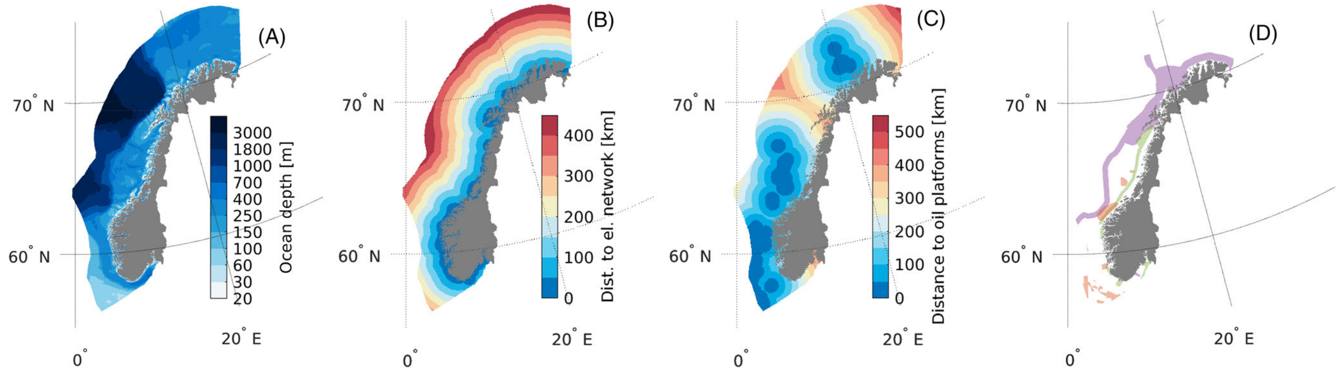


**FIGURE A2** Criteria considered in the techno-economical category: (A) ocean depth (m); (B) distance (km) to the closest central electricity network; (C) distance (km) to the closest oil and gas installation; (D) valuable areas in categories. Purple: biodiversity; green: bird and coastal areas; orange: fish growth and spawning grounds. Colors are transparent to see overlapping valuable areas.

Furthermore, we divide all the LCoE values with the $LCoE_{Mono}$ value at 10 m to obtain the nonlinear fractional change in cost with depth, here called the "cost ratio" (CR).

$$CR = \frac{LCoE}{LCoE_{Mono,10m}} \quad 0 < h \leq 1000, \tag{A2}$$

The CR increases rapidly up to 50 m ocean depth as the steel mass increases. The ratio continues to rise further as the technology transitions from bottom-fixed foundations to floating turbines at about 50 m (going from bottom-fixed jacket structures to Spar buoys), but the rise is more gradual now as the major increases in cost with depth are connected to mooring lines. Our cost-related ocean depth indicator gives an increase in cost of about 3% at 20 m depth, compared to 10% at 30 m and 13% increase at 75 m. It should be noted that an additional penalty is put on regions where the ocean depth exceeds 50 m through the technological risk indicator (see Section A.2.3), an indicator that reflects the increased cost and technology risks associated with exploiting deeper ocean depths, in terms of both bottom-fixed and floating technologies. See Figure A2A for the ocean depth used to calculate the ocean-depth function.

### A.2.2 | Distance to central electricity network and oil and gas installations

Besides local electricity storage, a wind farm has to be connected to an electricity grid for transmission of the produced power. The main driver of the network connection cost is related to the length of the cable, which is a function of the distance to the electricity grid. We calculate the minimum distance from each grid point to the Norwegian central electricity network (DCEN),[§] reflecting the cable costs for a new offshore wind farm installation at each location.

Figure A2B demonstrates the minimum DCEN for each grid point. Considering only electricity network distances, the grid points close to the Norwegian mainland are the most suitable for offshore wind power installation.

Most oil and gas activities on the Norwegian continental shelf use gas turbines to provide electricity for on-site activities such as pumping, drilling, accommodation, and so forth. This gas turbines use accounted for 26.7% of Norway's domestic $CO_2$ emissions in 2020.[46] In the light of Norway's international obligations toward emission reduction, an alternative to fossil fuel generated electricity is to use local, green, offshore wind power. Therefore, we include the possibility for a wind farm to provide electricity for an nearby oil and gas platform. For each grid point, we calculate the minimum distance to another point with oil and gas activity (DOP). Grid points with a short DOP will be rewarded with a larger criterion weighting than those further away. Considering only DOP as a criterion, Figure A2C reveals that the most suitable grid points are located in close proximity to oil and gas activity.

[§]Power stations larger than 132 kV.

### A.2.3 | Technological risk

Technological risk (TR) reflects the cost- and technology uncertainty tied to immature technological solutions. Both floating turbines and bottom-fixed solutions at greater ocean depths ($h > 50$ m) presents such challenges and are immature solutions. The grid points where $h \geq th_1$ receive a smaller score due to increased technology risk:

$$TR = \begin{cases} 1, & 0 \leq h < th_1, \\ 1 - r, & h \geq th_1, \end{cases} \tag{A3}$$

where $r$ is the risk factor (here $r = 1$), $h$ is the ocean depth at each grid point, and $th_1 = 50$ m, and the limits where the technology is either at a depth where bottom-fixed solutions not yet have been deployed or requires a floating turbine system. Considering technological risk alone the most applicable sites are close to the shore where the ocean depth is less than $th_1$.

## A.3 | Social acceptance

Opening new areas for offshore wind activity is restricted by environmental, technical, legal, economic, as well as social aspects and considerations. Below are descriptions of the interests that potentially cause social and area conflicts that are included in this study. Figure A3 illustrates the data fields for the four criteria in this category.

### A.3.1 | Shipping and fishing activity

An offshore wind farm in the middle of a high-traffic shipping route or in a region with significant commercial fishing activity could cause area conflicts. "Shipping activity" (SA) encompasses information on shipping and offshore transportation (see Figure A3A). SA is estimated as the number of ship registrations in each grid cell for large vessels (>45 m) for 2020. The data is based on the Norwegian Mapping Authority's Automatic Identification System (AIS), which produces shipping density data in a $50 \times 50$ m horizontal grid. For computational purposes, we only retain every

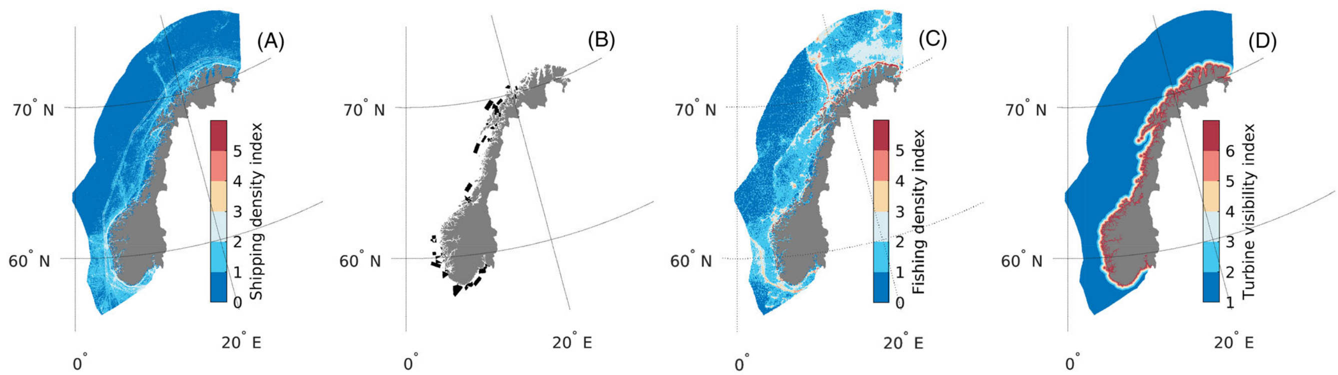


**FIGURE A3** The data categorized in the "social acceptance" category. (A) Shipping activity; (B) military areas; (C) fishing activity; (D) turbine visibility.

**TABLE A1** Categorization of AIS shipping density and fishing activity data.

| Scale | Occurrence | Description |
|---|---|---|
| 0 | 0–10 | Almost no activity/no data |
| 2 | 11–50 | Some activity |
| 3 | 51–100 | Moderate activity |
| 4 | 101–200 | Frequent activity |
| 5 | 201–400 | High activity |

*Note*: "Occurrence" represents the number of ship registrations per grid point ($3 \times 3$ km) in 2020.

second grid point, resulting in data with 100 m resolution. The AIS data is projected on to the NORA3-WP grid ($3 \times 3$ km) using linear interpolation and extrapolation in terms of missing data. After projection, the data are categorized according to Table A1.

The shipping routes with the highest traffic activity are located in some of the Norwegian fjords (Figure A3A), with several crossings per day. However, routes along the Norwegian coast from north to south are also moderately active.

The Norwegian economic zone has been used for fishing activities for centuries. Since 2016, this has contributed to 4% of the Norwegian country's gross national product.[47] Considering possible conflicts with the fishing industry is therefore important for offshore wind power planning. The open-access position-registration data can be retrieved from the data archive at The Norwegian Directories of Fisheries.[21] The fishing activity data (FA) yields registration of positions for larger Norwegian vessels (>15m) travelling at less than 5 knots. The fishing activity density data are obtained by counting occurrences of fishing vessels in each grid cell of NORA3-WP ($3 \times 3$ km) for 2020. The fishing activity follows the categorization in Table A1. Figure A3C illustrates the categorization of the FA data. Areas less suitable for wind farms, based solely on FA, include the regions on the slope of the Norwegian channel, those in coastal areas of northern Norway and areas close to the Norwegian continental shelf slope.

#### A.3.2 | Turbine visibility and coastal proximity

Societal reluctance to accept onshore wind farms in Norway has been considerable. Therefore, it is important to include acceptance of offshore wind prior to installation of an offshore wind farm to prevent legal litigation and reversal of ongoing projects.[48]

Auditory and visual noise are two factors that influence social acceptance of wind farms.[49] Both factors are functions of the distance between populated areas and a wind farm: in this case, the distance to shore. We use the turbine visibility (TV) index derived by Sullivan et al.[50]:

$$TV = 7.3589e^{-0.037D}, \tag{A4}$$

where D is the shortest distance from each grid point to the shore. The TV ranges from 0 to 6, where at level 0 the turbines are not visible at all, while at 6 the turbines fill most of the visual field. See Figure A3D for a map representing the turbine visibility index. In the context of TV, areas far off the Norwegian coast are the most suitable for wind power installation.

### A.4 | Environmental considerations

This category contains information on Norwegian offshore areas of special ecological value. The data comes from the Norwegian Environmental Agency and are hosted by the “geonorge” database.[24] Damage to these valuable areas can result in long-term and even irreversible ecological consequences. This category is divided into three subcategories: biological diversity, representing areas with rich biological variety; bird nesting and coastal zones, including areas critical for bird breeding and growth as well as ecologically important coastal areas; and fish growth and spawning grounds, which includes critical areas for growth and spawning of fish. See Figure A2D for these valuable areas. The colored areas correspond to regions with conflicts due to their environmental value. Some smaller regions may even have an overlap between all three categories, being particularly unsuitable for wind power application.

### A.5 | Met-ocean constraints

The criterion “met-ocean constraints” is divided into “inaccessibility” and “extreme conditions”. These categories reflect the reduced accessibility of an offshore wind farm and the need for site-specific wind turbine design parameters due to harsh met-ocean conditions. Inaccessibility relates to a reduction in the operation time of a wind facility due to operations and maintenance (O&M) in a harsh environment. The inaccessibility is a function of the accumulated hours of waiting time (AWT) for an O&M-vessel due to demanding met-ocean conditions, as well as the minimum transportation distance from each grid point to a major port in mainland Norway. Extreme conditions include aspects of the specific met-ocean environment that the turbines, substructure, anchoring, and so forth have to withstand. These are indicated by the average yearly maximum of hourly wind speed and significant wave height (hs).

#### A.5.1 | Accumulated waiting time

The accumulated waiting time (AWT) is here defined as the sum of hours when the met-ocean conditions are too harsh to perform O&M. The AWT for each grid point is obtained by summing the hours of waiting-time, which is calculated based on an operational threshold $th_o$ persisting more than the waiting-time thresholds $th_{wt}$ (see Table A2). We use three different scenarios to calculate the AWT depending on the size and duration of the O&M to be performed: "catamaran," "helicopter," and "crane vessel." The two first categories include small O&M tasks, while the last indicates heavier operations.

The upper row in Figure A4 exhibits the accumulated waiting time for all three O&M operations. Figure A4A shows that regions south and west of Norway are exposed to persistent high wind speed events ($u \geq 12$ m/s for >8 h). Along the Norwegian coast and in the fjords are sheltered regions with almost no waiting time caused by high winds, which are therefore the most suitable areas for wind power in terms of accumulated waiting time for light O&M operations that can be performed by helicopter.

The total accumulated waiting time for light O&M activity performed by catamaran is a function of the wave height only. Figure A4B illustrates the harsh wave environment in the western part of the NEZ, where the grid points feature wave heights too extreme for O&M operations

**TABLE A2** Scenarios for met-ocean waiting times.

| | Thresholds | | |
|---|---|---|---|
| | Operation ($th_o$) | | Waiting time ($th_{wt}$) |
| O&M operation | hs | u | hours |
| Light - Catamaran | 2 m | inf | 8 |
| Light - Helicopter | inf | 12 m/s | 8 |
| Heavy - Crane vessel | 2 m | 12 m/s | 24 |

*Note*: Operational thresholds ($th_o$) are listed for three different types of O&M operations. In addition, the waiting-time thresholds ($th_{wt}$) for the total accumulated waiting time are also given. hs = significant wave height (m); u = wind speed (m/s).

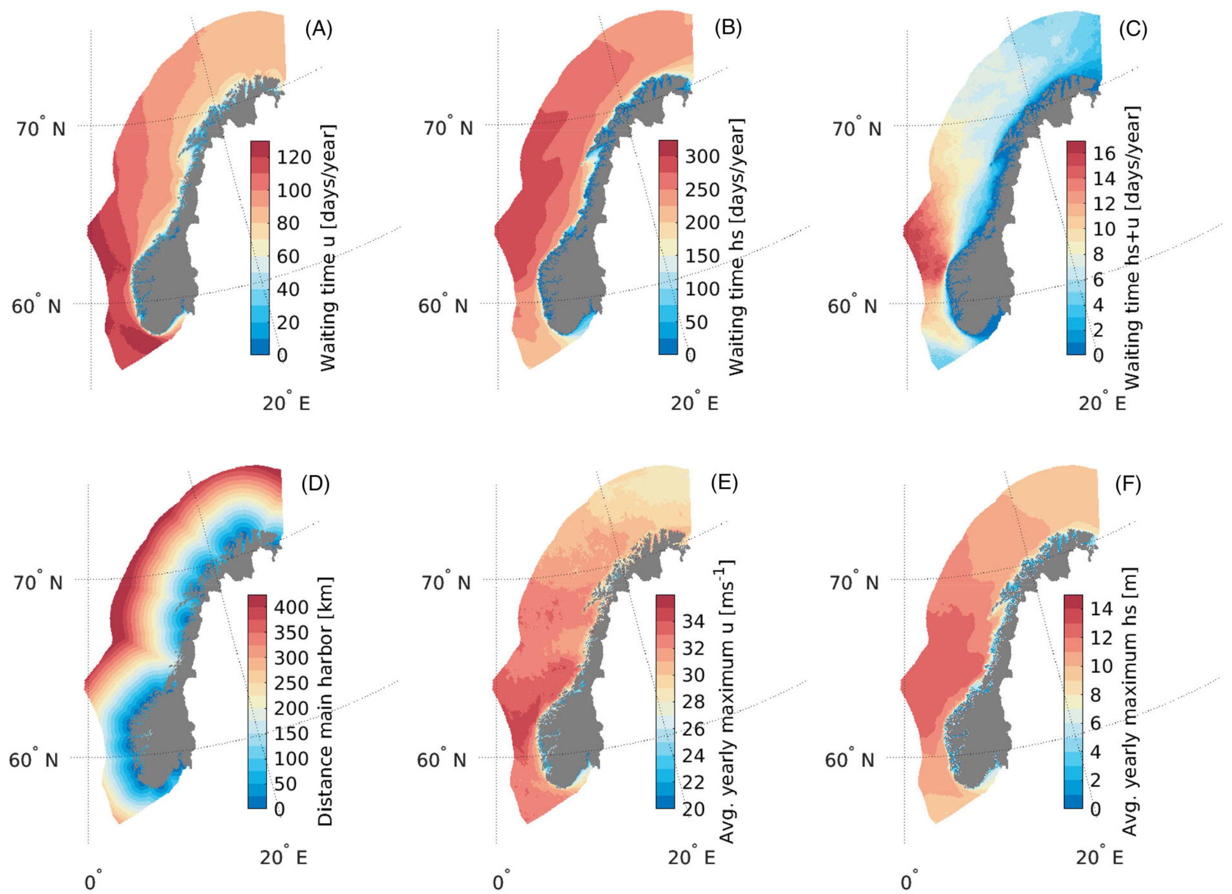


**FIGURE A4** Data fields for the criteria under the met-ocean category. (A) Wind speed (u) accumulated (AWT) waiting time (days/year) where the wind speed exceeds 12 m/s with a time duration of >8 h; (B) AWT of significant wave height (hs) exceeding 2 m lasting more than 8 h; (C) AWT time of hs + u, where u > 12 m/s and hs > 2 m lasting more than 24 h; (D) distance (km) to the closest major port; (E) the average yearly maximum of hourly wind speed (u); (F) the average yearly maximum of hourly significant wave height (hs) covered by a catamaran (hs > 2m) for more than 75% of the year. The most suitable areas for wind power based on total accumulated waiting time connected to high waves are those close to the shore and in Skagerak. But the eastern part of the Barents Sea and the southern part of the NEZ are also less exposed to high waves than the offshore areas west of Norway.

The waiting time for heavy operations, represented by the waiting time for a crane vessel, is sensitive to the combination of high wind speeds ($u \geq 12\,\text{m/s}$) and high waves (hs > 2 m). Figure A4C illustrates that the accumulated waiting time (>24 h) for heavy O&M is extremely high in the far offshore northwestern parts of the North Sea and southern parts of the Norwegian Sea, with AWT of around 15 days/year. The most suitable regions for wind power, considering only the waiting time for a crane vessel, represent a combination of the most accessible areas for helicopters and catamarans: along the coast and in fjords, in addition to southeastern and northeastern offshore regions.

### A.5.2 | Distance to major port

The distance to the closest major port is of interest due to the issue of wind farm inaccessibility for O&M-vessels. If an offshore wind farm is located far away from a major port this will reduce the wind farm's accessibility, and the feasibility of the wind farm will decrease due to a lower operating time. For each grid point, we calculate the minimum distance to a major port. Figure A4D illustrates the distance to the closest major port.

### A.5.3 | Average yearly maximum wind speed and significant wave heights

When installing wind turbine equipment, it is important to know the site-specific extremes of met-ocean parameters. Extreme met-ocean conditions pose loads on the equipment that influence the design as well as wear and tear on equipment. The most widely used international standard for offshore wind turbine designs is that drawn up by the International Electrotechnical Commission (IEC 61400-3).[51] There, the 50-year return value for hourly wind speed and significant wave heights, in addition to swell, tides, and currents, are used for extreme loads. However, the study period of 24 years is too short for the usage of extreme value theory. In addition, the influence of individual weather systems was too prominent, resulting in unrealistically noisy return-value maps, where the path of certain strong low pressure systems were visible. Therefore, we use the grid-point-specific average yearly maximum of hourly wind speed and significant wave height to illustrate extreme environmental conditions.

Figure A4E shows the average yearly maximum of hourly wind speed (max u). The northwestern parts of the North Sea and the areas along the northwestern coast have "max u" values of 33–34 m/s (above hurricane force). Besides the fjords, the northern and eastern-most parts of NEZ have a max u between 25 and 30 m/s (whole gale force) and are thus the most suitable regions for wind power production in terms of extreme wind loads on the installed equipment. A similar pattern is seen for significant wave heights (Figure A4F), showing that in parts of NEZ the turbines will on average experience significant wave heights above 12 m every year.

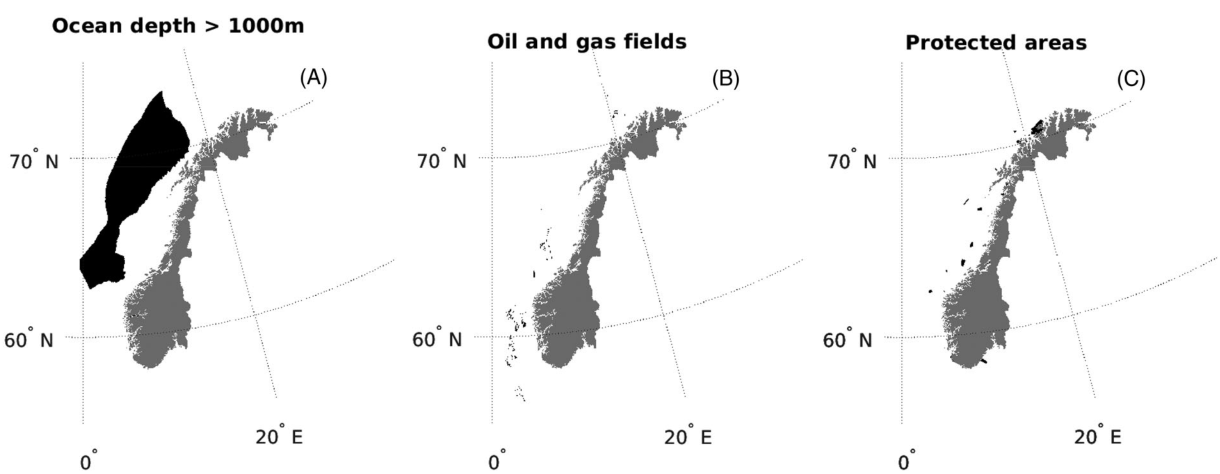


**FIGURE A5** The four criteria categorized as excluded grid points. (A) Ocean depth > 1000 m; (B) grid points occupied by oil and gas fields; (C) protected areas.

**TABLE A3** Pairwise criterion comparisons using Saaty's priority scale (Table 3) for the five main criteria (WRA, TEA, SA, EC, and MO) for the baseline scenario.

| Criteria to compare | Saaty's priority scale value | Comment |
|---|---|---|
| WRA vs. TEA | 2 | WRA is "*equal to moderately more important*" than TEA. WRA that indicates spatial income differences is slightly more important than TEA, which represents spatial costs differences through capital expenditures. |
| WRA vs. SA | 3 | WRA is "*moderately more important*" than SA. Reflects the importance of economically attractiveness for wind farm projects to be realized without ignoring social aspects. |
| WRA vs. EC | 3 | WRA is "*moderately more important*" than EC. Reflects the importance of economically attractiveness for wind farm projects to be realized without ignoring environmental aspects. |
| WRA vs. MO | 3 | WRA is "*moderately more important*" than MO. Reflects the importance of economically attractiveness for wind farm projects to be realized without ignoring spatial costs differences related to operation and maintenance and design requirements |
| TEA vs. SA | 2 | TEA is "*equal to moderately more important*" than SA. Reflects the major importance of a wind farm up-front costs without ignoring conflicts of interests through social acceptance. |
| TEA vs. EC | 2 | TEA is "*equal to moderately more important*" than EC. Reflects the major importance of wind farm up-front costs without ignoring environmental considerations. |
| TEA vs. MO | 2 | TEA is "*equal to moderately more important*" than MO. Around 75% of the LCoE for a wind power project is tied to the up-front costs (WindEurope). Since TEA (up-front costs) and MO (O&M and up-front costs) represent spatial cost differences and not the cost itself, we rank TEA only slightly more important than MO. |
| SA vs. EC | 1 | SA has "*equal importance*" over EC. For the baseline, we do not weight these two criteria differently. |
| SA vs. MO | 1 | SA has "*equal importance*" over MO. For the baseline, we do not weight these two criteria differently. |
| EC vs. MO | 1 | SA has "*equal importance*" over MO. For the baseline, we do not weight these two criteria differently. |

*Note*: The table also contains a column with comments rationalizing the given priority-scale value.
Abbreviations: EC, environmental considerations; MO, met-ocean constraints; SA, social acceptance; TEA, techno-economic aspects; WRA, wind resource attractiveness.

### A.6 | Excluded areas

We categorize some regions as "excluded grid points." Due to costs and weight issue of moorings, we have excluded areas with an ocean depth greater than 1000 m (Figure A5A).[52] In addition, regions already occupied by installations related to oil and gas activities are also excluded (Figure A5B). Lastly, we have ruled out areas that are protected for special species, environments, and types of nature. These are listed in a marine protection plan carried out by the Norwegian Environmental Agency, which has been constructed to ensure biological diversity and to protect vulnerable and valuable ecosystems typical of the Norwegian offshore areas. The category of "excluded areas" also includes protected coral reefs designated by the Norwegian Directorate of Fisheries. See Figure A5C for the protected marine areas.

### A.7 | Criterion comparisons

In this section, you can find all the criterion comparisons with a short description.

**TABLE A4** Pairwise criterion comparisons for the subcriteria in the baseline scenario.

| Criteria to compare | Saaty's priority scale value | Comment |
|---|---|---|
| **Wind resource attractiveness** | | |
| CF vs. HARR/YARR | 5 | CF have "*strong importance*" over HARR/YARR. CF is site specific and directly proportional to the income. HARR and YARR reflects wind power production variability on different time scales, and can partly be mitigated. |
| HARR vs. YARR | 1 | HARR have "*equal importance*" over YARR. HARR and YARR are both tied to wind power variability. |
| **Techno-economic aspects** | | |
| ODF vs. DCEN | 1 | ODF have "*equal importance*" over DCEN. Both ODF and DCEN reflect CapEx tied to investment and installation which are important factors for an offshore wind farm. |
| ODF/DCEN vs. TR | 3 | ODF and DCEN have both "*moderate importance*" over TR. ODF and DCEN reflect CapEx tied to investment and installation which are more important than the risk related to immature technology solutions. |
| ODF/DCEN vs. DOP | 5 | ODF and DCEN have both "*strong importance*" over DOP. DOP reflects an opportunity to produce local wind power for an oil and gas platform. This will be less improtrant compared to the up-front costs of an wind farm (ODF/DCEN). |
| TR vs. DOP | 2 | TR is "*equal to moderately important*" over DOP. DOP reflects an opportunity to produce local wind power for an oil and gas platform, while TR reflects an economical risk and is therefore slightly more important. |
| **Social acceptance** | | |
| FA vs. SH | 2 | FA is "*equal to moderately important*" over SH. FA is ranked as more important than SH due to the non-flexibility of the spatial fish patterns and the large contribution to the Norwegian GNP.[47] |
| FA vs. TV | 3 | FA is "*moderately important*" over TV. Even though TV, through auditory and visual disturbance, are important for social accept of a wind farm FA generates income and social benefits and are hence more important than TV. |
| FA vs. MA | 4 | FA has "*moderately to strong importance*" over MA. Unlike areas for fishing, regions for military activity (MA) can be moved. Therefore FA is ranked more important than MA. |
| SH vs. TV | 2 | SH has "*equal to moderate importance*" over TV. A wind farm in the middle of a trafficked shipping route would hamper the transportation (SH), hence SH is slightly more important than TV |
| SH vs. MA | 3 | SH is "*moderately important*" over MA. A wind farm in the middle of a trafficked shipping route would hamper the transportation (SH), hence SH is more important than MA |
| TV vs. MA | 2 | TV has "*equal to moderate importance*" over MA. Taking into account the number of protests toward the onshore wind farm industry, TV receiver slightly higher relative importance than MA. |
| **Environmental considerations** | | |
| BD vs. BC vs. FS | 1 | BD, BC and FS has all "*equal importance*". The three criteria are all linked to different environmental considerations and are not distinguished in terms of relative criterion importance. |
| **Met-ocean constraints** | | |
| IACC vs. EXT | 1 | IACC has "*equal importance*" over EXT. The inaccessibility of a wind farm for inspections and O&M (IACC), and site specific equipment design parameters depending on the harsh met-ocean conditions are both important parameters for offshore wind power. |
| AWT vs. DMP | 3 | IACC is "*moderately important*" over DMP. The AWT reflects loss of income due to harsh met-ocean conditions. This loss of income affects the wind farm profitability, and therefore AWT more ranked important than DMP. |
| L1 vs. L2 | 1 | L1 has "*equal importance*" over DMP. Small inspections and maintenance of the turbines or the farm can be performed by catamaran (L1) and helicopter (L2). These two options are set to be equally importance |
| L1/L2 vs. H1 | 5 | L1/L2 has "*strong importance*" over H1. Heavier and critical operations, e.g. replacing a rotor blade, is performed more seldom than light inspections. Hence, L1 and L2 are more important than H1. |
| max u vs. max hs | 1 | max u has "*equal importance*" over max hs. max u and max hs are linked to site-specific design parameters and are therefore equal important. |

Abbreviations: CapEx, capital expenditure; CF, capacity factor; DCEN, distance to the Norwegian central electricity network; DOP, distance to oil and gas platforms; HARR, hourly wind power variability; ODF, ocean-depth function; OpEx, operating expenses; TR, technological risk; YARR, yearly wind power variability.

**TABLE A5** The pairwise criterion comparisons using Saaty's priority scale (see Table 3) for the subcriteria for the three actors: "Investor," "Enironmentalist," and "Fisherman."

| Criteria to compare | Saaty's priority scale | | |
|---|---|---|---|
| | Investor | Environmentalist | Fisherman |
| **Wind resource attractiveness** | | | |
| CF vs HARR | 9 | 9 | 9 |
| CF vs YARR | 7 | 9 | 9 |
| HARR vs YARR | 1/3 | 1 | 1 |
| **Techno-economic aspects** | | | |
| ODF vs. DCEN | 1 | 1 | 1 |
| ODF/DCEN vs. TR | 4 | 3 | 3 |
| ODF/DCEN vs. DOP | 5 | 9 | 5 |
| TR vs. DOP | 2 | 5 | 3 |
| **Social acceptance** | | | |
| FA vs. SH | 2 | 3 | 5 |
| FA vs. MA | 4 | 5 | 7 |
| FA vs. TV | 3 | 3 | 7 |
| SH vs. MA | 3 | 3 | 3 |
| SH vs. TV | 2 | 1/3 | 3 |
| TV vs. MA | 2 | 5 | 1 |
| **Environmental considerations** | | | |
| BD vs. BC | 1 | 1 | 1 |
| BD vs. FS | 1 | 1 | 1/7 |
| BC vs. FS | 1 | 1 | 1/7 |
| **Met-ocean constraints** | | | |
| IACC vs. EXT | 1 | 1 | 1 |
| AWT vs. DMP | 3 | 3 | 3 |
| L1 vs. L2 | 1 | 1 | 1 |
| L1/L2 vs. H1 | 5 | 5 | 5 |
| max u vs. max hs | 1 | 1 | 1 |

*Note*: Fractional comparison values means that the first criterion is less important than the second criterion. For example, SH vs. TV = 2 (1/2) -> SH more (less) important than TV.
Abbreviations: AWT, accumulated waiting time; BC, important offshore and costal areas for bird nesting; BD, areas with high biodiversity; CF, capacity factor; DCEN, distance to the Norwegian central electricity network; DMP, distance major port; DOP, distance to oil and gas platforms; EXT, extreme conditions; FA, fishing activity; FS, areas for fish growth and spawning; HARR, hourly wind power variability; H2, heavy O&M by crane vessel; IACC, inaccessibility; L1, light O&M by catamaran; L2, light O&M by helicopter; MA, military areas; max hs, average yearly maximum of hourly significant wave height; max u, average yearly maximum of hourly wind speed; ODF, Ocean-depth function; SH, shipping; TR, technological risk; TV, turbine visibility; YARR, yearly wind power variability.

## APPENDIX B: COMPARISON MATRICES

This section includes the comparison matrices for the four scenarios: Baseline (BL); Investor (Inv.); Environmentalist (Env.); Fisherman (Fish.).

### B.1 | Main criteria

Wind resource attractiveness: $m_1$; techno-economic aspects: $m_2$; social acceptance: $m_3$; environmental considerations: $m_4$; met-ocean constraints: $m_5$.

$$BL:\begin{array}{c}\begin{matrix} m_1 & m_2 & m_3 & m_4 & m_5\end{matrix}\\ \begin{bmatrix} 1 & 2 & 3 & 3 & 3\\ 1/2 & 1 & 2 & 2 & 2\\ 1/3 & 1/2 & 1 & 1 & 1\\ 1/3 & 1/2 & 1 & 1 & 1\\ 1/3 & 1/2 & 1 & 1 & 1\end{bmatrix}\end{array}\begin{matrix}\\ m_1\\ m_2\\ m_3\\ m_4\\ m_5\end{matrix},Inv.:\begin{array}{c}\begin{matrix} m_1 & m_2 & m_3 & m_4 & m_5\end{matrix}\\ \begin{bmatrix} 1 & 2 & 4 & 4 & 3\\ 1/2 & 1 & 3 & 3 & 2\\ 1/4 & 1/3 & 1 & 1 & 1/3\\ 1/4 & 1/3 & 1 & 1 & 1/3\\ 1/3 & 1/2 & 3 & 3 & 1\end{bmatrix}\end{array}\begin{matrix}\\ m_1\\ m_2\\ m_3\\ m_4\\ m_5\end{matrix},$$

$$Env.:\begin{array}{c}\begin{matrix} m_1 & m_2 & m_3 & m_4 & m_5\end{matrix}\\ \begin{bmatrix} 1 & 4 & 3 & 1 & 4\\ 1/4 & 1 & 1/2 & 1/4 & 1\\ 1/3 & 2 & 1 & 1/3 & 2\\ 1 & 4 & 3 & 1 & 4\\ 1/4 & 1 & 1/2 & 1/4 & 1\end{bmatrix}\end{array}\begin{matrix}\\ m_1\\ m_2\\ m_3\\ m_4\\ m_5\end{matrix},Fish.:\begin{array}{c}\begin{matrix} m_1 & m_2 & m_3 & m_4 & m_5\end{matrix}\\ \begin{bmatrix} 1 & 4 & 1 & 2 & 4\\ 1/4 & 1 & 1/4 & 1/3 & 1\\ 1 & 4 & 1 & 2 & 4\\ 1/2 & 3 & 1/2 & 1 & 3\\ 1/4 & 1 & 1/4 & 1/3 & 1\end{bmatrix}\end{array}\begin{matrix}\\ m_1\\ m_2\\ m_3\\ m_4\\ m_5\end{matrix},$$

Wind resource attractiveness

Capacity factor = $a_1$; absolute hourly ramp rate of power production = $a_2$; average absolute yearly change in CF = $a_3$

$$BL:\begin{array}{c}\begin{matrix} a_1 & a_2 & a_3\end{matrix}\\ \begin{bmatrix} 1 & 5 & 5\\ 1/5 & 1 & 1\\ 1/5 & 1 & 1\end{bmatrix}\end{array}\begin{matrix}\\ a_1\\ a_2\\ a_3\end{matrix},Inv.:\begin{array}{c}\begin{matrix} a_1 & a_2 & a_3\end{matrix}\\ \begin{bmatrix} 1 & 9 & 7\\ 1/9 & 1 & 1/3\\ 1/7 & 3 & 1\end{bmatrix}\end{array}\begin{matrix}\\ a_1\\ a_2\\ a_3\end{matrix},Env.,Fish.:\begin{array}{c}\begin{matrix} a_1 & a_2 & a_3\end{matrix}\\ \begin{bmatrix} 1 & 9 & 9\\ 1/9 & 1 & 1\\ 1/9 & 1 & 1\end{bmatrix}\end{array}\begin{matrix}\\ a_1\\ a_2\\ a_3\end{matrix}$$

Techno-economic aspects

Ocean depth = $b_1$; dist to central electricity network = $b_2$; technological risk: $b_3$; distance to oil and gas activity: $b_4$

$$BL,Fish.:\begin{array}{c}\begin{matrix} b_1 & b_2 & b_3 & b_4\end{matrix}\\ \begin{bmatrix} 1 & 1 & 3 & 5\\ 1 & 1 & 3 & 5\\ 1/3 & 1/3 & 1 & 3\\ 1/5 & 1/5 & 1/3 & 1\end{bmatrix}\end{array}\begin{matrix}\\ b_1\\ b_2\\ b_3\\ b_4\end{matrix},Inv.:\begin{array}{c}\begin{matrix} b_1 & b_2 & b_3 & b_4\end{matrix}\\ \begin{bmatrix} 1 & 1 & 4 & 5\\ 1 & 1 & 4 & 5\\ 1/4 & 1/4 & 1 & 2\\ 1/5 & 1/5 & 1/2 & 1\end{bmatrix}\end{array}\begin{matrix}\\ b_1\\ b_2\\ b_3\\ b_4\end{matrix},Env.:\begin{array}{c}\begin{matrix} b_1 & b_2 & b_3 & b_4\end{matrix}\\ \begin{bmatrix} 1 & 1 & 3 & 9\\ 1 & 1 & 3 & 9\\ 1/3 & 1/3 & 1 & 5\\ 1/9 & 1/9 & 1/5 & 1\end{bmatrix}\end{array}\begin{matrix}\\ b_1\\ b_2\\ b_3\\ b_4\end{matrix},$$

Social acceptance

Fishing activity: $c_1$; shipping: $c_2$; military practice: $c_3$; turbine visibility: $c_4$.

$$BL:\begin{array}{c}\begin{matrix} c_1 & c_2 & c_3 & c_4\end{matrix}\\ \begin{bmatrix} 1 & 2 & 4 & 3\\ 1/2 & 1 & 3 & 2\\ 1/4 & 1/3 & 1 & 1/2\\ 1/3 & 1/2 & 2 & 1\end{bmatrix}\end{array}\begin{matrix}\\ c_1\\ c_2\\ c_3\\ c_4\end{matrix},Inv.:\begin{array}{c}\begin{matrix} c_1 & c_2 & c_3 & c_4\end{matrix}\\ \begin{bmatrix} 1 & 2 & 4 & 3\\ 1/2 & 1 & 3 & 2\\ 1/4 & 1/3 & 1 & 1/2\\ 1/3 & 1/2 & 2 & 1\end{bmatrix}\end{array}\begin{matrix}\\ c_1\\ c_2\\ c_3\\ c_4\end{matrix},$$

$$Env.:\begin{array}{c}\begin{matrix} c_1 & c_2 & c_3 & c_4\end{matrix}\\ \begin{bmatrix} 1 & 3 & 5 & 3\\ 1/3 & 1 & 3 & 1/3\\ 1/5 & 1/3 & 1 & 1/5\\ 1 & 3 & 5 & 1\end{bmatrix}\end{array}\begin{matrix}\\ c_1\\ c_2\\ c_3\\ c_4\end{matrix},Fish.;\begin{array}{c}\begin{matrix} c_1 & c_2 & c_3 & c_4\end{matrix}\\ \begin{bmatrix} 1 & 5 & 7 & 7\\ 1/5 & 1 & 3 & 3\\ 1/7 & 1/3 & 1 & 1\\ 1/7 & 1/3 & 1 & 1\end{bmatrix}\end{array}\begin{matrix}\\ c_1\\ c_2\\ c_3\\ c_4\end{matrix},$$

Environmental considerations

Biodiversity: $d_1$; bird nesting and coastal areas: $d_2$; areas for fish growth and spawning: $d_3$.

$$BL, Inv, Env: \begin{array}{c} \begin{matrix} d_1 & d_2 & d_3 \end{matrix} \\ \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \end{array} \begin{matrix} d_1 \\ d_2 \\ d_3 \end{matrix} \quad , Fish: \begin{array}{c} \begin{matrix} d_1 & d_2 & d_3 \end{matrix} \\ \begin{bmatrix} 1 & 1 & 1/7 \\ 1 & 1 & 1/7 \\ 7 & 7 & 1 \end{bmatrix} \end{array} \begin{matrix} d_1 \\ d_2 \\ d_3 \end{matrix},$$

Met-ocean constraints

Accessibility: $e_1$; extreme conditions: $e_2$

$$BL, Inv., Env., Fish.: \begin{array}{c} \begin{matrix} e_1 & e_2 \end{matrix} \\ \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \end{array} \begin{matrix} e_1 \\ e_2 \end{matrix},$$

Waiting time: $f_1$; distance to major port: $f_2$

$$BL, Inv., Env., Fish.: \begin{array}{c} \begin{matrix} f_1 & f_2 \end{matrix} \\ \begin{bmatrix} 3 & 1 \\ 1 & 1/3 \end{bmatrix} \end{array} \begin{matrix} f_1 \\ f_2 \end{matrix}$$

Waiting time for catamaran ($g_1$), helicopter ($g_2$), crane vessel ($g_3$).

$$BL, Inv., Env., Fish.: \begin{array}{c} \begin{matrix} g_1 & g_2 & g_3 \end{matrix} \\ \begin{bmatrix} 1 & 1 & 5 \\ 1 & 1 & 5 \\ 1/5 & 1/5 & 1 \end{bmatrix} \end{array} \begin{matrix} g_1 \\ g_2 \\ g_3 \end{matrix}$$

Mean yearly max wind speed u ($h_1$) and significant wave height hs ($h_2$)

$$BL, Inv., Env., Fish.: \begin{array}{c} \begin{matrix} h_1 & h_2 \end{matrix} \\ \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \end{array} \begin{matrix} h_1 \\ h_2 \end{matrix}$$