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Multi-Criteria Decision Analysis for Proposed Areas for Offshore Wind Implementation with Monte Carlo Method

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Abstract. This research presents a comparative study on offshore wind energy site selection, focusing on technological, environmental, social, and regulatory barriers, while ensuring compatibility with other marine activities and habitats. The study applies Multi-Criteria Decision Analysis (MCDA) through the Analytic Hierarchy Process (AHP) and contrasts it with a probabilistic approach based on Monte Carlo simulations. Although AHP is widely used, its deterministic nature limits the representation of uncertainty in decision-making. To address this, Monte Carlo methods are applied independently, extending previous approaches by incorporating additional design criteria and enhancing robustness. Results demonstrate that integrating probabilistic uncertainty significantly improves the reliability of site selection, identifying optimal zones with higher confidence. Overall, the study highlights the advantages of Monte Carlo simulations over AHP in supporting sustainable and reliable offshore wind energy planning.

1 Introduction

Climate change remains one of the greatest global challenges, largely driven by greenhouse gas emissions from fossil fuel use. Renewable energies, such as offshore wind, provide sustainable alternatives. Yet, despite advancements in onshore wind, offshore development in Europe faces significant technological and regulatory barriers (MITECO, 2023).

Commonly employed in offshore wind farm site selection are Multi-Criteria Decision Analysis (MCDA) methods (Díaz et al., 2022; Saaty & Vargas, 2012). They include the Analytic Hierarchy Process (AHP), which decomposes complex decisions into parts, assigning weights and rankings to each aspect of the problem (Diaz et al, 2022; Vagiano & Karanikolas, 2012). Previous applications have demonstrated AHP's value but also its limitations. For instance, comparisons between AHP and Multiple Attribute Decision Analysis (MADA) for floating offshore wind farms showed that while AHP is simple, transparent, and computationally efficient, it struggles with uncertainty and complex datasets, where MADA can provide stronger support (Díaz et al., 2022). Similarly, in GIS-based spatial analyses, fuzzy AHP (FAHP) has been developed to address the rigidity of crisp numerical judgments in traditional AHP, allowing experts to express preferences as ranges through triangular fuzzy numbers and thus capturing the vagueness of real-world decision-making (Vahidnia et al., 2008).

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

Recently, probabilistic methods have been incorporated to further enhance robustness, such as combinations of FAHP and Monte Carlo simulations to evaluate floating offshore wind farm locations (Díaz, Teixeira, et al., 2022). Their study demonstrated that while AHP and FAHP can produce reliable rankings, Monte Carlo adds the ability to quantify uncertainty through probability distributions of outcomes, thereby providing confidence levels for site suitability. Monte Carlo approaches have also been applied in renewable energy investment risk analysis (Mazurek & Strzałka, 2022), confirming their broader value in capturing uncertainty in multi-criteria contexts.

This study builds on this background but adopts a distinct perspective. Unlike most prior research that integrates AHP and Monte Carlo into a hybrid model, this work directly compares the outcomes of traditional AHP with two independent Monte Carlo simulation approaches. The integration of Monte Carlo simulation methodology helps incorporate probabilistic uncertainty, perform comprehensive sensitivity analyses through extensive simulations, and provide confidence levels for site rankings capabilities that traditional AHP alone cannot achieve. By separating rather than merging the two methods, this research provides a clear evaluation of their respective strengths, highlighting how probabilistic approaches reshape site rankings and reveal the relative importance of criteria. Ultimately, the study aims to support energy transition by identifying optimal sites for offshore wind development while ensuring compatibility with environmental protection and socio-economic activities.

Taking Spain as an example, this research conducts a comparative analysis of site suitability, integrating both qualitative and quantitative approaches. Wind, environmental, technical data, local marine datasets, socio-economical, and ecological aspects will be evaluated. Three subdivisions are analysed: North Atlantic, Levantine-Balearic, and Canary Islands Marine Subdivisions following guidelines from Spain's Maritime Spatial Planning (MSP) (MITECO, 2023).

2 Methods and Materials

This chapter describes the methods and materials used in the study. The regulatory framework surrounding offshore wind development in Spain is explained, as well as the three subdivisions considered in this study. The wind resource assessment is explained after which the technical and environmental characteristics are presented. Lasty, the Multi-Criteria Decision Analysis, AHP and Monte Carlo methods used in this study are explained.

2.1 Regulatory Framework

Spain's Maritime Spatial Planning (MSP) framework provides guidelines for sustainable offshore wind energy development while balancing environmental protection with socio-economic activities, in line with EU directives and under the supervision of the Ministry for Ecological Transition (MITECO, 2023). The framework designates Offshore Wind Energy High Potential Zones (ZAPER) within three main subdivisions, each with distinct regulatory considerations.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

The North Atlantic Subdivision, covering areas along the Galician and Basque coasts, prioritizes sites close to existing electrical grids to facilitate integration. Development must avoid Natura 2000 protected areas (*Natura 2000 Viewer*, 2024), key maritime routes, and fishing grounds to minimize ecological and economic conflicts. Within this context, NOR-1 was identified as an optimal site due to its low overlap with restricted zones (MITECO, 2023).

The Levantine-Balearic Subdivision, which includes Catalonia and the Balearic Islands, is characterized by high biodiversity and numerous Marine Protected Areas (MPAs), restricting development in sensitive habitats. Offshore wind projects must also respect tourism, fishing, and shipping activities. Despite these constraints, sites such as LEBA-1 were found suitable, offering favourable wind speeds and limited interference with reserved zones (MITECO, 2023).

The Canary Islands Subdivision combines significant wind resources with deep ocean waters, making it particularly suitable for floating wind technology. Site selection requires careful avoidance of MPAs, Special Areas of Conservation, and high-density tourist zones, while ensuring proximity to ports and substations. The area CAN GC-1 emerged as highly favourable, with minimal environmental conflicts and strong logistical advantages such as good proximity to ports and substations (MITECO, 2023).

2.2 Wind Resource Characteristics

Wind data from Global Wind Atlas and the use of Wind Atlas Analysis and Application Program (WAsP) was crucial to simulate wind farm layouts and obtain main wind resource characteristics like mean speed, proportional wake loss, Net Annual Energy Production (AEP), full loading hours, and power density.

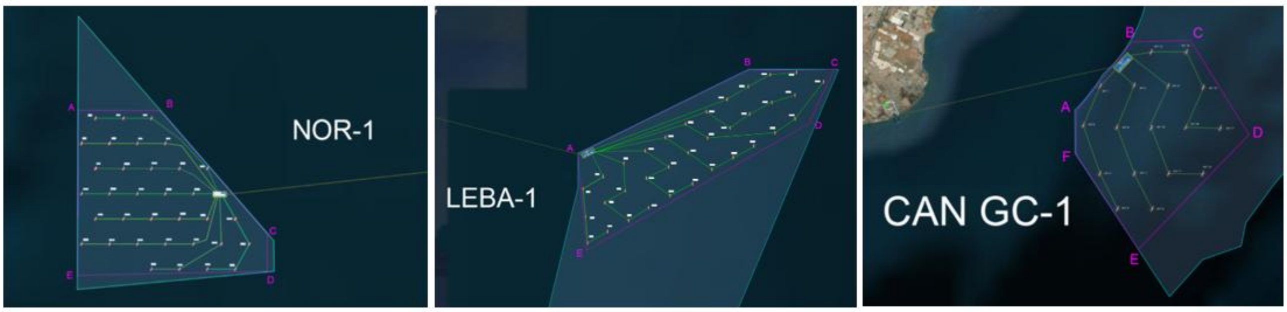
The Global Wind Atlas was used to assess wind resources through a multi-scale modelling approach that refines large-scale climate data down to local levels. The GWA methodology includes a data reduction process in which large-scale wind climate data from the ERA5 dataset (2008-2017) is used on an initial 30 km grid. Then, through meso-scale modelling, the ERA5 data is applied to the WRF model, generating wind climate data at a 3 km resolution. Finally, DTU Wind Energy's micro-scale modelling system further refines this data to a 250 m grid, providing detailed local wind climate estimates at five different heights (10 m to 200 m), essential for offshore wind resource assessment.

To model and predict wind resources, the WAsP software was also used, enabling the creation of wind resource maps and the evaluation of energy potential at specific sites. Through visual analyses with wind rose diagrams, regional patterns in predominant wind directions were identified. In the North Atlantic, winds predominantly come from the north, showing a strong and consistent pattern in that direction. In the Levantine-Balearic subdivision, winds also concentrate from the northwest, indicating a more localized wind regime. In the Canary Islands subdivision, the dominant wind pattern comes from the north, reflecting a uniform direction across the region.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

Once the wind data was collected for the three ZAPER areas selected, initial layouts were established, where the turbine distribution has a separation of 10 times the diameter of the turbine for downstream direction, and 3 times the diameter for crosswind direction (Brower, 2012). The wind turbine model used in this project was IEA Wind 15-Megawatt Offshore Reference Wind Turbine (Gaertner et al., 2020).

Figure 1 presents the three optimal layouts for the areas selected since the overall wake losses obtained were smaller than 7% (Brower, 2012). Each layout is delimited by a polygon that contains the wind turbines, the interconnection cables and the offshore substation. For the North Atlantic and Levantine-Balearic subdivisions, the wind farm capacity was established at 510 MW since they will be connected to peninsular substations. However, the Canary subdivision will be connected to a substation in the Canary Islands where the wind farm capacity was set at 255 MW since the electricity capacity there is lower.



(a) (b) (c)

Figure 1: 510 MW Offshore Wind Farm Layout in the North Atlantic Subdivision (a), 510 MW Offshore Wind Farm Layout in the Levantine-Balearic Subdivision (b) and 255 MW Offshore Wind Farm Layout in the Canary Island Subdivision (c)

WAsP was employed to design and simulate the wind farms, assessing site feasibility based on wind speed distribution, turbulence intensity, and energy potential. The main simulation results are summarized in Table.1. To calculate the number of full loading hours, estimated electricity production was adjusted to account for various losses: 3% for electrical losses, 5% for operation and maintenance losses (3% from turbine losses and 2% from grid unavailability), and 5% for losses due to power curve limitations and blockage (Brower, 2012). An overall efficiency of 87.54% was then applied to the Net AEP, which already considers wake losses.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

Table 1. Wind Resource Characteristics

Subdivision	North Atlantic	Levantine-Balearic	Canary Islands
Wind Farm Capacity [MW]	510	510	255
Number of Turbines [-]	34	34	17
Total Net AEP [GWh]	2079.73	2461.47	1337.90
Proportional Wake Loss [%]	6.21	3.3	3.77
Capacity Factor [%]	46.5	55.1	59.9
Mean Speed [m/s]	8.57	10.96	10.03
Power Density [W/m²]	774	1761	986
Full Loading Hours [h]	3569.80	4225.04	4592.93

Furthermore, for the North Atlantic region, the energy generated will be transmitted to the Atios 220 substation, located 38.71 km away. In the Levantine-Balearic area, the Santa Llogaia 400 substation is situated much closer at approximately 17.33 km. Conversely, the Canary Islands benefit from an exceptionally proximity to the Bco Tirajana B III 220/66 substation, which is only 1 km away facilitating more efficient energy evacuation and potentially lowering associated costs. Each of these substations are managed by Red Eléctrica Española (*Red Eléctrica Española*, 2024).

2.3 Technological and Environmental Characteristics

Other variables were studied such as environmental impacts, and factors that affect construction and operation conditions. For this analysis, sources like the Spanish Ministry for Ecological Transition and Demographic Challenge's INFOMAR portal (*Visor INFOMAR - MITECO, CEDEX*, 2024), EMODnet (*Home | European Marine Observation And Data Network (EMODnet)*, 2024), IH-CANTABRIA (*Marine Spatial Planning*, 2024), Oceanography Services portal of Puertos del Estado (*Oceanografía | Puertos del Estado*, 2024), and Natura 2000 Network (*Natura 2000 Viewer*, 2024) were used.

2.3.1 Bathymetry, marine slope and seabed composition

First, bathymetry and marine slope studies indicated significant variances in water depth and seabed composition among the subdivisions. The Canary Islands subdivision, with an average bathymetry of 247.52 m and a steep marine slope of 3.95º, present challenging conditions, necessitating advanced floating turbine technology, adding complexity and cost. The Levantine-Balearic subdivision, at 213.45 m depth and a moderate slope of 0.91º, offers a relatively balanced environment requiring also the use of floating turbines. The North Atlantic, with the smallest depth (167.30 m), a gentle slope of 0.23º and 40.41% presence of rock and boulders in the seabed of the area, also requires floating turbines (*Home | European Marine Observation And Data Network (EMODnet)*, 2024; *Marine Spatial Planning*, 2024).

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

2.3.2 Fisheries and mollusk conservation

Fishing activity, measured in hours per km2 per month, is notably higher in the North Atlantic (0.815) compared to the Levantine-Balearic (0.219) and Canary Islands subdivisions (0.144) (*Home | European Marine Observation And Data Network (EMODnet)*, 2024). This indicates a greater potential for conflict with local fisheries in the North Atlantic, necessitating cooperative planning to avoid economic disruptions. In terms of mollusk conservation, the North Atlantic and Levantine-Balearic regions exhibit substantial overlap with conservation zones along the export cable length, whereas the Canary Islands have no such interference, enhancing its appeal from a conservation perspective (*Visor INFOMAR - MITECO, CEDEX*, 2024).

2.3.3 Protected areas and endanger species

Environmental factors, such as proximity to conservation areas and protected species habitats are critical for minimizing environmental impact. The Canary Islands subdivision exhibits a significant distance from Special Protection Areas for Birds (SPAs), reducing potential ecological disturbance. The North Atlantic, conversely, has a closer proximity, increasing the need for stringent environmental assessments and mitigation strategies (*Natura 2000 Viewer*, 2024).

2.3.4 Maritime routes and nearby ports

Maritime route density, also higher in the North Atlantic (234.51 routes per km² per year), poses additional challenges for wind farm layout and safety, whereas the Canary Islands, with a lower density (132.13 routes), offer fewer logistical conflicts (*Home | European Marine Observation And Data Network (EMODnet)*, 2024). The proximity of each subdivision to ports and substations greatly influences the logistical and economic viability of energy transmission. The Canary Islands subdivision benefits from a short distance to both ports and substations, making it an ideal candidate for efficient energy integration and maintenance. In contrast, the North Atlantic requires extensive export cabling and has significant onshore distance to the nearest substation, adding considerable costs and complexity to project development.

2.3.5 Wave resource and marine currents

Furthermore, wave conditions significantly affect turbine stability, construction, and maintenance windows. The North Atlantic experiences the highest wave heights, with a central estimate for significant wave height at 13.42 m (50-year return period), along with a peak period of 16.39 s, indicating intense oceanic conditions that challenge operational stability. Conversely, the Canary Islands exhibit more moderate wave heights (5.1 m) and a peak period of 11.15 s, suggesting a more manageable environment for offshore structures (*Oceanografía | Puertos del Estado*, 2024). The Levantine-Balearic subdivision falls in between with wave heights of 8.35 m, indicating a balanced environment that could facilitate operations but still requires rigorous design considerations. These values were obtained from Extreme Regime data collected from three nearby buoys: Cabo Silleiro, Cabo Begur, and Las Palmas Este.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

Moreover, the availability of operational windows without adverse weather impacts is critical to reduce downtime. For this calculation, Mean Regime data from the same three buoys was used. The Levantine-Balearic region demonstrated the most favourable 8-hour weather windows per year (887.62), enhancing operational flexibility, while the Canary Islands and North Atlantic offer fewer windows (834.01 and 423.47, respectively). Additionally, mean current velocity data show stronger currents in the Canary Islands (97.33 cm/s), which may influence turbine design to withstand these forces (*Oceanografía | Puertos del Estado*, 2024). Table 2 sums up all the technical and environmental variables that were used for the MCDA.

Table 2. Technical and Environmental Characteristics

Subdivision	North Atlantic	Levantine-Balearic	Canary Islands
Bathymetry [m]	167.30	213.45	247.52
Marine Slope [º]	0.23	0.91	3.95
Rock Presence	Yes	No	No
Fisheries [hours per km per month]	0.815	0.219	0.144
Mollusk Conservation [m]	17406.52	16870.85	0
Annual Maritime Route Density [routes per km² per year]	234.51	139.38	132.13
Distance to SPAs [m]	174.18	320.39	20071.99
Lists of Sites of Community Importance [m]	3349	0	0
Distance to port [m]	25284.59	22660.41	6893.62
Visual Impact (min. Distance to coast) [m]	24002.85	13871.59	6955.72
Export Cable [m]	25143.11	23669.92	9365.17
Onshore distance to substation [m]	38704.88	17329.46	1001
Central Estimate of H_S (50 years) [m]	13.42	8.35	5.1
8-hour Weather Window/year	423.47	887.62	834.01
Mean Current Velocity [cm/s]	79.75	90	97.33

2.4 Multicriteria Analysis

This research enhances MCDA with Monte Carlo simulations to evaluate potential sites for offshore wind development. MCDA, specifically the Analytic Hierarchy Process, was used for initial rankings, followed by 2 simulation approaches for incorporating Monte Carlo simulations to address probabilistic uncertainties and enhance decision reliability.

2.4.1 Analytic Hierarchy Process (AHP)

The AHP methodology organizes the decision-making process into a structured hierarchy, dividing the analysis into four primary categories: wind resources, operational and construction conditions, environmental factors, and social aspects as shown in Table 3.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

Table 3. Criteria categories

Category	Criteria
Wind Resource	Proportional Wake Loss [%], Mean Speed [m/s], Power Density [W/m²], Full Loading Hours [h]
Operational/Construction Conditions	Bathymetry [m], Marine Slope Study [º], Rock Presence, Central Estimate of H_S (50 years) [m], 8-hour Weather Window/year, Mean Current Velocity [cm/s], Onshore distance to substation [m], Export cable [m]
Environmental	Mollusk Conservation [m], Special Protection Area for Birds [m], Lists of Sites of Community Importance (LIC) [m]
Social	Fisheries [hours per km per month], Annual Maritime Route Density [routes per km² per year], Visual Impact (min. Distance to coast) [m], Distance to port [m]

This approach involved a hierarchical structure with pairwise comparisons assigning relative importance (from 1 to 7) (Saaty & Vargas, 2012), reflecting each criterion's role in decision-making. Wind resources received the highest importance, followed by operational conditions, environmental factors, and social aspects. Pairwise comparisons were used to obtain weights for each variable. Moreover, a consistency test was done where Consistency Index (CI) and Consistency Ratio (CR) are calculated with Eq. (2) and Eq. (3), respectively, being λ_{max} the largest eigenvalue of the comparison matrix, and n the number of criteria (Saaty & Vargas, 2012). This test confirmed the reliability of these judgments by obtaining a CR < 0.1.

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{pmatrix} = \begin{pmatrix} \frac{w_1}{w_1} & \cdots & \frac{w_1}{w_n} \\ \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \cdots & \frac{w_n}{w_n} \end{pmatrix} = \begin{pmatrix} 1 & \cdots & \frac{w_1}{w_n} \\ \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \cdots & 1 \end{pmatrix} \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

Each variable is assigned a score from 0 to 10, where 10 corresponds to the most favourable value and 0 to the least, with intermediate values scaled proportionally. Variables to be maximized assign a 10 to the highest numerical value, while those to be minimized award a 10 to the lowest. Finally, the scores for each alternative are multiplied by the corresponding weights of the criteria to obtain weighted scores.

To establish the order of importance, opinions from experts from Univergy Solar, who work on the development of onshore and offshore wind projects, were used. The matrix's structure was generated by assigning specific importance values based on each category's relevance to the main objective. Wind Resource, being the most critical category, was assigned a relative importance of 7 in comparison against other criteria. Operational and construction conditions received a relative importance of 5, environmental impact was valued at 3, and social factors at 1. To implement this, a square matrix was created where

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

diagonal elements were set to 1, as each criterion is equally important to itself. The off-diagonal elements were then filled in based on the relative importance values assigned between each pair of criteria.

2.4.2 Monte Carlo Simulations

Two Monte Carlo simulation approaches were implemented to refine the AHP results by accounting for weight variability through normal distributions. The first approach applied random weights across all criteria using normal distribution functions, parameterized by the mean and standard deviation of the weights derived from the AHP method. A total of 10,000 simulations were conducted, and the results were aggregated to identify which of the three candidate locations achieved the highest frequency of selection as the preferred site.

The second approach also incorporated AHP-derived weights but constrained them within predefined ranges for each category. The total contribution of each category within the AHP was first determined, leading to the establishment of the following ranges: Wind Resource (40–60), Operational/Construction Conditions (25–35), Environmental (5–25), and Social (0–10). For each category, 10,000 random normal distribution functions were generated using the mean and standard deviation of its defined range, thereby refining the variability of weights while maintaining consistency with the AHP structure.

2.4.3 Sensitivity Analysis

Since the second Monte Carlo approach still incorporated a degree of subjectivity in the assignment of category weights, a sensitivity analysis was performed to further evaluate influential factors on the final rankings. This analysis systematically rotated the predefined weight ranges of the four key site selection categories: Wind Resource, Operational/Construction Conditions, Environmental, and Social, across all possible combinations. As a result, 24 distinct simulation scenarios were generated, as presented in Table 4. This procedure provided a more robust assessment of how variations in weight allocations could affect the prioritization of offshore wind farm sites. Simulation number 1 corresponds to the initial configuration of the second Monte Carlo approach, while the remaining 23 scenarios represent alternative probability-weighted combinations, offering a broader understanding of the stability and sensitivity of the site selection process

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

Table 4. Combination of Weights for Sensitivity Analysis

Number	Wind Resource	Environmental	Social	Operational/ Construction
1	(40, 60)	(5, 25)	(0, 10)	(25, 35)
2	(40, 60)	(5, 25)	(25, 35)	(0, 10)
3	(40, 60)	(0, 10)	(5, 25)	(25, 35)
4	(40, 60)	(0, 10)	(25, 35)	(5, 25)
5	(40, 60)	(25, 35)	(5, 25)	(0, 10)
6	(40, 60)	(25, 35)	(0, 10)	(5, 25)
7	(5, 25)	(40, 60)	(0, 10)	(25, 35)
8	(5, 25)	(40, 60)	(25, 35)	(0, 10)
9	(5, 25)	(0, 10)	(40, 60)	(25, 35)
10	(5, 25)	(0, 10)	(25, 35)	(40, 60)
11	(5, 25)	(25, 35)	(40, 60)	(0, 10)
12	(5, 25)	(25, 35)	(0, 10)	(40, 60)
13	(0, 10)	(40, 60)	(5, 25)	(25, 35)
14	(0, 10)	(40, 60)	(25, 35)	(5, 25)
15	(0, 10)	(5, 25)	(40, 60)	(25, 35)
16	(0, 10)	(5, 25)	(25, 35)	(40, 60)
17	(0, 10)	(25, 35)	(40, 60)	(5, 25)
18	(0, 10)	(25, 35)	(5, 25)	(40, 60)
19	(25, 35)	(40, 60)	(5, 25)	(0, 10)
20	(25, 35)	(40, 60)	(0, 10)	(5, 25)
21	(25, 35)	(5, 25)	(40, 60)	(0, 10)
22	(25, 35)	(5, 25)	(0, 10)	(40, 60)
23	(25, 35)	(0, 10)	(40, 60)	(5, 25)
24	(25, 35)	(0, 10)	(5, 25)	(40, 60)

3 Results

3.1 Traditional AHP method

For the traditional AHP method with weights assigned by industry experts the final scores indicated that the Levantine-Balearic site achieved the highest score with 47.84% of the victories, followed by the Canary Islands subdivision with 41.02%, and the North Atlantic site with a score of 11.14%.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

3.2 Monte Carlo

For the first approach with random weights across all criteria, by using normal distribution functions with the mean and standard deviation obtained from the weights in the AHP method, a simulation with 10000 iterations was carried out. The Canary Islands emerged as the preferred location in over 83.53% of cases, followed by Levantine-Balearic with 16.34% and less than 1% for the North Atlantic.

For the second approach with adjusted weights within the AHP defined ranges the results showed that, across 10000 simulations for each combination from Table 4, the Canary Islands subdivision achieved an 83.53% victory rate, indicating its strong suitability for offshore wind development under the given criteria. In comparison, the Levantine-Balearic subdivision only achieved a 16.47% victory rate, while the North Atlantic subdivision did not rank as the top choice in any simulation.

Figure 2 presents a cumulative Monte Carlo simulation graph, which visually illustrates the outcomes across different combinations of decision criteria from Table 4 that were used for the second Montecarlo approach. In the graph, victories for the Levantine-Balearic subdivision are represented in blue, while those for the Canary Islands are shown in orange. Results indicate that the North Atlantic subdivision never emerges as the winning option, whereas the Canary Islands dominate in most combinations, consistently outperforming the other regions across the 10,000 simulations. Considering all 24 combinations, the Canary Islands subdivision achieved an 83.53% victory rate, indicating its strong suitability for offshore wind development under the given criteria. In comparison, the Levantine-Balearic subdivision only achieved a 16.47% victory rate, while the North Atlantic subdivision did not rank as the top choice in any simulation.

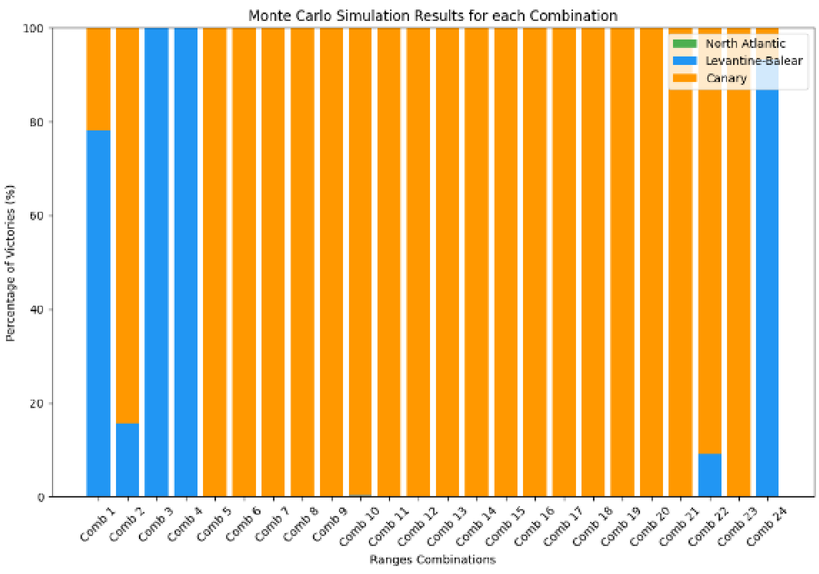


Figure 2: Monte Carlo Simulation results for each combination.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

3.3 Comparisons

For the first combination from figure 2, the order of importance between the four categories is the same as the one stated in the traditional AHP method. Figure 3 confirms the primary finding of the Levantine-Balearic region being the most suitable, followed by the Canary Islands subdivision. However, for most of the other simulations in the rest of the combinations, the Canary Islands subdivision stands out with most of the victories. Figure 4 shows how the impact of each category affects the combinations where the Levantine-Balearic has won through the simulations. These combinations are the first, third, fourth and the twenty fourth combination. It can be concluded that operational/construction conditions and wind resource have the highest impact on the results of this location. Another aspect that favours this region is to give small weights to the environmental and social categories, since these are criteria that make Canary subdivision stand out.

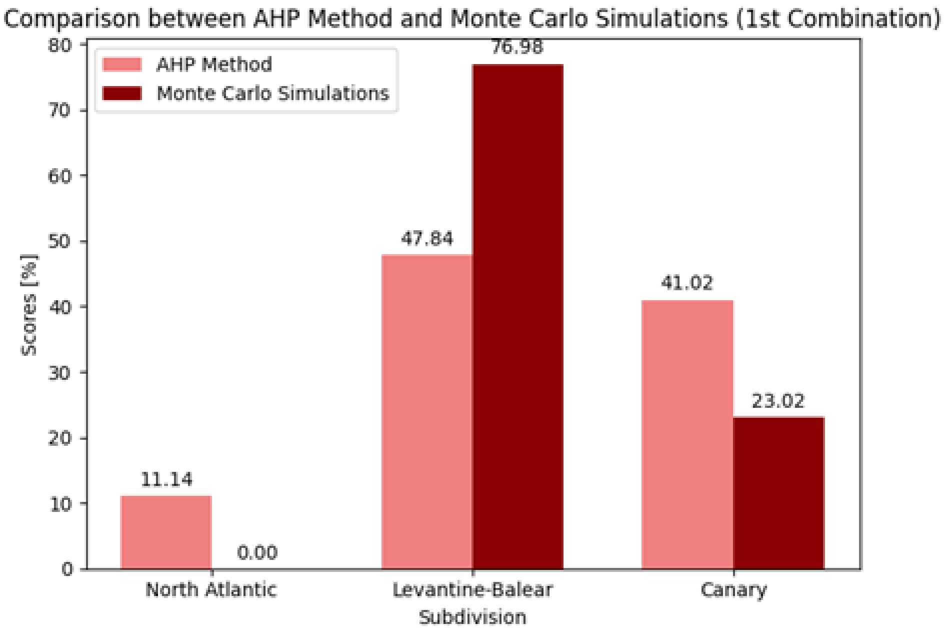
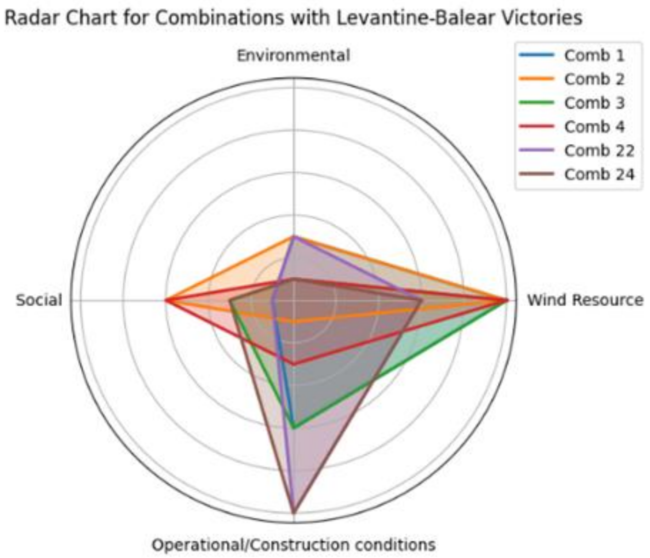


Figure 3: Comparison between AHP Method and Monte Carlo Simulations (1st Combination).

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025



255 **Figure 4: Radar Chart for Combinations with Levantine-Balearic Victories.**

Finally, results from both Monte Carlo approaches used in the Monte Carlo method were analysed. Figure 5 shows that the second approach gives similar results as the first one. It can be concluded that adding the uncertainty factor for both cases and, therefore, avoiding subjectivity, gives a clear result of Canary Islands subdivision as winner of the site selection, confirming its robustness under variable conditions.

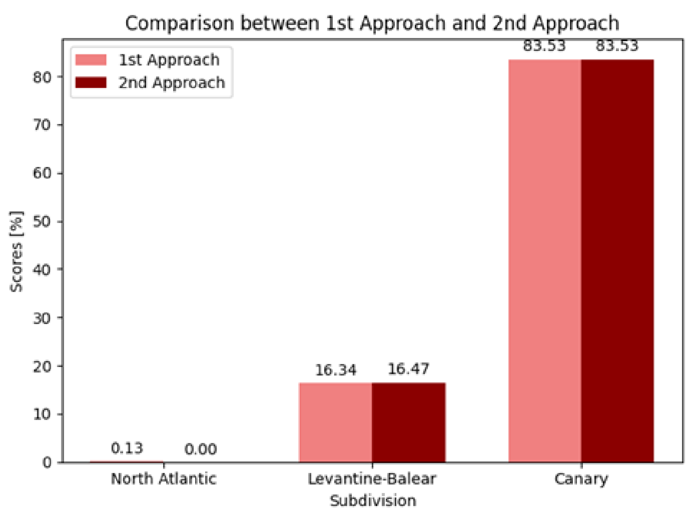


Figure 5: Comparison between both Monte Carlo Approaches.

https://doi.org/10.5194/wes-2025-188
Preprint. Discussion started: 30 October 2025

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3.4 Relative importance of different categories

Using a colour gradient, figure 6 provides a visual representation of the relative impact of four key categories wind resource, environmental, social, and operational/construction conditions on the suitability and prioritization of wind energy projects. Darker colours indicate a higher level of impact, meaning that these factors are more critical for decision-making in that area, while lighter colours suggest lesser influence or no impact at all. This map is useful for decision-makers in sectors like energy production, infrastructure planning, and environmental conservation, particularly in the context of wind energy projects. The map ranks each variable based on its impact value in each region, without factoring in the specific weights of each variable. As described in Section 2.4.1, for each criterion, the score of each location is calculated relative to the maximum and minimum observed values. The site with the highest value for a criterion to be maximized is assigned a score of 10, while the lowest value receives a score of 0, with intermediate values interpolated accordingly. For criteria to be minimized, the procedure is inverted so that the lowest value receives a score of 10 and the highest a score of 0. In cases where maximum and minimum values are equal, a constant score of 10 is assigned to all sites to avoid distortions. This normalization ensures comparability across criteria and allows a standardized evaluation of all alternatives. This map provides a preliminary understanding of how the analyzed variables are objectively assessed, without yet incorporating any Multi-Criteria Decision Analysis (MCDA) methods such as AHP or Monte Carlo simulations.

An analysis of the heat map reveals that each category holds a different level of impact across the three regions. Wind Resource is most favorable in the Levantine-Balearic region, indicating strong potential for wind energy projects, with moderate potential in the Canary Islands and no influence in the North Atlantic. Environmental impact is most conflictive in the North Atlantic region with the lowest score, likely due to ecological sensitivity, moderate concerns in Levantine-Balearic and less in the Canary Islands, making the Canary Islands the alternative with highest score in this category. Social impact gradually decreases its score from Canary Islands to North Atlantic, suggesting a rising level of social involvement or concern, making the North Atlantic the most conflicted area for local communities. Meanwhile, operational/construction conditions are relatively consistent across all regions, implying that logistical and construction challenges are similar. Overall, the heat map emphasizes the need for a balanced, multi-category approach when making decisions about wind energy development.

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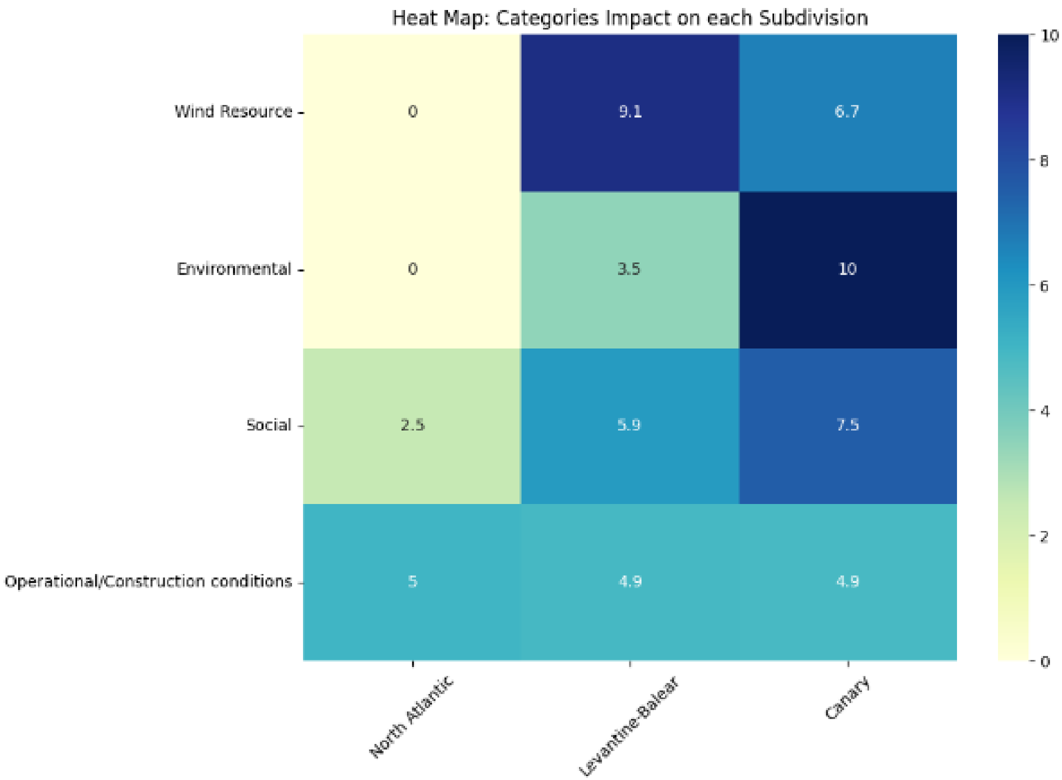

Figure 6: Heat map with categories impact on each subdivision.

4 Conclusions

This study conducts comparative analysis of three potential locations for offshore wind farms in Spain using a MCDA method. It compares the traditional AHP and a standalone Monte Carlo simulation approach. Unlike earlier research, which often integrates Monte Carlo techniques into AHP to address probabilistic uncertainty, this study uniquely separates the two methods, allowing a direct comparison of their outcomes and effectiveness. Monte Carlo simulations were used to address the limitations of AHP by introducing probabilistic uncertainty, allowing the model to better reflect real-world uncertainties and complexities. The Monte Carlo results revealed a strong preference for the Canary Islands directly contrasted with the AHP results. This discrepancy suggests that when uncertainty is explicitly accounted for, the Canary Islands consistently emerge as the optimal site due to favourable wind conditions, infrastructure proximity, and resilience under different weightings of environmental and social factors.

In conclusion, separating AHP and Monte Carlo methods offers a more comprehensive and reliable approach to offshore wind farm site selection. Monte Carlo simulations, by independently capturing uncertainty through extensive sensitivity

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analysis (10,000 iterations across 24 configurations), significantly enhance the robustness of site rankings and reduce the risk of subjective biases inherent in AHP. This methodological innovation contributes to MCDA practices by showing how probabilistic models can validate or complement deterministic approaches, particularly in high-stakes sectors like renewable energy. The findings reinforce the importance of explicitly integrating uncertainty into decision-making frameworks, providing a more realistic and reliable basis for strategic infrastructure planning.

Finally, future research could expand this analysis by incorporating broader environmental variables (e.g., biodiversity and cumulative impacts), detailed economic and social assessments, and technological considerations such as floating turbines, hydrogen production, and energy storage integration. Comparative international case studies and climate change resilience analysis would further enhance the model's applicability, strengthening its role as a decision-support tool in offshore wind energy planning.

Data availability

The models and data used in this paper can be requested from the corresponding author upon reasonable request.

Author contribution.

CM: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – original draft preparation. DR: Conceptualization, Methodology, Writing – original draft preparation. NA: Writing – review & editing.

Competing interests

The authors declare that they have no conflict of interest.

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