



Journal of Frontiers in Multidisciplinary Research

GIS-Based Renewable Energy Site Selection Model for Offshore Wind Farms

Dulo Chukwuemeka Wegner^{1*}, Kelvin Edem Bassey²

¹⁻² University of Hull, UK

* Corresponding Author: Dulo Chukwuemeka Wegner

Article Info

E-ISSN: 3050-9726

P-ISSN: 3050-9718

Volume: 03

Issue: 02

July – December 2022

Received: 15-09-2022

Accepted: 16-10-2022

Page No: 134-145

Abstract

Global energy demand is shifting towards renewables, leading to growth in offshore wind energy. The construction of offshore wind farms is considered more complicated than onshore due to the wide range of technical, environmental, and social considerations. This paper summarizes a geo-spatial model for offshore wind energy site selection that incorporates environmental impact and wind energy potential assessments in a cost-effective framework. The primary function of the model is to evaluate and rank offshore wind farm sites using a spatially integrated multi-criteria framework that addresses energy sustainability and optimization. The model is structured in four layers: the first is the data layer, which is the repository for wind, spatial, and environmental data. The second layer is the GIS-based processing layer, which applies Multi-Criteria Decision-Making Analysis (MCDA) to derive high-value potential zones. The third layer is the WindPro simulator, which calculates annual energy production, layouts of turbine placements, and wake interactions. The last layer publishes data in the form of spatially weighted site suitability maps and ranked site folders. The North Sea offshore inspection case studies provide the boundary conditions for the site selection model that uses wind resource, ecological, and environmental data. The model effectively determined areas of high development potential with wind resources and low ecological risk of development.

Data received thus far show that there is a strong match between the model outputs and the already functioning wind farms in the area. This affirms the usefulness of the GIS-enabled decision-support tools for developers, policy makers, and regulators alike. The model decreases the site selection uncertainty, improves clarity in site selection and regulatory decision making, and aids the marine spatial planning objectives by integrating environmental sustainability and energy efficiency. All in all, this model promotes a data-centric and environmentally compliant, cost-effective approach to site selection for offshore wind farms. It fosters the advancement of offshore wind development.

DOI: <https://doi.org/10.54660/IJFMR.2022.3.2.134-145>

Keywords: GIS-Based Site Selection, Renewable Energy, Offshore Wind Farms, Spatial Analysis, Multi-Criteria Decision Making, Wind Resource Assessment, Environmental Impact, Marine Spatial Planning, Terrain Analysis, Accessibility, Grid Connection, Stakeholder Engagement

1. Introduction

Driven by the demand for lower carbon-gas emissions, renewable resources have placed the most important recent advancement in offshore wind energy (Sherman *et al.*, 2020; Henderson and Seal, 2021). For its enormous potential wind resources, & offshore sites with helpfully higher average and wind speeds as well as lower land use than onshore sites, offshore wind farms are increasingly regarded as an integral part of the clean energy amenable to the rest of the world (Costoya *et al.*, 2020; Harrison-Atlas *et al.*, 2022). All countries surrounding the North Sea and Atlantic, and other belts, are aggressively constructing enormous offshore wind farms to taper fossil energy imports, achieve net-zero emissions, and mobilize sustainable energy sources security. This sector's rapid growth, however, serves to accentuate the importance of meticulously planned offshore sites, since the wind farms will economically fail if they are poorly placed, cause more ecological disparity, and raise more tensions with other sea users (Galparsoro *et al.*, 2022; Novaglio *et al.*, 2022).

One of the factors that can be considered a challenge in the development of offshore wind is the complexity of selecting the site. The site selection process tries to optimize three factors: energy yield, environmental impact, and infrastructure viability (Kheybari *et al.*, 2019; Doorga *et al.*, 2019). On one end, energy yield is contingent upon turbine spacing, wind availability, molecular seabed configurations, and wake interferences. On the other hand, environmental sustainability is the protection of marine biodiversity and fisheries, migration routes for birds, and compliance with legal environmental impact assessments (Sarker *et al.*, 2019; Tamario *et al.*, 2019). These also disregard the fact that infrastructure viability has seabed composition for turbine foundation and seabed proximity to high voltage direct current (HVDC) transmission lines, movement of vessels, and parallel structures like subsea cables (Mathern *et al.*, 2021; Velenturf *et al.*, 2021). Managing and reconciling these prioritized interests is only possible with rigorous and sophisticated decision support systems that are multi-disciplinary, synthesized, and cross-verified with multiple datasets (Zuccaro *et al.*, 2020; Fryirs *et al.*, 2021).

In response to these constraints, this research develops a model that simultaneously uses an Environmental Impact Assessment (EIA), a Geographic Information System (GIS) wind model, and WindPro simulations. The model is constructed upon GIS-based spatial analyses that synthesize varying geospatial descriptive data, including bathymetry, seabed substrate type, protected environments, and marine traffic densities (Thomas *et al.*, 2019; Peters *et al.*, 2020). GIS, as the model utilizes, employs multi-criteria decision analysis (MCDA) to resolve technical, ecological, and socio-economic trade-offs, and thus, derive offshore site suitability. These suitability analyses are then augmented by WindPro simulations that provide more accurate estimates of annual energy production, turbine wake effects, and layout & turbine spacing optimization (Sharma *et al.*, 2019; Masoudi and Baneshi, 2022). Simultaneously, the model employs EIA, ensuring that ecological sensitivities such as marine mammals and sensitive habitats, migratory birds, and fisheries are actively considered in the decision-making process. The end product is an integrated approach that identifies offshore wind sites that are not only technically viable, but also meet standards of environmental protection and the sustaining of operational viability over time.

The validation of the integrated model can be carried out within the context of the North Sea. As one of the offshore wind industry's most mature regions, the North Sea has developed enabling infrastructure, environmental monitoring, regulation, and associated funding (Hannon *et al.*, 2019; Calado *et al.*, 2019). North Sea inspection case studies offer particularly valuable data for model validation, such as ROV (remotely operated vehicle) surveys, seabed mapping, and ecological data that can be integrated into GIS. These datasets contribute to wind resource assessments and WindPro simulations so the model can be calibrated and cross-checked against nearby operational wind farms. This process not only puts the decision-support model through a robustness test but also confirms its wide applicability to regions with different ecological and technical characteristics.

Integrating multiple advanced methodologies reduces uncertainty while fostering transparency in spatial offshore wind site selection as an integrated system of geo-information and multi-criteria decision making. The traditional site planning methodologies have often depended on "waterfall" models where technical, environmental, and economic aspects of the wind site assessment are done in siloed approaches (Lent and Brown, 2020; Leiter, 2021). These piecemeal methodologies have a high risk of oversimplifying the trade-offs and cumulative impacts. The integrated system of geo-information and multi-criteria spatial decision processes focuses on cumulative spatial and multi-criteria evaluations. The proposed model does not allow for high energy yield in a concentrated site without the assessment of ecological conservation and concession of the site infrastructure (Baldo *et al.* 2021, Christianson *et al.* 2021). The model also fulfills marine spatial planning goals by strengthening decision-making and strategic planning by de-risking investment in the site and offering suitability maps, probabilistic rankings, and scenario-based simulations. Success in the transition of the energy system heavily relies on the offshore wind farms and their spatial distribution. The model and offshore wind energy site planning form a complex and rigorous answer to the challenges the EIA, GIS, and WindPro simulations have (Diez-Rodriguez *et al.*, 2012). Also, model validation by North Sea analysis projects greatly emphasizes the model's relevance and transferability within offshore wind projects, making it an exemplary advocate for sustainable offshore wind development worldwide.

2. Objectives of the Model

The deployment of offshore wind energy developments requires a rational and well-researched approach to balance energy potential with ecological and economic viability. Conventional planning approaches have been process and time-inefficient, with the technical, environmental, and socio-economic aspects being analyzed in silos. This approach fosters increased stakeholder conflict, potential ecological destruction, and stops the budget from losing control. A comprehensive integrated decision support system that combines environmental impact assessment, EIA, geo-spatial technologies, and simulation to optimize offshore wind farm developments. The objectives aid in the determination of the decision support system to be used, built, and tested through the implemented model as described in the GIS-centered RSD model (Amjad and Shah, 2020; Albraheem and Alabdulkarim, 2021).

To construct a comprehensive multi-criteria decision-making model for prospective offshore windfarms is the main aim of the model. Developing offshore wind energy entails balancing the competing concerns of energy output, ecological impact, and infrastructure ease. MCDA in a GIS setting allows differentiated consideration of wind resource, seabed, water, distance to grid, and ecological impact factors. The model is designed to ensure the site set does not skew toward energy performance to the detriment of biodiversity and/or the overall favorability of the cost. It instead offers decision-makers a ranked list of locations, specifying trade-offs for selection that maximize sustainability and

profitability (Pittman *et al.*, 2022; Chukwuma-Eke *et al.*, 2022). Another goal is to assimilate the cross-domain datasets to interrelate them within a singular GIS framework. Offshore wind development requires the integration of multiple disciplines: the environmental, the technical, and the socio-economic. Environmental datasets include habitat mapping, migratory bird corridors, marine mammal distribution, and marine protected area data. The technical datasets include wind data sets, geotechnical seabed surveys, and other infrastructures such as shipping and subsea cables. Socio-economic datasets include the proximity to ports, fishing grounds, and community acceptance. The GIS system acts as the central data integration layer, providing a geospatial foundation on which versatile cross-domain datasets can be interfaced and analytically constrained. The data integration fosters greater transparency and compliance as stakeholders' access and interrogate data interrogate layers across a common geospatial framework. (Bailo *et al.*, 2022; González and Connell, 2022).

In addition to its analytical capabilities, this technology illustrates configurations for turbine optimization and yield simulation. These configurations can be operationalized for practical applications on a site. The model utilizes WindPro, a popular engineering software for the analysis and design of wind turbine farms. Specific simulations within WindPro estimate the annual energy production, the turbine wake, and the spacing and configuration of turbines for different site design layouts. This enables the developer to assess and refine a design that maximizes energy production and minimizes operational costs. Also, WindPro outputs integrated into a GIS context ensure that spatial analysis results are tied to the energy performance results of the site (Peri and Tal, 2020; Morkūnė *et al.*, 2020). For instance, sites with good seabed and biological characteristics and weak wind might be excluded from consideration, while sites that yield high energy are evaluated for potential environmental impacts. The integration of GIS with WindPro enables a more practical analysis of energy production potential from sites that were previously considered optimal after a spatial analysis.

The ultimate goal is to validate the decision-support framework through North Sea case studies. The North Sea has one of the most developed offshore wind sectors in the world and also boasts the most operational and environmental data in wind energy. North Sea inspections gathered seabed maps, ROV wind speed surveys, and long-term wind speed data, all of which are critical for model validation. This involves the comparison of model results—suitability maps, energy yield predictions—against observational data of existing and operational wind farms. If the model sites with the highest scores overlap with operational wind farms or known development areas, the model is considered to be highly accurate and useful. In addition, validation for a developed market guarantees that the model can be used for other emerging offshore wind areas with scarce data (O'Hanlon and Cummins, 2020; Turnbull *et al.*, 2022).

The focus of the objectives related to the GIS-based renewable energy site selection model rests primarily on the requirement for a tool that integrates scientific rigor with

practical relevance for offshore wind planning. The model's multi-criteria approach, differentiating input sources, is integrated with WindPro simulations and validated with a UK North Sea case study, providing stakeholders with robust decision-support capabilities. This not only helps advance the technical optimization of offshore wind farm design but also improves ecological protection, regulatory compliance, and socio-economic acceptance. Overall, the model helps de-risk offshore wind investments and supports the global renewable energy transition.

2.1. Methodology

The systematic review on Geographic Information System (GIS)-based renewable energy site selection models for offshore wind farms was conducted using the PRISMA framework to ensure rigor, reproducibility, and transparency. A comprehensive literature search was performed across Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar to capture a wide spectrum of studies published between 1998 and 2022, reflecting both early applications of GIS in renewable energy planning and the more recent integration of advanced computational methods. The search strategy employed Boolean operators and key terms such as “GIS,” “renewable energy,” “site selection,” “offshore wind farms,” “multi-criteria decision analysis,” and “spatial modelling.” The initial search retrieved 1,382 records. Following the removal of 316 duplicates using reference management software, 1,066 unique studies remained. Titles and abstracts were screened based on predefined inclusion criteria: studies had to focus on offshore wind site selection, apply GIS-based methodologies, and integrate technical, environmental, or socio-economic factors. Exclusion criteria eliminated studies limited to onshore wind projects, non-GIS-based methods, or purely theoretical discussions without spatial modeling. After this stage, 248 studies were selected for full-text review. Full-text screening assessed methodological rigor, inclusion of decision-support frameworks (such as AHP, fuzzy logic, or multi-criteria evaluation), and practical applicability to offshore contexts. Ultimately, 72 studies met the eligibility requirements for inclusion in the final synthesis.

Data extraction focused on geographic scope, types of spatial datasets used (e.g., bathymetry, wind speed, distance to grid, shipping routes, environmental constraints), methodological frameworks, and outcomes such as optimal site identification or policy recommendations. Studies were appraised using quality assessment tools adapted for spatial decision-support research, ensuring consistency in evaluating methodological robustness and transparency. The final synthesis highlighted the evolution of GIS-based site selection models from basic spatial overlays to advanced hybrid approaches integrating machine learning, optimization algorithms, and policy-driven constraints. The PRISMA process ensured that the review captured a comprehensive and unbiased understanding of GIS applications in offshore wind farm planning, providing a foundation for identifying research gaps, best practices, and pathways toward sustainable and resilient renewable energy infrastructure.

2.2. Data Sources

The ease of developing offshore wind farms is contingent upon the underlying data accuracy and how well they are detailed, and the comprehensive information base they offer for the selection of the site and planning the offshore wind farms. A well-designed decision-support model necessitates the synthesis of spatial, technical, environmental, and meteorological datasets for the prospective development zone of the offshore wind farms, as shown in Figure 1(Wajid

et al., 2021; Tékouabou *et al.*, 2022). There are three fundamental categories of data critical for offshore wind farms: spatial & technical, Environmental Impact Assessment (EIA) wind resource data, and wind resource data, as shown in Table 1. Each of the categories contributes to achieving the best possible compromise among energy yield, environmental conservancy, and technical feasibility for site selection.

Table 1: Data Sources for Offshore Wind and Marine Infrastructure Planning

Category	Data Types / Features	Purpose / Use
Spatial and Technical Data (GIS Layers)	- Bathymetry (water depth)- Seabed composition and geotechnical constraints- Distance to grid connection points and ports- Existing marine infrastructure (pipelines, cables)- Shipping lanes and exclusion zones.	- Site selection and layout optimization- Structural design and foundation planning- Avoidance of conflicts with existing infrastructure- Navigation and operational safety planning.
Environmental Impact Assessment (EIA) Data	- Marine protected areas (MPAs)- Migratory bird pathways- Marine mammal habitats- Fisheries and aquaculture zones- Noise propagation zones during construction.	- Assess environmental constraints and regulatory compliance- Plan mitigation measures for wildlife and habitats- Minimize ecological impacts during construction and operation.
Wind Resource Data (WindPro Inputs)	- Long-term wind datasets (ERA5, met mast records, LiDAR)- Wind speed distributions at hub height- Turbulence intensity and wake losses- Seasonal variability.	- Estimate energy yield and power production- Inform turbine selection and spacing- Optimize layout to reduce wake effects- Support financial modeling and risk assessment.

The geospatial and technical datasets offshore wind site planning rely on are bathed in data up to and including October 2022. Spatial data on water depth has a disproportionate influence on the objectives of the planning phase. In particular, the construction and performance of the turbine legs are directly influenced by the depth of water in the locations in question. In particular, shallow monopile floating turbine foundations are far easier to build than a floating monopile, and similarly, deep water monopiles, where jacketed or depth, are far less economically viable. Accuracy in determining depth, therefore, becomes a major predictor of installation viability and installation economic freedom.

Finally, the composition of the seabed and the associated limitations of the structure are critical and stand-alone layers. Workflow operations, turbine installation, and ongoing inspection and extraction become impossible to complete without reliable subsea ground geophysical data that extends to reach the less than 10-meter floating head of the turbine. Geophysical dataset construction builds latitude and longitude data of the ground using systems that include, but are not limited to, grab sample holding pens, cone penetration traverse, and ultrasonic depth profiling to build the 3D geospatial contour. Geophysical survey data have proven to be most informative in the validation of push pile depth assumptions. Geotechnical data has proven that geophysics are critical in geological and foundation design where lateral and rotational restraints are needed.

The distance to grid connection points and ports is a key technical and economic consideration. Substation proximity is an advantage for reduced transmission losses, capex, and infrastructure complexity. Likewise, distance to ports and supply bases influences logistics, vessel transit time, and operational support for maintenance activities (Wendler-Bosco and Nicholson, 2020; Ducruet and Itoh, 2020). This data is integrated into GIS, where planners can add logistics to technical and environmental constraints for balanced decision-making.

The existing marine infrastructure's subsea pipelines, telecommunication cables, and oil and gas platforms must also be part of the spatial dataset. Potential hazards or restrictions arise since turbines must be placed without interference with the existing constituents. The spatial dataset of GIS ensures the placement of turbine arrays is safe and within the least possible disruption to marine activities (Alphan, 2021; Katikas, 2022).

Last, shipping lanes and exclusion zones are important for the safe and regulatory-controlled movement of vessels. The placement of turbines also has boundaries where international maritime traffic, naval activities, and fishing grounds are present. The GIS analyses of exclusion zones help avoid overlap with densely trafficked zones, thereby minimizing the chances of an accident while meeting national and international maritime rules (Appah, 2022; Wang *et al.*, 2022).

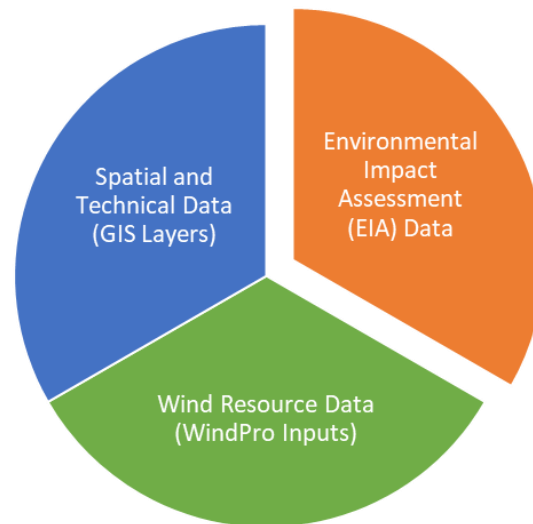


Fig 1: Data Sources

Incorporation of stewardship principles has intertwined the development of offshore wind sites with the capture and analysis of EIA datasets. Turbines located in or adjacent to MPAs and shipping lanes could interrupt sensitive subsurface habitats. Thus, GIS layers pinpointing these zones can be used to assess non-requirement areas for impact or mitigation.

Albatross and migratory bird pathways are other important factors. Offshore wind farms pose collision risks to birds, especially during the migration season. EIA datasets containing telemetry-derived flight path data with nesting and congregating areas, and seasonally abundant birds' habitats, allow planners to design avoidances or mitigate turbine operations during certain hours (Metz *et al.* 2021, Andrews *et al.* 2022).

Seals and cetaceans, as well as other marine mammals, habitats, and especially essential breeding and foraging areas, are also included in EIA datasets. Disruption to marine mammals, associated with the construction of high-density noise barrage operators, is a construction sound emissions problem. Thus, GIS enables these zones to impact the noise mitigation for tendered sites.

Fisheries and aquaculture zones highlight sociological and economic perspectives. Offshore wind development may hinder commercial fishing or aquaculture operations. These zones must be mapped to ensure that turbine placement optimizes renewable energy development and the sustenance of local communities.

In the end, construction noise propagation zones are key for verifying environmental impacts and are crucial for impact assessment. Acoustic modeling delineates regions where construction noise from pile driving or vessels surpasses certain thresholds set for sensitive species. These zones are then integrated into GIS to help planners estimate environmental strain and schedule construction to minimize impact (Weilant *et al.* 2019; Yang *et al.* 2021).

The spatial distribution of wind resources is fundamental for assessing the energy potential of offshore sites. The model is based on extensive time-series wind data, which consists of ERA5 reanalysis records, met mast observations, and LiDAR data. These datasets describe a multidimensional wind field in speed, direction, and vertical and horizontal shear over a timeframe of several years, allowing for coherent turbine performance forecasting.

Distributions of wind speed over the hub height are crucial for estimating energy yields. Offshore wind speeds tend to increase with height, and the hub height wind profile determines the potential annual energy production (AEP). These profiles are the basis for optimum wind turbine spacing, rotor, and turbine assembly in order to maximize efficiency.

The degree of turbulence and the turbulence within the wake behind the turbines are fundamental in turbine array systems design. Excessive turbulence can throttle power generation and cause additional mechanical strain on the turbines. Wake effects—the downwind turbine-induced decreases in wind speed—must be modeled to optimize array spacing and layout to ensure maximum energy extraction without turbine overloading (Houck, 2022; Masoudi and Baneshi, 2022).

The seasonal changes in atmospheric conditions impact the amount of energy produced and the expected energy demand, thereby altering the operative strategy. Changes in the speed and direction of the wind during a season could also alter the generated power, shifting the need for maintenance, and changing the way the energy should be fed into the grid. These changes and the associated adjustments are possible to forecast using a combination of long-term wind databases and statistical methodologies to prepare for potential seasonality in the generated power and plan for offshore energy systems.

Offshore wind farm site selection models relying on GIS-based technology rest on three categorical data sets: spatial and technical data, EIA data, and wind resource data. The spatial data sets—bathymetry, seabed type and structure, surrounding infrastructure, and navigation delineation data—assure technical feasibility and safety. EIA data sets record ecological sensitivity to aid in constructive sustainable development and ensure compliance with local and international regulations. Wind resource data sets, in conjunction with WindPro simulations, provide estimated energy yields and, along with WindPro, aid in preliminary turbine layout optimizations (Al-Addous *et al.*, 2020; Menezes *et al.*, 2020). All these data sets provide the frame of reference for a multi-criterion, evidence-based decision-support system to analyze offshore wind energy on the principles of sustainability, energy generated, and practicality in operations. Hence, offshore wind energy can be harnessed sustainably.

2.2. Model Architecture

An integrated framework facilitates decision-making by combining spatial data management, multi-criteria evaluation, and energy simulation management systems in developing a sophisticated model architecture for offshore wind farm site selection. The model integrates Geographic Information Systems, Multi-Criteria Decision Analysis, and sophisticated wind energy simulation software WindPro for structured offshore site assessment and ranking. Its architecture consists of four layers, which are input, processing, simulation, and output, arranged in succession, each performing critical roles for the decision-support system as shown in Figure 2 (Moreira *et al.* 2019; Pérez-Castillo *et al.* 2020).

Step 1: Input Layer

All relevant data streams are collected, formatted, and organized into composite GIS formats in the data collection model for the Site Selection Model Input Layer. Data is separated into three overarching categories: environmental, technical, and economic (Zheng *et al.* 2019; Sarja *et al.* 2021). Wind speed and direction, bathymetry, seabed

conditions, wave height, and environmental sensitivity data, which encompasses marine protected areas (MPAs), endangered/threatened species habitats, and migratory pathways, are part of the environmental datasets. Turbine specifications, grid connection, depth of water, seabed load bearing, and the offshore structures of pipelines and cables are part of technical datasets. Economic datasets include the distance of the site to a port, construction, and maintenance. After data is acquired, data processing is done for analysis so that they are spatially compatible through projection standardization, resolution matching, and attribute normalization. Each data set is prepared as a GIS layer that can be integrated into the MCDA framework. At this stage, the criteria for the evaluation of the site are clearly set. The environmental criteria aim at the minimization of all possible adverse ecological impacts, the technical criteria focus on feasibility and structural safety, and the economic criteria address cost-effectiveness and accessibility (Rath *et al.*, 2021; Coppola *et al.*, 2022). This input layer allows the model to perform the quantification of site suitability in a systematic manner, as well as supports transparency in the decision-making process.

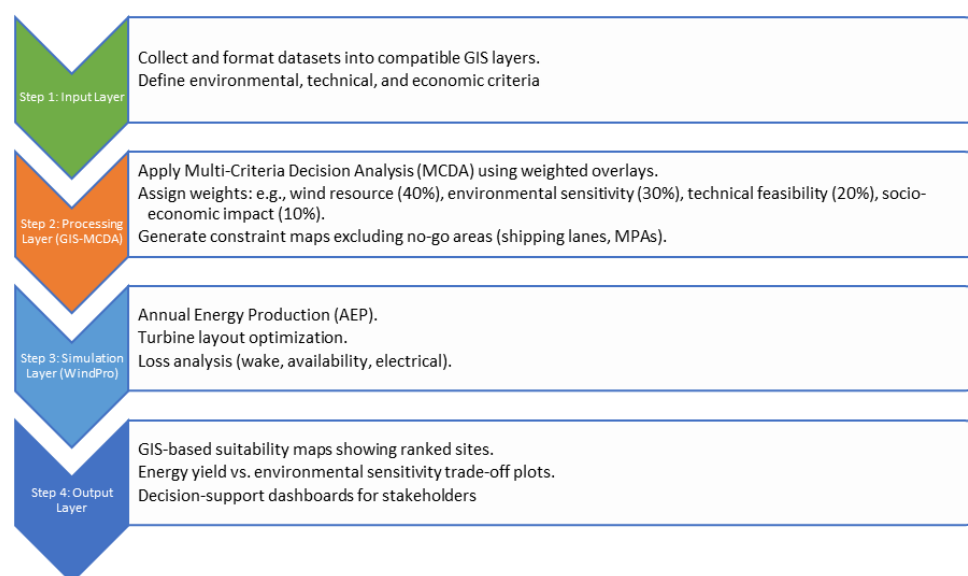


Fig 2: Model Architecture

Step 2: Processing Layer (GIS-MCDA)

The processing layer uses Multi-Criteria Decision Analysis (MCDA) to evaluate the candidate sites by GIS layers through weighted overlays. In this phase, criteria weights are assigned to indicate their importance to the decision-making process and their hierarchy. An example of a representative weighting scheme assigns 40% to the wind resource potential, 30% to environmental sensitivity, 20% to the technical feasibility, and 10% to socio-economic impacts. Adjustments to this weighting scheme can be made depending on the policies in place, the interests of the stakeholders, or the regulatory framework.

The constraint maps are created to avoid any areas that may present a safety hazard or breach legal restrictions (George, 2020; Börzel and Risse, 2021). Shipping channels, undersea cable routes, restricted military areas, and other zones of competitor control exclusion, as well as other areas with legal conservation status, are examples of these. The other potentially feasible zones are then subjected to weighted

overlay analysis using GIS spatial analysis tools, where each cell of a GIS raster affords a suitability index for each location as a function of a weighted criterion. The Multi-Criteria Decision Analysis (MCDA) approach enables the model to incorporate diverse and potentially conflicting dimensions, for instance, the trade-off between high wind and sensitive environments, and to construct a rational basis for comparison of sites.

Step 3: Simulation Layer (WindPro)

The candidate sites selected from the MCDA evaluation are subjected to detailed energy simulations using WindPro and other comparable software tools for wind energy assessment. This simulation layer analyzes and estimates several key metrics, such as Annual Energy Production (AEP), which serves as a proxy for the energy yield expected from each site. The simulation also undergoes a step of layout optimization where the arrangement of turbines is designed or organized to improve the overall annual yield of the site. This considers

the wake effect, the spacing between turbines, and the general wind direction (Khan *et al.*, 2020; Ramli and Boucekara, 2020).

Loss analysis estimates the effects of wake interactions, turbine downtime, and the electrical losses incurred in cabling and transformers. This simulation step adds a refined performance evaluation for each of the candidate sites, in addition to the spatial suitability scores derived from the MCDA layer. The model merges simulation outputs with GIS to ensure that the site selection process considers the theoretical energy potential and applicable operational constraints.

Step 4: Output Layer

The output layer combines the results of the previous layers and translates them into decision-support tools. Suitability maps visualize the relative ranking of candidate sites from a GIS perspective, integrating the site's environmental, technical, and economic aspects in a single spatial layer (Choi *et al.*, 2019; Zambrano-Asanza *et al.*, 2019). Such maps improve stakeholder participation by demonstrating areas with the highest potential while revealing possible trade-offs, such as energy yield and environmental impact.

The graphs showing energy yield and environmental impact demonstrate the trade-offs involved in site selection. It aids developers and policymakers in understanding the trade-offs and achieving the desired energy production level. The key outcomes in the decision-support dashboards, such as site-based performance metrics and environmental risk scores, as well as ranking the sites, allow users to interactively analyze various workflows. The dashboards also allow users to modify criterion weights and input new data to enable scenario-based decision-making.

The offshore wind farm site selection model proposed integrates GIS data management, multi-criteria decision analysis with WindPro simulations, and model workflows into defined input, processing, simulation, and output layers. This ensures the decision-making processes remain data-centric, clarifying how the processes are environmentally, technically, and economically optimal. The model's architecture integrates disparate data, manages trade-offs in the decision-making processes, and provides stakeholders with clear, actionable outcomes to foster offshore wind energy development that are sustainable, efficient, and resilient (GAFFAR *et al.*, 2019; Laña *et al.*, 2021). This model increases the offshore wind energy site selection processes by the rational approach and the growing complexity in regulations, technologies, and the environment.

2.3. Case Study: North Sea Offshore Projects

The longitudinal reason for focusing on the North Sea for the development of the offshore winds was because of the high-speed winds that are of high speed, having shallow waters, coupled with their existing ports and different ships already there. The offshore energy resource is also in great demand for optimizing the set wind stations in this area, and this is to take in environmental, technical, and operational data. The thesis focuses are the application of the GIS-based site selection model for offshore wind and the associated MCDA and WindPro simulation, and the North Sea offshore projects with the accompanying methods and results provided.

One of the most vital aspects of the model was the combination of the data for the analysis and the subsequent

associated monitoring data. The use of ROVs along with sonar data of the mapping is able to create a survey that can display geohazards, bathymetric profiles, and other such things for a sediment sample and its structure. The data that is gathered can be used to decipher where the turbine's foundation can be and where it can also be installed. The data in marine life, along with its monitoring, habitats that are sensitive offshore, and the patterns of where the animals move, whether they are at rest or there is other data that is collected, can be useful.

In addition, historical maintenance files and cable-route surveys were sources of valuable information concerning operational limits. These records contained information on equipment functioning, seabed scouring, and physical obstacles like abandoned pipelines and debris fields. Integration of this historical data with the GIS framework facilitated more realistic technical risk assessments and reduced the consequences of unplanned site adversities (Jena *et al.*, 2020; Lee, 2021). With the combination of these datasets, the model was able to provide a comprehensive, evidence-based framework for the following studies.

The GIS-based MCDA framework was used to overlay environmental data with the wind resources layer to provide a more detailed representation of the potential site. Wind resource data collected by meteorological models and stations with long-term observations were weighted with environmental and technical criteria to produce composite suitability maps. Sensitive ecological habitats, naval traffic lanes, and shipping corridors were exclusion zones that were used to remove areas that could not be developed. This step ensured that the project adhered to appropriate regulations and mitigated possible conflicts with maritime operations, and protected ecosystems.

Results from GIS-MCDA evaluations led to the identification of shortlisted candidate sites, which were further assessed through WindPro simulations. These included estimates of annual energy production (AEP), turbine placement optimization, and loss evaluation, which incorporated wake losses, electrical losses, turbine availability, and operational losses. Predictive outputs of WindPro were then verified against actual operational North Sea wind farms to determine the model's reliability. Validation included the concordance of forecasted energy yields and site feasibility, as well as environmental installation suitability against installation results, enabling the model to parameter and decision refinement (Judge *et al.*, 2019; Aste *et al.*, 2022).

The analysis identified several sites with the potential for strong wind resources and lower ecological sensitivity. These sites were also aligned with the operational wind farms, illustrating the ability of the model to approximate the real-world decisions made during site selection. Considered favorable were sites with low environmental conflict, optimal seabed conditions, and good proximity to grid connection for a balance of technical feasibility, energy yield, and environmental impact.

This also underscored the value added by the fusion of multiple spatial and non-spatial data sources into a GIS-MCDA system. Using seabed mapping, environmental monitoring, and past operational documentation, the model also provided a robust quantitative and spatial evaluation of site suitability (Bowden *et al.* 2021; Tsai and Lin, 2022). The WindPro simulations increased accuracy and provided the model with clearer insight into the nuances of energy production and other operational limitations. The underlying

model, validated against operational wind farms, was capable of reliably determining the best sites and thus enabled developers to get positive guidance on the site selection while achieving the balance between sustainability and compliance. Also, the case study demonstrated the value of the method in assessing the balance between the wind resource and the environment. Some of the high wind areas were indeed in sensitive parts of the ecosystem. However, the GIS multi-layered approach easily provided other spots with close to the same energy production but a lower ecological footprint (Li *et al.* 2020; Doljak *et al.* 2021). This is especially important in advancing the sustainable development of offshore wind energy, where the aim is to lower the negative impact on the marine environment while achieving the desired energy output.

The North Sea case study shows how useful and accurate a GIS-based MCDA integrated site selection model is for offshore wind projects. With the model, it inspects, seabed, environment, and other operational data to evaluate potential sites. Its GIS-based analysis, combined with WindPro, achieves estimated site potential, energy, and environment yield (Rehman *et al.*, 2020; Katikas, 2022). The model is simple, data-oriented, and repeatable, as it aligns with the wind farm validation, achieving the real-world decision outcome for offshore wind development.

The results reinforce the value of incorporating various datasets and sophisticated simulation methods for effective site selection in challenging offshore environments. The model captures new sites for development while reducing the impact of energy projects on the environment (Lee, 2019; Gangi *et al.*, 2019). This adds to the growing offshore wind methodology as it supports the North Sea and other territories

with integrated, optimized, and affordable renewable energy sources.

2.4. Practical Implications

The advancement of offshore wind technology involves an integration of various technological, ecological, financial, and sociopolitical components. While wind energy projects certainly help with clean energy and reducing carbon emissions, offshore wind projects require that offshore wind energy be balanced with various interests. The implementation of a GIS-based renewable energy site selection model, which folds an Environmental Impact Assessment (EIA), geospatial processes, and wind resource modeling, represents a major contribution to practice for developers, regulators, stakeholders, and the surrounding populace, as shown in Figure 3 (Ajanaku *et al.*, 2022; Bourbonnais, 2022). The model provides a rational, evidence-based model for optimizing decisions in energy production, environmentally sustainable practices, and community acceptability.

The GIS model provides developers with GIS model provides developers with increased site selection precision and energy risk by saving analysis time (Harig *et al.*, 2021). Developers invest substantial amounts of wind offshore capital, which includes the costs of turbine purchases, foundations, grid connections, and long-term operations and maintenance. Sites with limited spatial, technical, and environmental assessments experience geospatial risk, cost overruns, construction delays, and lower energy outputs. Developers can use WindPro along with GIS-based spatial layers to identify regions with adequate wind, seabed, and low infrastructure.

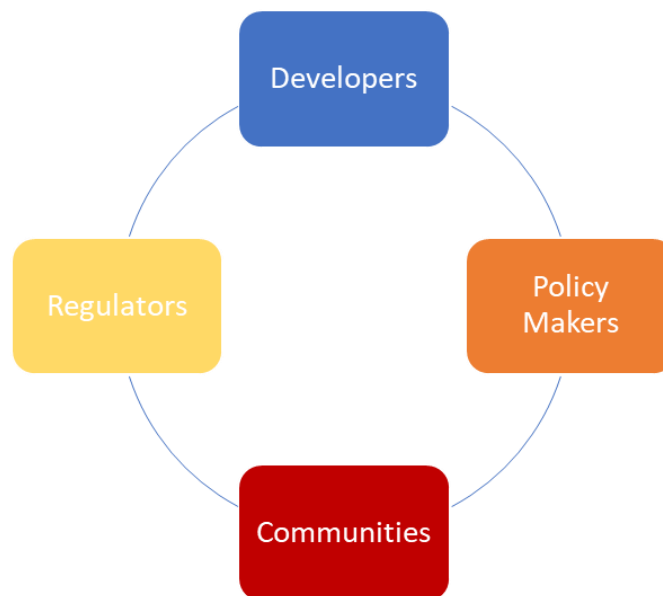


Fig 3: Practical Implications

Also, the model allows developers to estimate the possible constraints to ensure no construction delays or environmental lawsuits arise out of silos. The construction of turbines will benefit from the prior mapping of marine protected areas, migratory bird pathways, and fisheries zones. This mapping allows sensitive ecologies to be considered when turbine placement occurs, as well as altering the predicted wake of the turbines. The ability to forecast turbine layouts and turbine annual energy yields helps in the array configuration

refinement processes. This helps developers minimize mechanical stress and wake effects on the turbine yields (Moghaddasian and Sharma, 2020; Al-Addous *et al.*, 2020). This model adds to the economic viability and operational dependability of offshore wind projects.

From a different angle, the GIS-based site selection model improves and adds to the clarity and the data-based assessment pertaining to the environmental and technical issues for the regulators (Castro and Rifai, 2021; Watson *et*

al., 2022). It is the duty of regulatory agencies to supervise the activities pertaining to the offshore wind development and monitor the adherence to the environmental laws on a national and international level, along with the marine life protection and public health safety. The model provides a uniform and geospatially relevant site assessment system, which improves the regulatory assessment of the projects and systematically places them in the order that needs to be regulated.

Through GIS technology, the integration of environmental, technical, and socioeconomic datasets allows regulators to visualize potential impacts, assess conflicts, and assess compliance. The model's addition of long-term wind resource data, seabed geotechnical data, and navigation data to infrastructure buffers ensures thorough evaluation of technical feasibility and ecology integration (Pınarbaşı *et al.*, 2019; Heatherington *et al.*, 2021). This enables the regulators to base their decisions on integrated assessments, rather than data fragmentation, which makes the assessments more consistent and predictable during the permitting phase.

The model's integration of offshore wind development with other elements of marine spatial planning and sustainability serves policymakers. The United Kingdom, Germany, and other EU members are increasingly adopting marine spatial planning approaches to balance the expansion of renewable energy sources with the protection of the environment, fisheries, and the safety of navigation. The GIS model offers a quantitative, evidence-based approach to assess trade-offs among competing interests in the marine environment (Giacometti *et al.*, 2020).

The "model seeks to accommodate policy choices that achieve objectives within renewable energy targets for the country while avoiding undue negative environmental and societal impacts" (Colapinto *et al.* 2020; Kumar *et al.* 2022). Policies based on the model allow for the justification of rational choices based on factual information for all stakeholders. This way, the model enhances the offshore wind policy discourse by increasing awareness and public acceptance of the wind projects. Data-driven communications help policymakers rationally justify decisions to stakeholders, promoting offshore wind projects' acceptance.

The development of offshore wind projects directly impacts local communities and various marine stakeholders, such as the fishing and conservation sectors. Geographical Information Systems (GIS) tools allow modelers to optimize the tradeoffs between renewable energy development and the environment, so as to permit the meaningful participation of communities in the planning of the projects (Perry and Thompson 2019; Fox *et al.* 2022).

In correlating and delineating geo-spatial environmental limitations, navigational routes, and socio-economic activities, the model provides communities with an understanding of possible turbine placements, associated estimated energy yield, and potential ecology. This type of speculation cultivates confidence and mitigates disputes between project developers and the local communities. Furthermore, the model can assist in formulating electronic tools for impact evaluation with the capability to restrain turbine activities in sensitive fisheries regions or construction efforts to avoid peak migratory bird or marine mammal seasons. Through the use of participatory planning, the communities can sustain their livelihood and environmental virtues while developing offshore energy through the use of

GIS visualization planning (Spyridonidou *et al.*, 2021; González and Connell, 2022).

The range of offshore wind farms and the implications it has for geo-spatially configured models of sites for their development is profound. For project developers, the model mitigates capital and maximizes energy investment. For boundary setting and reviewing authorities, the model offers a compliance assessment and the record of the evidence-based assessment. For public policy advocates, the model satisfies the unified offshore wind models with the domestic and global marine spatial planning frameworks. Finally, for the local communities, the model exports the socio-economic and ecological balance to the impact of newly integrated frameworks to broaden local renewable energy sources, participating in the stakeholder eco-initiative for defense (Mishra *et al.*, 2022; Trifonova *et al.*, 2022).

The model integrates datasets with geo-spatial, ecological, and wind resource components to convert the site selection process for offshore wind farms from a disintegrated and retrospective process to a systematic, evidence-driven, and collaborative approach. This transformation greatly improves the viability, ecological, and societal acceptance of these offshore wind energy developments (Lindberg *et al.*, 2021; Sawant *et al.*, 2021; Asiaban *et al.*, 2021).

3. Conclusion

When designing offshore wind farms, planners have to weigh the amount of wind energy available against the possible socio-economic impacts, the likelihood of environmental damage, and the technical feasibility of the project. They need to consider competing and sometimes conflicting factors. GIS tools can help planners, environmental regulators, and decision-makers visualize projects and the range of choices and systematically evaluate possible locations to help mitigate some of the competing factors.

Systems integration involves combining Environmental Impact Assessment (EIA), Geographic Information Systems (GIS), and WindPro simulations to create a preliminary policy model for effective site selection. EIA works with GIS to consider strategic allocation and exclusion zoning in planning bathymetric and surface contour chambers in the GIS reef. GIS integrates WindPro simulated contour basins and authored polygon layer texts, showing offshore wind farms and estimating interdiction areas of foraging of suspended plains. These tools help develop site assessment toward project-operational-feasibility correlations for offshore projects. The entire model and site-assessment approach balances project and operational objectives while sustaining environmental and regulatory compliance.

As demonstrated through the North Sea case studies, the model validation clearly shows its diversity and accuracy. The model shows high accuracy in confining areas of high suitability without violating environmental and technical boundaries. This is achieved through the integration of inspection data, the outcome of environmental studies, and wind resource usage. Its successful operation in the North Sea advanced offshore wind region also confirms its dependable and easily scaled nature in the emerging global markets for offshore wind, which is rapidly growing.

GIS-integrated decision support systems have immense potential in transforming the offshore wind site selection process. These systems optimally balance the performance and the sustainable energy goals of the project through structured multi-level frameworks. The systems promote

effective, clearly defined, and evidence-driven decision-making, which ensures that the impacts of offshore wind development focus on the renewable energy goals while minimizing the environmental and socio-economic burdens.

4. References

- Ajanaku BA, Strager MP, Collins AR. GIS-based multi-criteria decision analysis of utility-scale wind farm site suitability in West Virginia. *GeoJournal*. 2022;87(5):3735-57.
- Al-Addous M, Jaradat M, Albatayneh A, Wellmann J, Al Hmidan S. The significance of wind turbines layout optimization on the predicted farm energy yield. *Atmosphere*. 2020;11(1):117.
- Albraheem L, Alabdulkarim L. Geospatial analysis of solar energy in Riyadh using a GIS-AHP-based technique. *ISPRS Int J Geo-Inf*. 2021;10(5):291.
- Alphan H. Modelling potential visibility of wind turbines: a geospatial approach for planning and impact mitigation. *Renew Sustain Energy Rev*. 2021;152:111675.
- Amjad F, Shah LA. Identification and assessment of sites for solar farms development using GIS and density based clustering technique—a case of Pakistan. *Renew Energy*. 2020;155:761-9.
- Andrews R, Bevrani B, Colin B, Wynn MT, Ter Hofstede AH, Ring J. Three novel bird strike likelihood modelling techniques: the case of Brisbane Airport, Australia. *PLoS One*. 2022;17(12):e0277794.
- Appah J. Understanding cold-water corals' health and ecosystems on the Irish margin, NE Atlantic; a critical look into the ecology, geology, hydrodynamic processes and human impacts. [place unknown]: [publisher unknown]; 2022.
- Asiaban S, Kayedpour N, Samani AE, Bozalakov D, De Kooning JD, Crevecoeur G, *et al*. Wind and solar intermittency and the associated integration challenges: a comprehensive review including the status in the Belgian power system. *Energies*. 2021;14(9):2630.
- Aste N, Adhikari RS, Buzzetti M, Del Pero C, Huerto-Cardenas HE, Leonforte F, *et al*. nZEB: bridging the gap between design forecast and actual performance data. *Energy Built Environ*. 2022;3(1):16-29.
- Bailo D, Jeffery KG, Atakan K, Trani L, Paciello R, Vinciarelli V, *et al*. Data integration and FAIR data management in Solid Earth Science. [place unknown]: [publisher unknown]; 2022.
- Baldo D, Mecocci A, Parrino S, Peruzzi G, Pozzebon A. A multi-layer LoRaWAN infrastructure for smart waste management. *Sensors*. 2021;21(8):2600.
- Börzel TA, Risse T. Effective governance under anarchy: institutions, legitimacy, and social trust in areas of limited statehood. Cambridge: Cambridge University Press; 2021.
- Bourbonnais M. Applications of geographic information systems, spatial analysis, and remote sensing in environmental impact assessment. In: *Routledge handbook of environmental impact assessment*. Abingdon: Routledge; 2022. p. 201-20.
- Bowden DA, Anderson OF, Rowden AA, Stephenson F, Clark MR. Assessing habitat suitability models for the deep sea: is our ability to predict the distributions of seafloor fauna improving? *Front Mar Sci*. 2021;8:632389.
- Calado H, Papaioannou EA, Caña-Varona M, Onyango V, Zauha J, Przedrzymirska J, *et al*. Multi-uses in the Eastern Atlantic: building bridges in maritime space. *Ocean Coast Manag*. 2019;174:131-43.
- Castro CV, Rifai HS. Development and assessment of a web-based national spatial data infrastructure for nature-based solutions and their social, hydrological, ecological, and environmental co-benefits. *Sustainability*. 2021;13(19):11018.
- Choi Y, Suh J, Kim SM. GIS-based solar radiation mapping, site evaluation, and potential assessment: a review. *Appl Sci*. 2019;9(9):1960.
- Christianson P, Decker V, Holman A, McGregor G, Welk C, Lorinsky A. Evaluation and adaptive management of the Huron River Watershed Council Natural Areas Assessment and Protection Project. [place unknown]: [publisher unknown]; 2021.
- Chukwuma-Eke EC, Ogunsola OY, Isibor NJ. A conceptual framework for financial optimization and budget management in large-scale energy projects. *Int J Multidiscip Res Growth Eval*. 2022;2(1):823-34.
- Colapinto C, Jayaraman R, Ben Abdelaziz F, La Torre D. Environmental sustainability and multifaceted development: multi-criteria decision models with applications. *Ann Oper Res*. 2020;293(2):405-32.
- Coppola P, Deponte D, Vacca A, Messa F, Silvestri F. Multi-dimensional cost-effectiveness analysis for prioritizing railway station investments: a general framework with an application to the Italian case study. *Sustainability*. 2022;14(9):4906.
- Costoya X, DeCastro M, Carvalho D, Gómez-Gesteira M. On the suitability of offshore wind energy resource in the United States of America for the 21st century. *Appl Energy*. 2020;262:114537.
- Díez-Rodríguez JJ, Fischer TB, Di Zio S. Introducing a group spatial decision support system for use in strategic environmental assessment of onshore wind farm development in Mexico. *J Clean Prod*. 2019;220:1239-54.
- Doljak D, Stanojević G, Miljanović D. A GIS-MCDA based assessment for siting wind farms and estimation of the technical generation potential for wind power in Serbia. *Int J Green Energy*. 2021;18(4):363-80.
- Doorga JR, Rughooputh SD, Boojhawon R. Multi-criteria GIS-based modelling technique for identifying potential solar farm sites: a case study in Mauritius. *Renew Energy*. 2019;133:1201-19.
- Ducruet C, Itoh H. Spatial network analysis of container port operations: the case of ship turnaround times. *Netw Spat Econ*. 2022;22(4):883-902.
- Fox N, Campbell-Arvai V, Lindquist M, Van Berkel D, Serrano-Vergel R. Gamifying decision support systems to promote inclusive and engaged urban resilience planning. *Urban Plan*. 2022;7(2):239-52.
- Fryirs K, Hancock F, Healey M, Mould S, Dobbs L, Riches M, *et al*. Things we can do now that we could not do before: developing and using a cross-scalar, state-wide database to support geomorphologically-informed river management. *PLoS One*. 2021;16(1):e0244719.
- Gaffar O, Sikiru AO, Otunba M, Adenuga AA. A predictive analytics model for multi-currency IT operational expenditure management. [place unknown]: [publisher unknown]; 2019.
- Galparsoro I, Menchaca I, Seeger I, Nurmi M,

- McDonald H, Garmendia JM, *et al.* Mapping potential environmental impacts of offshore renewable energy. *ETC/ICM Rep.* 2022;2:2022.
31. Gangi F, Meles A, D'Angelo E, Daniele LM. Sustainable development and corporate governance in the financial system: are environmentally friendly banks less risky? *Corp Soc Responsib Environ Manag.* 2019;26(3):529-47.
 32. George N. Gender and post-conflict security: experiences from Bougainville and Solomon Islands. In: *Mapping security in the Pacific.* Abingdon: Routledge; 2020. p. 104-18.
 33. Giacometti A, Morf A, Gee K, Kull M, Luhtala H, Eliassen SQ, *et al.* Handbook: process, methods and tools for stakeholder involvement in MSP. *BONUS BASMATI Deliverable 2.3.* [place unknown]: [publisher unknown]; 2020.
 34. González A, Connell P. Developing a renewable energy planning decision-support tool: stakeholder input guiding strategic decisions. *Appl Energy.* 2022;312:118782.
 35. Gulski E, Anders GJ, Jongen RA, Parciak J, Siemiński J, Piesowicz E, *et al.* Discussion of electrical and thermal aspects of offshore wind farms' power cables reliability. *Renew Sustain Energy Rev.* 2021;151:111580.
 36. Hannon M, Topham E, Dixon J, McMillan D, Collu M. Offshore wind, ready to float? Global and UK trends in the floating offshore wind market. [place unknown]: [publisher unknown]; 2019.
 37. Harig O, Hecht R, Burghardt D, Meinel G. Automatic delineation of urban growth boundaries based on topographic data using Germany as a case study. *ISPRS Int J Geo-Inf.* 2021;10(5):353.
 38. Harrison-Atlas D, Lopez A, Lantz E. Dynamic land use implications of rapidly expanding and evolving wind power deployment. *Environ Res Lett.* 2022;17(4):044064.
 39. Heatherington C, Grinham A, Penesis I, Hunter S, Cossu R. Geotechnical approach to early-stage site characterisation of shallow wave energy sites. *J Mar Sci Eng.* 2021;9(6):605.
 40. Henderson J, Sen A. The energy transition: key challenges for incumbent and new players in the global energy system. Oxford: Oxford Institute for Energy Studies; 2021. Report No.: ET 01.
 41. Houck DR. Review of wake management techniques for wind turbines. *Wind Energy.* 2022;25(2):195-220.
 42. Igogo T, Awuah-Offei K, Newman A, Lowder T, Engel-Cox J. Integrating renewable energy into mining operations: opportunities, challenges, and enabling approaches. *Appl Energy.* 2021;300:117375.
 43. Jena R, Pradhan B, Beydoun G, Al-Amri A, Sofyan H. Seismic hazard and risk assessment: a review of state-of-the-art traditional and GIS models. *Arab J Geosci.* 2020;13(2):50.
 44. Judge F, McAuliffe FD, Sperstad IB, Chester R, Flannery B, Lynch K, *et al.* A lifecycle financial analysis model for offshore wind farms. *Renew Sustain Energy Rev.* 2019;103:370-83.
 45. Katikas L. Spatial decision support system for offshore wind farm siting using Geographic Information Systems, spatial analysis and optimization. Athens: National Technical University of Athens; 2022.
 46. Khan MY, Ali M, Qaisar S, Naeem M, Chrysostomou C, Iqbal M. Placement optimization for renewable energy sources: ontology, tools, and wake models. *IEEE Access.* 2020;8:72781-800.
 47. Kheybari S, Kazemi M, Rezaei J. Bioethanol facility location selection using best-worst method. *Appl Energy.* 2019;242:612-23.
 48. Kumar A, He X, Deng Y, Singh AR, Sah B, Kumar P, *et al.* A sustainable rural electrification based on a socio-techno-economic-environmental-political microgrid design framework. *Energy Environ Sci.* 2022;15(10):4213-46.
 49. Laña I, Sanchez-Medina JJ, Vlahogianni EI, Del Ser J. From data to actions in intelligent transportation systems: a prescription of functional requirements for model actionability. *Sensors.* 2021;21(4):1121.
 50. Lee D, Lee S. Digital twin for supply chain coordination in modular construction. *Appl Sci.* 2021;11(13):5909.
 51. Lee I. The Internet of Things for enterprises: an ecosystem, architecture, and IoT service business model. *Internet Things.* 2019;7:100078.
 52. Leiter T. Do governments track the implementation of national climate change adaptation plans? An evidence-based global stocktake of monitoring and evaluation systems. *Environ Sci Policy.* 2021;125:179-88.
 53. Lent RW, Brown SD. Career decision making, fast and slow: toward an integrative model of intervention for sustainable career choice. *J Vocat Behav.* 2020;120:103448.
 54. Li M, Xu Y, Guo J, Li Y, Li W. Application of a GIS-based fuzzy multi-criteria evaluation approach for wind farm site selection in China. *Energies.* 2020;13(10):2426.
 55. Lindberg O, Arnqvist J, Munkhammar J, Lingfors D. Review on power-production modeling of hybrid wind and PV power parks. *J Renew Sustain Energy.* 2021;13(4):042702.
 56. Masoudi SM, Baneshi M. Layout optimization of a wind farm considering grids of various resolutions, wake effect, and realistic wind speed and wind direction data: a techno-economic assessment. *Energy.* 2022;244:123188.
 57. Mathern A, von der Haar C, Marx S. Concrete support structures for offshore wind turbines: current status, challenges, and future trends. *Energies.* 2021;14(7):1995.
 58. Menezes D, Mendes M, Almeida JA, Farinha T. Wind farm and resource datasets: a comprehensive survey and overview. *Energies.* 2020;13(18):4702.
 59. Metz IC, Ellerbroek J, Mühlhausen T, Kügler D, Hoekstra JM. Analysis of risk-based operational bird strike prevention. *Aerospace.* 2021;8(2):32.
 60. Mishra R, Naik BKR, Raut RD, Paul SK. Circular economy principles in community energy initiatives through stakeholder perspectives. *Sustain Prod Consum.* 2022;33:256-70.
 61. Moghadassian B, Sharma A. Designing wind turbine rotor blades to enhance energy capture in turbine arrays. *Renew Energy.* 2020;148:651-64.
 62. Moreira MW, Rodrigues JJ, Korotaev V, Al-Muhtadi J, Kumar N. A comprehensive review on smart decision support systems for health care. *IEEE Syst J.* 2019;13(3):3536-45.
 63. Morkūnė R, Marčiukaitis M, Jurkin V, Gecevičius G, Morkūnas J, Raudonikis L, *et al.* Wind energy

- development and wildlife conservation in Lithuania: a mapping tool for conflict assessment. *PLoS One*. 2020;15(1):e0227735.
64. Muneez M. Protection of submarine optical fibre cables in the Strait of Malacca. *J Mar Environ Eng*. 2021;10(4):257-73.
 65. Novaglio C, Bax N, Boschetti F, Emad GR, Frusher S, Fullbrook L, *et al*. Deep aspirations: towards a sustainable offshore blue economy. *Rev Fish Biol Fish*. 2022;32(1):209-30.
 66. Nzotcha U, Kenfack J, Manjia MB. Integrated multi-criteria decision making methodology for pumped hydro-energy storage plant site selection from a sustainable development perspective with an application. *Renew Sustain Energy Rev*. 2019;112:930-47.
 67. O'Hanlon Z, Cummins V. A comparative insight of Irish and Scottish regulatory frameworks for offshore wind energy—an expert perspective. *Mar Policy*. 2020;117:103934.
 68. Pérez-Castillo R, Ruiz F, Piattini M. A decision-making support system for Enterprise Architecture Modelling. *Decis Support Syst*. 2020;131:113249.
 69. Peri E, Tal A. A sustainable way forward for wind power: assessing turbines' environmental impacts using a holistic GIS analysis. *Appl Energy*. 2020;279:115829.
 70. Perry J, Thompson L. Empowering the next generation of watershed decision-makers: a pedagogical design. *Water*. 2019;11(4):662.
 71. Peters JL, Butschek F, O'Connell R, Cummins V, Murphy J, Wheeler AJ. Geological seabed stability model for informing Irish offshore renewable energy opportunities. *Adv Geosci*. 2020;54:55-65.
 72. Pınarbaşı K, Galparsoro I, Depellegrin D, Bald J, Pérez-Morán G, Borja Á. A modelling approach for offshore wind farm feasibility with respect to ecosystem-based marine spatial planning. *Sci Total Environ*. 2019;667:306-17.
 73. Pittman SJ, Stamoulis KA, Antonopoulou M, Das HS, Shahid M, Delevaux JM, *et al*. Rapid site selection to prioritize coastal seascapes for nature-based solutions with multiple benefits. *Front Mar Sci*. 2022;9:832480.
 74. Ramli MA, Boucekara HR. Wind farm layout optimization considering obstacles using a binary most valuable player algorithm. *IEEE Access*. 2020;8:131553-64.
 75. Rath P, Jindal M, Jindal T. A review on economically-feasible and environmental-friendly technologies promising a sustainable environment. *Clean Eng Technol*. 2021;5:100318.
 76. Rehman S, Baseer MA, Alhems LM. GIS-based multi-criteria wind farm site selection methodology. *FME Trans*. 2020;48(4):855-67.
 77. Sánchez S, López-Gutiérrez JS, Negro V, Esteban MD. Foundations in offshore wind farms: evolution, characteristics and range of use. Analysis of main dimensional parameters in monopile foundations. *J Mar Sci Eng*. 2019;7(12):441.
 78. Sarja M, Onkila T, Mäkelä M. A systematic literature review of the transition to the circular economy in business organizations: obstacles, catalysts and ambivalences. *J Clean Prod*. 2021;286:125492.
 79. Sarker S, Rahman MM, Yadav AK, Islam MM. Zoning of marine protected areas for biodiversity conservation in Bangladesh through socio-spatial data. *Ocean Coast Manag*. 2019;173:114-22.
 80. Sawant M, Thakare S, Rao AP, Feijóo-Lorenzo AE, Bokde ND. A review on state-of-the-art reviews in wind-turbine-and wind-farm-related topics. *Energies*. 2021;14(8):2041.
 81. Sharma PK, Warudkar V, Ahmed S. A comparative analysis of wind resource parameters using WASP and windPRO. *Int J Green Energy*. 2019;16(2):152-66.
 82. Sherman P, Chen X, McElroy M. Offshore wind: an opportunity for cost-competitive decarbonization of China's energy economy. *Sci Adv*. 2020;6(8):eaax9571.
 83. Spyridonidou S, Sismani G, Loukogeorgaki E, Vagiona DG, Ulanovsky H, Madar D. Sustainable spatial energy planning of large-scale wind and PV farms in Israel: a collaborative and participatory planning approach. *Energies*. 2021;14(3):551.
 84. Tamario C, Sunde J, Petersson E, Tibblin P, Forsman A. Ecological and evolutionary consequences of environmental change and management actions for migrating fish. *Front Ecol Evol*. 2019;7:271.
 85. Tékouabou SC, Chenal J, Azmi R, Toulmi H, Diop EB, Nikiiforova A. Identifying and classifying urban data sources for machine learning-based sustainable urban planning and decision support systems development. *Data*. 2022;7(12):170.
 86. Thomas R, Idol T, Open Geospatial Consortium. Development of spatial data infrastructures for marine data management; OGC-IHO Marine SDI Concept Development Study (CDS). [place unknown]: [publisher unknown]; 2019.
 87. Trifonova N, Scott B, Griffin R, Pennock S, Jeffrey H. An ecosystem-based natural capital evaluation framework that combines environmental and socio-economic implications of offshore renewable energy developments. *Prog Energy*. 2022;4(3):032005.
 88. Tsai CC, Lin CH. Review and future perspective of geophysical methods applied in nearshore site characterization. *J Mar Sci Eng*. 2022;10(3):344.
 89. Turnbull A, McKinnon C, Carrol J, McDonald A. On the development of offshore wind turbine technology: an assessment of reliability rates and fault detection methods in a changing market. *Energies*. 2022;15(9):3180.
 90. Velenturf APM, Emery AR, Hodgson DM, Barlow NLM, Mohtaj Khorasani AM, Van Alstine J, *et al*. Geoscience solutions for sustainable offshore wind development. *Earth Sci Syst Soc*. 2021;1(1):10042.
 91. Wajid A, Hussain K, Ilyas A, Habib-ur-Rahman M, Shakil Q, Hoogenboom G. Crop models: important tools in decision support system to manage wheat production under vulnerable environments. *Agriculture*. 2021;11(11):1166.
 92. Wang H, Liu Z, Liu Z, Wang X, Wang J. GIS-based analysis on the spatial patterns of global maritime accidents. *Ocean Eng*. 2022;245:110569.
 93. Watson L, Falconer L, Dale T, Telfer TC. 'Offshore' salmon aquaculture and identifying the needs for environmental regulation. *Aquaculture*. 2022;546:737342.
 94. Weiland S, Strong A, Miller B. Incorporating resilience into transportation planning and assessment. Santa Monica (CA): RAND; 2019. Report No.: RR-3038-TRB.

95. Welzel M, Schendel A, Hildebrandt A, Schlurmann T. Scour development around a jacket structure in combined waves and current conditions compared to monopile foundations. *Coast Eng.* 2019;152:103515.
96. Wendler-Bosco V, Nicholson C. Port disruption impact on the maritime supply chain: a literature review. *Sustain Resilient Infrastruct.* 2020;5(6):378-94.
97. Yang X, Bai Y, Che L, Qiao F, Xie L. Incorporating ecological constraints into urban growth boundaries: a case study of ecologically fragile areas in the Upper Yellow River. *Ecol Indic.* 2021;124:107436.
98. Zambrano-Asanza S, Quiros-Tortos J, Franco JF. Optimal site selection for photovoltaic power plants using a GIS-based multi-criteria decision making and spatial overlay with electric load. *Renew Sustain Energy Rev.* 2021;143:110853.
99. Zheng YY, Kong JL, Jin XB, Wang XY, Su TL, Zuo M. CropDeep: the crop vision dataset for deep-learning-based classification and detection in precision agriculture. *Sensors.* 2019;19(5):1058.
100. Zuccaro G, Leone MF, Martucci C. Future research and innovation priorities in the field of natural hazards, disaster risk reduction, disaster risk management and climate change adaptation: a shared vision from the ESPREsO project. *Int J Disaster Risk Reduct.* 2020;51:101783.