CHEMICAL ENGINEERING TRANSACTIONS
VOL. 103, 2023

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Panos Seferlis, Yee Van Fan, Athanasios Papadopoulos

ISBN 979-12-81206-02-1; **ISSN** 2283-9216

DOI: 10.3303/CET23103039

Suitability Investigation and Technical Assessment Using Multi-Criteria Decision Analysis for Offshore Wind Farms in the Philippines

Pope John T. Sotto[a], Binoe E. Abuan[b], Louis Angelo M. Danao[b,*]

[a]Energy Engineering Graduate Program, University of the Philippines, Diliman, Quezon City, 1101 Philippines
[b]Department of Mechanical Engineering, University of the Philippines, Diliman, Quezon City, 1101 Philippines
louisdanao@up.edu.ph

This study aims to identify the potential sites based on a set of decision criteria and employ a Multi-Criteria Decision Analysis (MCDA) using the Analytic Hierarchy Process (AHP) method. Geographical data were processed into standardized layers by utilizing the Geographic Information System (GIS) capability of ArcGIS Desktop. The final suitability maps were generated from the product of the weighted analysis for factors layers, Boolean Raster from the constraints model, and wind speed datasets. Eight scenarios were produced in which Scenario 3A and Scenario 4A were selected as the most preferred set-up for bottom-fixed set-up and floating-type platforms, respectively. These two scenarios adopted the averaged factors and 200 m altitude datasets as they provided the highest technical resource potential for wind energy extraction of 710.78 GW for shallow bathymetric maps and 4,054.44 GW for deep waters. Locations with a suitability score index of 0.6 – 1.0 were observed as having good quality wind resources ranging from 9.07 m/s to 11.67 m/s. They were in the north of Ilocos Norte, the southeast portion of Oriental Mindoro, the southern part of Iloilo province, and some sections in Guimaras Strait. Finally, Wind Turbine #1 (Enercon E-126 7.580) was favored as it showed the largest Annual Energy Production (AEP) of 30,336,475 MWh/y for Scenario 3A and 172,894,869 MWh/y for Scenario 4A.

1. Introduction

Almost half of the energy supply of the Philippines implies that it is incredibly reliant on net imports rather than focusing on developing its indigenous resources for local and future consumption. The 2021 Total Primary Energy Supply (TPES) conducted by the Philippine Department of Energy (2021) states that renewable energy sources only amount to a third (33.2 %) of the whole energy mix of the country, while wind energy alone constitutes a meager percentage of the nation's supply situation. In the wind energy statistics for the years 2010 to 2020, the growth rate of onshore wind had significantly decreased in terms of its dependable capacity for the last 5 y while no wind power plant was commissioned and operated in the same period as evident in its stagnation on installed capacity. In 2020, the installed capacity of wind alone implies that only 6.37 % (443 MW) is being utilized as compared to its overall measured potential. A - 4 % (16 MW) decrease in growth rate was observed in its total installed generating capacity a year after. Selection of suitable sites off the shore requires an enormous capital outlay, and careful analysis must be considered to maximize the nation's power generation potential while minimizing risks.

Relevant parameters and Geographic Information System (GIS) modeling have been evident in spatial planning, siting of wind turbines, and decision-making problems, often discussed in scientific publications. Argin et al. (2019) explored possible locations of offshore wind farm installation in Turkey using a multi-criteria site selection process coupled with the Wind Atlas Analysis and Application Program (WAsP) ver. 11.2, a module in the WindPRO modeling software capable of conducting statistical analysis for site suitability. Gaveriaux et al. (2019) considered the technical, environmental, and socio-economic factors in which criteria were selected through pairwise scaling of a comparison matrix. The Analytic Hierarchy Process (AHP) was applied to evaluate several conflicting information by ranking them according to their impact and input maps were superimposed into one map to generate a suitability map of Hong Kong with the aid of open-source software, Quantum Geographical

Paper Received: 29 June 2023; Revised: 13 July 2023; Accepted: 08 August 2023
Please cite this article as: Sotto P.J.T., Abuan B.E., Danao L.A.M., 2023, Suitability Investigation and Technical Assessment Using Multi-Criteria Decision Analysis for Offshore Wind Farms in the Philippines, Chemical Engineering Transactions, 103, 229-234 DOI:10.3303/CET23103039

Information System (QGIS). Mahdy and Bahaj (2017) employed the principle of AHP and pairwise comparison methods to weigh factors involved in the decision-making and reflect it in the spatial assessment of Egypt. The Weighted Linear Combination (WLC) aggregation method was used with a Boolean overlay to analyze spatial data and develop a suitability model using an ArcGIS software package. The novelty of this work is to account for the decision-making of the expert's perspectives from various disciplines and to utilize unconventional criteria such as the ocean's characteristics, natural events, heritage sites, and shipwreck datasets in spatial modeling. Combining multiple criteria as a strategy was not yet demonstrated as an effective tool in the AHP analysis. Also, technical performance was incorporated to measure and validate the attractiveness of candidate areas.

2. Theory

Douvere (2008) pointed out that the maritime domain has its challenges, and finding the best possible site for offshore wind farm installation depends on the importance of relevant parameters. Factors and constraints to constructing wind farms in offshore parcels must be rigorous. Some places that are often restricted to the public, weather permitting, or just plainly infeasible for a wind power plant to operate.

2.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was used to systematically generate weights of intangible elements and rank relevant items in order of priority during decision-making. It is based on a mathematical model of aggregated individual judgments and is considered neutral and objective. To reduce inconsistency of errors in judgment, Saaty and Ozdemir (2003) recommend that factors with similar characteristics should be grouped to reduce the choices in no more than seven items as the span of absolute judgment and immediate memory impose severe limitations on the amount of information that a human mind can receive and process. Saaty's Nine-point Scale of Relative Importance was used to characterize the significance level between pairwise elements. In the comparison matrix, the upper triangle represents the input rating of the respondents, while the lower portion of the triangle is the inverse value of the former. As part of the AHP operational process, the Consistency Ratio (CR) sorts out inconsistencies in judgment where a value of less than 0.1 suggests consistency and is acceptable. At the same time, a recalculation is needed for values greater than 0.1. This is represented by Eq.(2), while the Consistency Index (CI) and Random Consistency Index (RCI) can be determined using Eq.(1) and Table 1, as proposed by Saaty (1980).

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

$$CR = \frac{CI}{RCI} \tag{2}$$

Table 1: Random consistency index values

Number of criteria	1	2	3	4	5	6	7	8	9	10	11
RCI value	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

2.2 Geographic Information System (GIS)

The Suitability Index (SI) was computed by getting the product of the standardized score of each factor layer (X_i) and the weight that was assigned for that specific factor (w_i) as represented in Eq.(3). The variables n, m, and c_j correspond to the number of factors, constraints, and constraint j.

$$SI = \sum_{i=1}^{n} w_i X_i \times \prod_{j=1}^{m} c_j \tag{3}$$

2.3 Technical parameters

To achieve the maximum output possible per site, Sheridan et al. (2012) expressed that there is a need to calculate the optimum required spacing and layout orientation. The effective footprint of a turbine (array spacing) is calculated using Eq.(4), while the number of turbines that can be installed in a specific location is computed using Eq.(5). Inter-turbine wake losses may be reduced by positioning the wind turbines in rows using 10 and 5 for the downwind and crosswind spacing factors.

$$\text{Array spacing} = (\text{rotor diameter})^2 * \text{downwind spacing factor} * \text{crosswind spacing factor} \tag{4}$$

$$\text{Number of Turbines} = \frac{\text{Total Available Area}}{\text{Array Spacing}} \tag{5}$$

The Annual Energy Production (AEP) represents the minimum assured power generated from the wind turbine, as Mattar and Guzman-Ibarra (2017) noted. Eq.(6) represents *E* as the annual energy production, *T* as the time period or 8,760 h, $P(V_2)$ as the Weibull probability density, and *P* as the power output.

$$E = T\int_0^{\infty} P(V_2)PdV \tag{6}$$

3. Methodology

Decision criteria were pre-determined and extrapolated from previous research to arrive at candidate areas. They were trimmed down to limit those criteria with no readily available information. Responses from various experts in the field were gathered as necessary input in ranking the pairwise elements in order of importance. The aggregated scores provided by the participants were normalized by getting the sum of the scores of all columns and dividing each element, noting that the normalized figures per column should equal 1 to validate its unity. A decision loop acted as a filter to check the consistency of the responses and allowed the participants to adjust their judgment as needed. The final product of this analysis is the relative weight of each criterion which is vital in spatial modeling of the weighted model analysis (factor layers).

ArcGIS Desktop ver. 10.8.1 (2022) was employed for modeling and georeferencing activity to refine vector files, rasterized metadata, and spatial overlays to create an integrated layer of the locally available and globally sourced dataset. Each layer was categorized as factors and constraints as the treatment differs when processed as spatial layers and reclassified according to linearized scores and buffer zones. For factors with multiple criteria, averaging the factors and a conservative approach are combination strategies applied on a cell-by-cell basis before integrating these layers in the weighted overlay function. Eq.(3) was utilized to produce an initial suitability map of aggregated product layers, and constraints were applied to mask out all unsuitable areas. Final suitability maps were generated using the 150 m and 200 m standardized wind speed datasets. They were further optimized to limit contiguous areas > 10 km^2 and with a suitability score of 0.6 and above.

Finally, a technical assessment was accomplished to identify the performance of selected wind turbines per case scenario. Critical parameters such as the technical resource potential of the site, the number of turbines applicable, and AEP were essential in determining the best scenario per bathymetry type and optimum wind turbine specification. These steps were completed simultaneously to arrive at the desired output, reducing applicable areas of interest that were only of paramount importance to this research. The approach was limited to technical and environmental indicators as socio-economic criteria were excluded. The method used in the calculation of AEP only applies to wind turbines with small rotor sizes for comparison purposes only.

4. Results and discussion

The discussion focuses on three main sections – data gathering, pre-processing, and post-processing.

4.1 Data gathering

Four wind turbines were selected based on commercial information with the highest power rating. It was gathered from the manufacturer's datasheet with the aid of Bauer and Matysik (2022). Enercon E-126 7.580, Aerovide SCD 8.0 / 168, W2E-215 / 9.0, and Vestas V164 / 9500 were compared and matched their performance in different locations. The composition of respondents was mainly divided into four sectors of various disciplines to understand better the mechanisms in the various stages of construction for an offshore wind farm. Six individuals from research institutions, government agencies, private industries, and local government units represented the technical and administrative functions such as policymaking initiatives, project planning, permitting process, and operational works. Parameters were categorized into technical and environmental criteria. The socio-economic part was excluded as renewable energy extraction, and power sustainability has the most priority in the energy ecosystem of the country. Only eight factors (wind resource, bathymetry, physical oceanography, geological hazards, distance to shore, substations, logistical access point, and shipwreck) and five constraints (marine protected areas, marine habitat, biological behavior, submarine assets, and aviation) remained and were grouped according to their similarity in their characteristics such as perceived importance and influence on the main objective.

4.2 Pre-processing

This stage involves two vital processes, AHP analysis, and GIS modeling.

4.2.1 AHP analysis

Excluding wind in the initial analysis, respondents ranked their answers on seven factors based on Saaty's Nine-Point Scale of Relative Importance. Bathymetry garnered 26 % of the total weight, while geological hazards, physical oceanography, substation, distance to shore, logistical access point, and shipwreck got 16.78 %, 16.59 %, 14.05 %, 12.49 %, 10.02 %, and 4.41 %. The ranking was determined by the calculated priority vector of weights and was used in the weighted overlay analysis.

4.2.2 GIS modeling

Several geographic maps were produced in this study and were used as a reference point for site suitability processing. This information must be reclassified to standardize cell values before integrating all the layers. Factors with multiple criteria were combined using two combination strategies – averaging the factors and using a conservative approach. The first method is to get the average of all layers to produce one feature class. The conservative approach retains cells with the lowest suitability score by performing a specified conditional statement on top of a base map. With the restriction of AHP to reduce the factors into seven criteria for better consistency, the annual significant wave height raster and upwelling areas criteria were combined to produce the physical oceanography layer. At the same time, the geohazard maps of earthquakes, active fault lines and trenches, typhoons, and tsunamis coalesce to create the geological hazards factor.

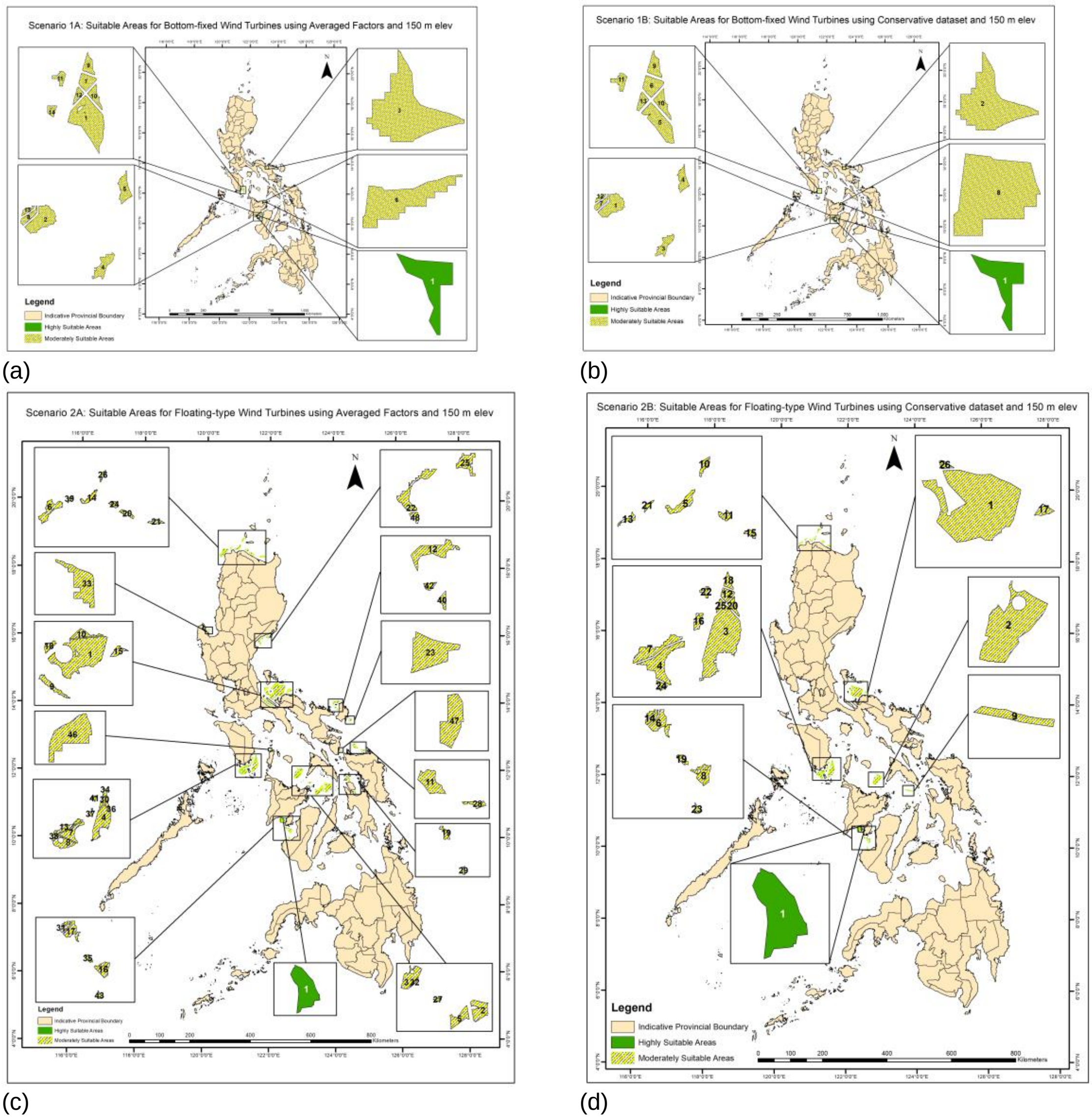

Figure 1: Eight scenario maps (a) scenario 1A; (b) scenario 1B; (c) scenario 2A; (d) scenario 2B;

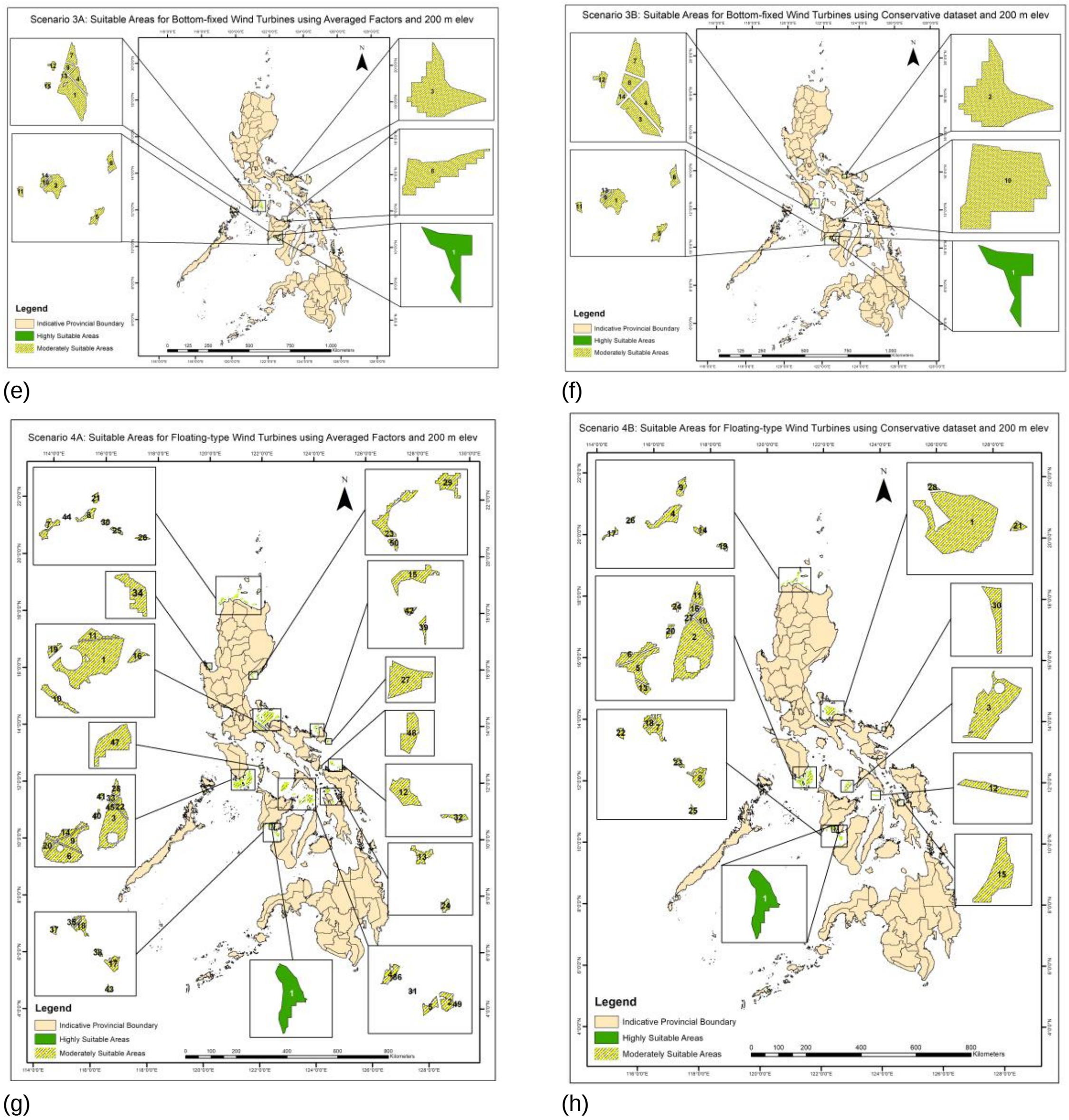

Figure 1: Eight scenario maps (continued) – (e) scenario 3A; (f) scenario 3B; (g) scenario 4A; (h) scenario 4B

Four initial suitability maps created by merging the Boolean raster with the weighted models were processed with the standardized wind speed datasets and further optimized into contiguous areas. Eight scenario maps were made due to incorporating three types of datasets – bathymetry (water depth), combination strategies for multiple criteria, and wind speed of different altitudes. For scenarios 1A, 1B, 3A, and 3B, areas had better wind profiles of 9.07 m/s ~ 10.76 m/s in the southeastern portion of Oriental Mindoro and south of Iloilo province. For scenarios 2A, 2B, 4A, and 4B, sites with good quality wind resources ranging from 9.07 m/s ~ 11.67 m/s were evident in the southeastern portion of Oriental Mindoro, south of Iloilo province, Guimaras Strait, and the northern sections of Ilocos Norte and Cagayan. Only one site rated with a suitability index of 0.8 – 1.0 (highly suitable) was situated south of Iloilo with a mean wind speed of 9.09 m/s ~ 9.18 m/s.

4.3 Post-processing

Total area, mean wind speed, and wind power density values were derived from Global Wind Atlas (GWA) wind resource simulations using zonal statistics in ArcMap. The theoretical power output of each turbine was computed, and the respective power curves were utilized to extract the actual power output per unit. The maximum number of turbines per site was determined using Eq.(4) and Eq.(5). AEP was identified by interpolating the values from the relationship curve of AEP and wind speed, which was derived using a wind energy calculator. Scenario 3A was the preferred choice for a bottom-fixed set-up, while Scenario 4A was the best option for a floating-type setting. These two scenarios utilized the averaged factors and 200 m altitude datasets to generate the maximum resource potential of 710.78 GW for shallow bathymetric maps and 4,054.44 GW for deep waters. While Scenario 3B and 4B can provide the same result in the highly suitable classification, applying these is not advisable as employing the conservative approach datasets is tedious and requires longer processing time. Enercon E-126 7.580 was preferred as it can provide the highest AEP. As a result, Scenario 3A had a combined output of 30,336,475 MWh/y, while the energy production in Scenario 4A was 172,894,869 MWh/y. However, it can be noted that the number of turbines needed to produce the amount for Scenarios 3A and 4A is 59.93 % higher than that of Vestas V164/9500.

5. Conclusion

This study utilized the MCDA-AHP technique to determine the ranking of factors considered in the investigation and a GIS component to model the potential sites. Only eight factors and five constraints remained for site suitability processing. Averaged factors and a conservative approach were used as combination strategies, generating eight scenarios, and each site's profile was presented individually. Sixty-eight maps were rendered using ArcGIS Desktop as a product of the GIS process. The technical assessment suggests using Wind Turbine #1 (Enercon E-126 7.580) to extract the most power output annually. However, careful consideration of the technical and economic implications on the number of turbines to be deployed when yielding to the chosen equipment must be implemented as the cost may outweigh the benefit and becomes an unattractive option. Lastly, the averaged factors method is a more practical approach than the conservative dataset as the latter is too restrictive and eliminates most of the areas. To maximize the generation potential of the country, Scenario 3A is recommended for areas in the 'shallow' category, while Scenario 4A is preferred for 'deep' waters. Sites with high-quality wind resources are situated near existing onshore facilities or where current offshore wind service contracts are, further validating the attractiveness of offshore wind in the country. Future research work may be extended to employ a more appropriate layer, such as a propagation dataset for tsunamis and a risk analysis map for typhoons. If information is readily available, include seabed geology, restricted military sites, and socio-economic criteria for a more reliable result. Rather than creating a triangulated irregular network (TIN) for bathymetric maps, apply other methods to represent surface morphology to prevent loss of data structure.

Acknowledgments

Special thanks to the Department of Science and Technology – Science Education Institute (DOST-SEI) thru the Engineering Research and Development for Technology (ERDT) program for the funding and support.

References

ArcGIS, 2022, Desktop ver. 10.8.1, <https://desktop.arcgis.com/en/arcmap/latest/get-started/setup/arcgis-desktop-system-requirements.htm>, accessed 30.09.2022.

Argin M., Yerci V., Erdogan N., Kucuksari S., Cali U., 2019, Exploring the offshore wind energy potential of Turkey based on multi-criteria site selection. Energy Strategy Reviews, 23, 33-46.

Bauer L., Matysik S., Windturbines database. <en.wind-turbine-models.com/turbines>, accessed 07.10.2022.

Douvere F., 2008, The importance of marine spatial planning in advancing ecosystem-based sea use management, Marine Policy, 32, 762-771.

Gaveriaux L., Laverriere G., Wang T., Maslov N., Claramunt C., 2019, GIS-based multi-criteria analysis for offshore wind turbine deployment in Hong Kong, Annals of GIS, 25:3, 207-218.

Mahdy M., Bahaj A., 2017, Multi criteria decision analysis for offshore wind energy potential in Egypt. Renewable Energy, 118, 278-289.

Mattar C., Guzman-Ibarra M. C., 2017, A techno-economic assessment of offshore wind energy in Chile. Energy, 133, 191-205.

PH Department of Energy, 2021, Key Energy Statistics. PH Department of Energy, <www.doe.gov.ph/sites/default/files/pdf/energy_statistics/doe-key-energy-statistics-2021-pocket-size.pdf>, accessed 15.09.2022.

Saaty T.L., 1980, The Analytic Hierarchy Process, McGraw-Hill, New York, USA.

Saaty T.L., Ozdemir M., 2003, Why the Magic Number Seven Plus or Minus Two. Mathematical and Computer Modelling, 38, 233-244.

Sheridan B., Baker S., Pearre N., Firestone J., Kempton W., 2012, Calculating the offshore wind power resource: Robust assessment methods applied to the U.S. Atlantic Coast. Renewable Energy, 43, 224-233.