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MCDM Approach to Offshore Wind Farm Site Selection in Indian EEZ Considering Climate Change

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***Abstract* - This paper focuses at the use of Multi-Criteria Decision Making (MCDM) methodologies for optimal wind farm site selection in India. The study examines possible sites using a systematic process that incorporates the Analytical Hierarchy Process (AHP) and comprises data from stakeholder interactions, Geographic Information Systems (GIS), and remote sensing. In this study, wind speeds from climate model's ensemble are used to assess the influence of climate change on the suitability of identified regions. A comparison of selected regions under historical, near future, and far future scenarios is performed. The application of these methodologies is analyzed within Indian EEZ. The results show that 19% of the total study area falls under class 4 and class 5 categories, which are suitable for wind farm installation. In the near future, there is a 2% and 4% improvement in the selected regions under RCP 4.5 and RCP 8.5 scenarios, respectively, compared to historical period.**

***Index Terms*-- Climate models; Exclusive Economic Zone (EEZ); Geographic Information Systems (GIS); Multi-Criteria Decision Making (MCDM); Offshore wind energy.**

I. Introduction

India, a developing country, is increasingly relying on renewable energy sources in place of non-renewable ones. Although non-renewable sources like fossil fuels may not deplete soon, they take a long time to regenerate and their use increases carbon footprints, contributing to global warming and releasing toxic elements harmful to human health. Renewable energy sources such as wind, solar, geothermal, hydro, and biomass are essential to meet energy demands globally, in which wind energy is the most reliable and fastest-growing technology.

Offshore wind energy offers advantages over onshore wind energy, including reduced land use and visual impact. India, with its 7,600 km coastline [1] and an EEZ area of approximately 1,640,000 square kilometers (excluding the Andaman and Nicobar Islands), has set a target to install 30 GW of offshore wind energy plants by 2030[2]. Gujarat and Tamil Nadu alone have the potential for 70 GW of offshore wind power.

Many locations offshore are characterized by consistently higher and more predictable wind speeds, which results in greater amounts of energy per unit installed. However, the installation of offshore wind farm has its costs and risks which are relatively high especially during the initial stages due to transport of installation materials to the site plus the fact that the water is usually deeper off-shore. Environmental issues such as wind strength, effect on the surrounding environment, and vicinity of protected areas must be considered when establishing wind farms.

The selection of the preferred areas for the development of offshore wind farms is a comprehensive process which usually involves very thorough procedures and satellite tools such as MCDM and GIS. Different research works have used these approaches for constructing the suitability maps, which describe problems and issues encountered in suitable areas of different parts of the world. In 2015, Fetanat and Khorasaninejad [3] have introduced Fuzzy ANP, fuzzy ELECTRE, and DEMATEL in Iran to find the exact location of offshore wind farm successfully. Such an approach emphasized the importance of the integration of various factors which would increase the decision-making effectiveness and the criteria chosen for site selection. Chaouachi et al. [4] opted for AHP-based multi-criteria selection technique in the case of the Baltic States. As for their key objectives, they underlined versatility of application and primarily focused on work strategy improvements which aimed at maximising the social welfare for producers and consumers. This flexibility of MCDM procedures was also observed in the paper of Dimitra G. Vagiona and Manos Kamilakis [5] where they used AHP, TOPSIS, and GIS for the identification of fifteen viable areas for offshore wind farms in Greece. However, due to assessment, it was found that only two places are feasible for the sites, and rest have to be eliminated.

To demonstrate the universality of applying these methodologies, Mahdy and Bahaj [6] used fuzzy AHP to evaluate Egypt's offshore wind, in which the suitability map incorporated economic, technical, and environmental aspects. Their work showed that the potential for yield of power is very high, with preferred locations that can produce nearly 33 GW. Similarly, regarding assessment criteria, Eray Caceoğlu et al. [7] followed this approach where, in Northwest Turkey, they conducted the assessment of offshore wind farm sites using GIS and AHP technique. They stated seventeen criteria that can be categorized into exclusion and decision criteria which include aspects such as the connection of the power grid, speed of wind, and the environmental impact.

Isabel C. Gil-García et al. [8] have used a framework that was applied in the Gulf of Maine to select offshore wind farm site using TOPSIS, AHP, and fuzzy GIS methods. Using their description, they approximated that up to 8671 km² could be suitable for offshore wind power plants, and therefore reveal the versatility and accuracy of these approaches. Similarly, E. A. Mayaki et al. [9] used comparable considerations when assessing the suitability of sites for OWCs in Nigeria, with key factors including average wind speed, distance from airports, proximity to points of demand for power, and disruption of shipping lanes. They then used AHP to assign weights to the criteria and employed fuzzy TOPSIS for the selection process to arrive at the conclusion that Victoria Island (Lagos) was most suitable out of the three potential sites.

Lastly, Pawel Ziemba [10] used the fuzzy TOPSIS technique to evaluate potential investments for Poland's Open Water Fund. His study considered thirteen factors from technical, social, economic, geographical, and environmental groups, demonstrating the comprehensive nature of MCDM techniques in ranking preferred investments.

In this study, we focused on selecting suitable locations for offshore wind farms along the Indian EEZ. Further, the past research works considered average wind speed as a key technical criterion but neglected the influence of climate change on it, as climate change impact is a major limitation that needs attention as the wind speeds are susceptible to climate changes. Even a minute difference in predicted wind speed to the actual wind speed leads to high variations in future wind power calculations. To overcome these instabilities, the current research proposes the usage of wind speeds (historical, future projections) from a multi-model ensemble of six climate models as one of the evaluation criteria. A total of six evaluation parameters i.e. wind speed, water depth, distance to grid, distance to port, distance to shore, sediment thickness are considered for the identification of suitable OWF locations in the Indian EEZ. AHP MCDM and ArcGIS are used in the study.

These studies collectively underscore the importance of integrating multiple criteria and using sophisticated decision-making techniques for the identification of suitable offshore wind farm locations. By addressing economic, technical, environmental, and social factors, researchers have developed robust frameworks that can adapt to specific regional requirements and optimize site selection processes.

II. Methodology

A. Methodology

The methodology commences with literature review to select the criteria for identifications of suitable sites. An Analytic Hierarchy Process (AHP) matrix is then constructed to ascertain the relative importance of every criteria. Subsequently, Geographic Information System (GIS) data pertinent to the selected criteria are collected and reanalyzed to ensure precision and relevance. Climate model data for wind speeds under RCP 4.5 and RCP 8.5 scenarios are incorporated for analysis. The weights derived from the AHP process are assigned to each GIS layer, facilitating the identification of suitable regions based on these weighted criteria. The methodology concludes with a comparative analysis of the suitable regions identified for the future against historical periods, thereby providing insights into temporal changes and the potential impacts of different climate scenarios. The detailed steps are shown in Fig.1.

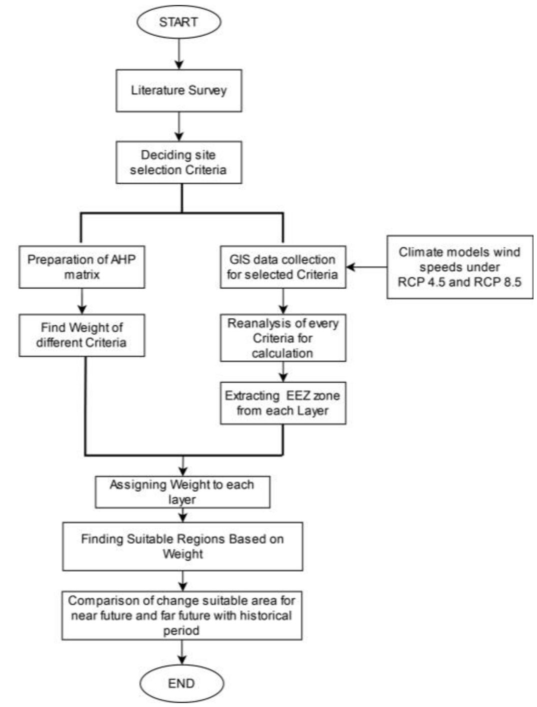

Figure 1. Schematic of flow chart of the study

B. Study Area

The present study was conducted in the Mainland India and Lakshadweep from Indian Exclusive economic zone (EEZ). It covers the area of 1,641,514 Km^2 (excluding Andaman and Nicobar Island) and located near equator within the boundary of 65°–90° East longitude and 4°–24° North latitude. Three seas namely Arabian Sea, Indian Ocean and Bay of Bengal were included the present study.

C. Wind Speed:

The most crucial parameter for wind farm site selection is the wind speed, as the energy produced is proportional to the third power of wind speed. The distribution of average annual wind speed in the Indian EEZ shows that India is a wind-speed-rich country, with several major regions experiencing average wind speeds of 6 m/s, which indicates the suitability for optimal wind farm operation. The wind speeds from Climate model's ensemble are considered for this study which were mentioned as suitable for Indian offshore region by Bhasuru et. al. [11]. The wind speeds for historical period (1979-2005) and near future (2020-2046) and far future period (2073-2099) under RCP4.5 and RCP 8.5 emission scenarios. The wind speed classifications along with other criteria are shown in Table 1.

structures, and maintenance is critical. Hence, it is necessary to strike a balance to minimize conflict with other coastal uses as well as enhance the wind characteristic; however, it is challenging due to other difficulties such as logistical constraints associated with a farther offshore site.

F. Sediment Thickness:

The nature of the seabed and the thickness of the sediment layer further determines foundation design and hence the type of installation technique to be used. Depending on the characteristics of the seabed there are different types of foundations – for example, monopiles can be used where the bottom is sandy, while rock bottom might require a different solution. Sediments thickness can also influence pile driving and whether other expensive methods of coming out with piles are required. Information regarding characteristics of the sediment also plays an important role in defining scour protection measures which should be implemented and analyzing geotechnical hazards as for example liquefaction or lateral spreading.

TABLE I. RECLASSIFICATION CRITERIA

Criteria\Score	0	1	2	3	4	5	Remarks
Wind speed (m/s)	<4	4–5	5–6	6–7	7–8	>8	
Water depth (m)	>150	100-150	75-100	50-75	25-50	<25	For historical, and near future
	>1000	500-1000	200-500	100-200	50-100	<50	For far future
Distance from ports (km)	<2, >150	2 – 5, 120–150	5 – 10, 100–120	10 – 15, 80–100	15 – 20, 50–80	20–50	
Distance from shore (km)	<1	1–5	5–10	10–15	15–20	>20	
Sediment thickness (km)	>12	10–12	8–10	5–8	2–5	0–2	

D. Water Depth:

Water depth, or bathymetry, is also a major parameter in determining the technical feasibility and cost of offshore wind farm construction. As water depth increases, more complex and costly foundation structures become necessary. Offshore wind farms are generally categorized into three types based on water depth: that is, shallow, transitional and deep water. They all demand different kinds of foundation such as monopiles /gravity base structures for the shallow water depth and floating structure for the deep-water depth. The shallow waters may be preferred by utilizing lower costs of construction but they are few, restricted, or associated with many environmental and social issues. As the water depth increases, there are increased number of potential locations to tap, though at higher risk and higher costs. For historical and near future the water depth level classification is considered lower according to the technology, however for far future higher water depths are considered [12], [13]

E. Distance to Shore and Ports:

The distance to shore and ports is another major parameter influencing various aspect from the establishment of wind farms and its functioning. This factor affects the costs of transmitting signals; where the distances under the sea are large, transmission medium mentioned as submarine cables is costlier and there can be larger power loss. It also affects facility installation and maintenance transportation since longer distances increase transportation time for vessels, and personnel, hence, may lead to higher costs and, therefore, time on non-operation. The next area which can be highly dependent is grid connection since the availability and location of the existing grid connection play an important role in the overall project viability. There is also the issue of visual presence; some farms may be sited further from shore and therefore unlikely to be the source of as much community dismay. Also, access to proper ports for construction materials import, assembly of the

G. Reclassification

Reclassification criteria for these factors are detailed, with specific score ranges for all six criteria. From the AHP technique, weights to these criteria are derived. The weights are emphasizing the importance of wind speed (52.35%), followed by water depth (27.23%), distance to shore (9.11%), distance to ports (7.37%), and sediment thickness (3.94%).

III. RESULTS

The AHP MCDM method of analysis has helped in the generation of knowledge pertaining to the future of wind energy possible under different climate change conditions. This comprehensive study categorizes areas into five classes based on their suitability for wind energy generation, with class 0 represents the lease suitable to class 5 represent the most. By comparing historical data with future projections under both RCP 4.5 and RCP 8.5 emission scenarios for near future (NF) and far future (FF) periods, the research provides a nuanced understanding of impact of climate change on wind energy potential in the region.

The results reveal a consistent trend of decreasing highly suitable areas (class 5) as we move from historical data into future projections. The spatial maps were shown in Fig.2. Historically, class 5 areas comprised 2.72% of the region, but this percentage decreases in both near and far future scenarios under both RCP 4.5 and RCP 8.5. Specifically, in the near future, these optimal areas reduce to 2.20% under RCP 4.5 and 1.72% under RCP 8.5. The far future projections show a further decline to 1.43% under RCP 4.5 and 1.35% under RCP 8.5. This trend suggests that climate change is likely to reduce the availability of the most optimal sites for wind energy generation over time.

Interestingly, while the most suitable areas are decreasing, there is a significant increase in moderately suitable areas (class 4). From a historical figure of 17.36%, class 4 areas increase to 17.81% (NF45) and 18.09% (NF85) in the near future, and further to 21.96% (FF45) and 20.73% (FF85) in the far future. This increase indicates a redistribution of suitability, suggesting that changing wind patterns and environmental conditions may create more areas of moderate suitability for wind energy generation.

The same output also reveals that class 3 areas, which include the biggest proportion of the region, fluctuate slightly and are relatively stable under all conditions. Hence the stability is an indication that a good percentage of the region will remain fairly suitable for wind energy generation even under the climate change effects. On the contrary, less suitable lands (class 2) slightly decline from the historical distribution at 8.36% and further to the near future (NF45 - 8.59%, NF85 - 7.64%) then to the far future (FF45 - 7.06% and FF85 - 3.12%). This coinage indicates that they are gradually moving into higher suitability classes over the years.

The percentage of area classification for historical and future periods is shown in Fig. 3. Overall, the analysis paints a picture of a changing landscape for wind energy generation potential due to climate change. While there is a reduction in the most suitable areas, there is a concurrent increase in moderately suitable areas, indicating a redistribution of suitability across the region. This shift highlights the need for adaptive strategies in planning and optimizing wind energy projects. As the impacts of climate change continue to unfold, it will be crucial for stakeholders in the wind energy sector to consider these projections in their long-term planning. By doing so, they can ensure sustainable and efficient energy generation in the face of changing environmental conditions, potentially identifying new opportunities in areas that may become more suitable for wind energy generation in the future.

IV. CONCLUSION

As India aims at various alternatives to fulfill the escalating energy requirements in future, wind energy enjoys a respectable space in the country's renewable energy consciousness. The offshore wind energy market in the country has huge prospects given its expanse of territorial waters and exclusive economic Zone, which has set an installation targets of 30 GW of offshore wind power by 2030.

The implication of climate change is showing an unstraightforward effect on the suitability of wind farms sites. There is a forecasted decrease of the best suitable areas (class 5) and at the same time, an expansion of the moderately suitable areas (class 4). This change of suitability distribution is due to changes of wind patterns and other environmental factors.

Altogether, the outcomes indicative of wind energy optimization stresses the importance of flexibility in the decision-making process in relation to wind project management. Due to the involvement of equally complex economic, technical, environmental, and social issue in site selection and project development, the application of complex decision-making methods like AHP MCDM alongside with GIS forms a strong framework for selecting sites.

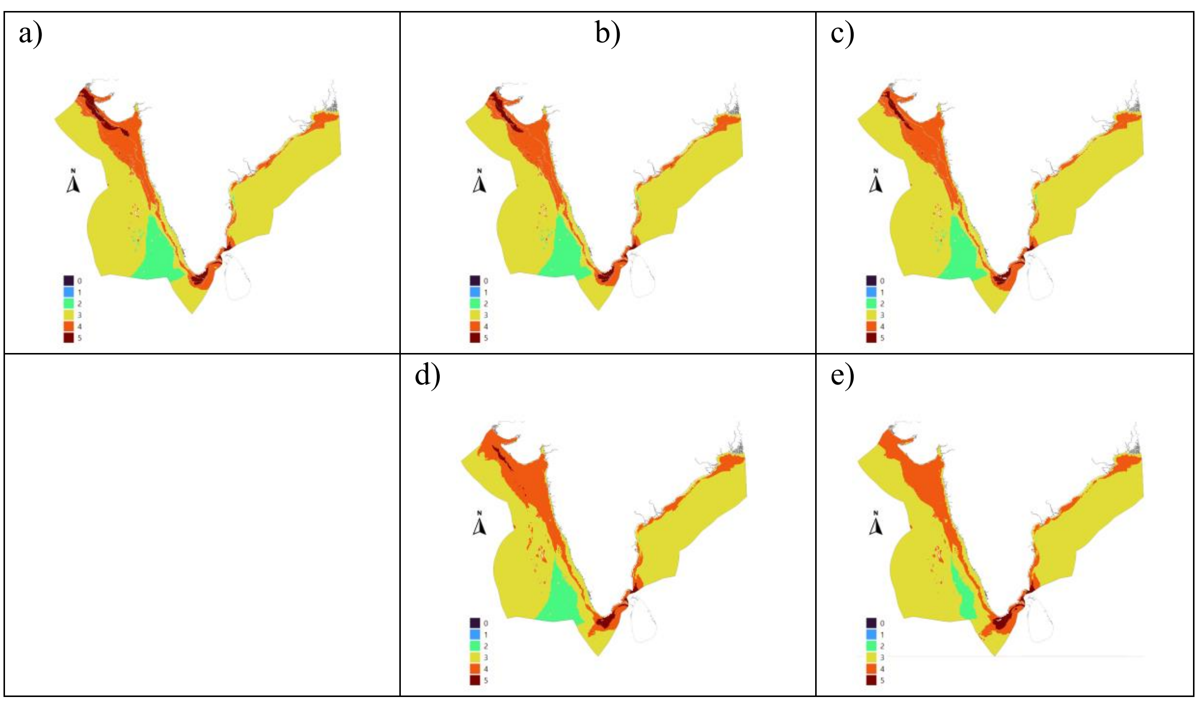

Figure 2. : The classifications of the area according to suitability level from 0 (less suitable) to 5 (highly suitable) for a) historical b) Near future under RCP 4.5 c) Near future under RCP 8.5 d) far future under RCP 4.5 and e) far future under RCP 8.5.

Moreover, this research underlines the need for utilizing the detailed long-term climate information in wind energy structures development. A major advantage of adopting this approach would be the fact that by taking the future into consideration while making business decisions, stakeholders are able to ensure a more efficient generation of energy and possibly discovery new opportunities in areas that may be more suitable for wind energy generation in future.

Therefore, while India actively explores the offshore wind energy, the approach suggested in this study can pose effective procedure for researchers, policy makers and industrial participants. By adapting planning and applying sophisticated analytical methods, India can achieve the greatest efficiency of its offshore wind energy, thus contributing effectively to the country's renewable energy plans and becoming a reference to other states around the world within the framework of the creation of a sustainable energy infrastructure.

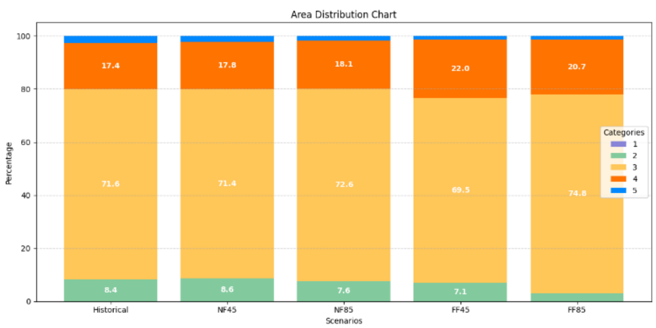

Figure 3. : The percentage of area classification for historical and future periods

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