Framework of Initial Selection of Offshore Energy Island Location for Sustainable Water Desalination

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Abstract. In this paper, a framework for the selection of an energy island location to supply power for water desalination plants with cleaner and more sustainable energy has been developed. The developed framework aims to evaluate the feasibility of creating offshore energy islands and select its location by considering factors such as renewable energy potential, site suitability, marine traffic, future developments, and proximity to desalination facilities. The energy and water data have been collected from available published data on marine traffic, water desalination production and government reports. Solar power data were obtained from the Ministry of Natural Resources via RETScreen, wave data were sourced from Windguru, and wind power data were obtained from both sources. The data were used for the Inverse Distance Weighting (IDW) interpolation and Multi-Criteria Decision Analysis (MCDA) to develop the framework. The developed framework has been utilized to develop an energy Island in the Red Sea to power the water desalination plants along the KSA west shore. The findings demonstrate the significant potential of energy islands to partly mitigate Carbon Dioxide (CO_2) emissions from desalination plants, advancing global efforts toward water sustainability and supporting long-term goals for achieving net-zero emissions. The study also emphasizes the importance of further research into wave energy in the Red Sea, as the lack of real-time data and comprehensive resources limits accurate assessments.

1. Introduction

Renewable technologies such as solar photovoltaic (PV), onshore wind, and wave energy have gained traction as viable alternatives. The concept of "Energy Islands" refers to offshore hubs combining wind, wave, and solar energy to transmit electricity to coastal desalination plants. This innovative approach is explored as a strategic solution where renewable energy sources converge to enhance energy security and sustainability [1]. The feasibility of developing the Energy Island has been demonstrated though the offshore setups like Poseidon80 and W2Power, showing significant improvements in power production and operational cost efficiencies [2].

Transitioning to offshore renewable energy platforms involves higher initial costs and complex logistics compared to onshore alternatives [3]. These figures highlight the economic considerations that must be factored into the planning and implementation of offshore renewable energy projects. Despite these challenges, the strategic benefits of offshore energy islands, such as more consistent wind speeds, the potential for larger installations, and reduced local opposition, make them a vital component in the shift towards sustainable energy solutions for the region. Although a promising technology, there are number of challenges that need to be considered in the initial design of Energy Islands. These include structural health monitoring, life cycle analysis (LCA), the best location of the Island, and many others. For structural health monitoring, offshore sensors were introduced as integral parts of the Energy Island design as explained by [4]. LCA of offshore wind energy structures was introduced by [5] to enhance the sustainability of this technology. The study proposed the use of land-based solar panels as a complementary solution to facilitate maintenance, reduce overall costs, and minimize the risk of wave-related damage.

Despite ongoing efforts to develop renewable energy solutions that meet future energy demands and reduce Carbon Dioxide (CO_2) emissions, including the introduction of the Energy Island concept, there is currently no established framework to guide the initial siting of such islands. This paper presents a novel framework for identifying optimal locations for offshore Energy Islands during the early design phase. The framework incorporates key factors such as renewable energy availability, initial investment costs, and risk management. To demonstrate its application, the framework is employed in a case study to determine a suitable location for an Energy Island in the Red Sea, aimed at supplying power for water desalination along the western coast of Saudi Arabia.

In addition to the global renewable energy agenda, water scarcity is also growing global issue caused by population growth, climate change, and overuse of freshwater resources. Many regions, especially arid and semi-arid areas, struggle to meet the water needs of their populations. Desalination is a technology that removes salt and other impurities from seawater, making it suitable for human use and agriculture [6]. Although effective, desalination can also be expensive and energy-intensive, raising concerns about environmental and economic sustainability. Despite these challenges, it remains a crucial solution in water-scarce areas where alternative freshwater sources are limited.

The Middle East and North Africa (MENA) region, heavily reliant on fossil fuels, faces significant environmental and economic challenges, particularly due to its energy-intensive desalination processes. Desalination, a key method for addressing water scarcity in this water-scarce region, requires substantial energy, which in turn contributes to the region's high CO_2 emissions. Transitioning to desalination systems powered by renewable energy is seen as crucial for mitigating the environmental impacts of fossil fuel consumption and for providing sustainable solutions to both climate change and water scarcity [7], [8]. With a high electrification rate, shifting to renewable energy sources for desalination is vital to reduce the region's carbon footprint and ensure long-term sustainability in meeting growing water demands. Saudi Arabia, with its significant renewable resources in the Red Sea region, is well-positioned to integrate offshore wind and wave energy into its desalination plants, thereby reducing operational costs and mitigating environmental impacts [9], [10].

The paper highlights the necessity of developing this comprehensive framework that integrates decision-analysis methods and spatial interpolation techniques to advance renewable energy solutions to select the site of energy island. Methods such as Inverse Distance Weighting (IDW) interpolation and Multi-Criteria Decision Analysis (MCDA) play a critical role in addressing spatial data gaps and supporting informed site selection. Specifically, the strategic integration of wind, solar, and wave energy resources to power desalination plants along Saudi Arabia's west coast offers a cost-effective and sustainable solution to mitigate water scarcity, reduce reliance on fossil fuels, and support the nation's decarbonization goals. Such an approach not only ensures environmental sustainability but also lays the groundwork for scalable renewable energy development across the region.

2. Methodology

2.1 Method used for developing the framework.

The framework outlines the process for selecting the site of the energy island that will power the desalination plants. Developing the framework for the initial design involves a structured, rigorous, and evidence-based approach. The goal is to ensure the process is not only creative but also methodical, reproducible, and aligned with scientific principles. Thus, in developing the framework, many factors had to be considered, including clearly defining the problem, conducting a literature review, defining system requirements and performance criteria, developing conceptual design options, using analytical and simulation tools, and iterating and refining the approach.

The developed framework requires interpolation technique for the micro location of the Energy Island. Two significant methods have been used to facilitate the identification of a favourable location for the energy island. Firstly, the IDW interpolation method [11], and then the MCDA [12] is applied to assist in deciding the best option among several alternatives. The focus of this framework is primarily on power; aspects of cost and risk management will be mentioned only briefly and without detailed exploration.

IDW is a spatial interpolation technique used to estimate values at unsampled locations based on the values of surrounding sampled points. The underlying assumption of IDW is that points closer to the location of interest have more influence on the estimated value than those that are farther away. This method is widely used in fields such as geography, environmental science, and geostatistics due to its simplicity and intuitive approach.

2.2 Data accuracy

Wave, solar, and wind data were obtained from real-time observations provided by various monitoring stations, with primary sources including Windguru [13] and RETScreen [14]. Wave data, sourced from Windguru, include wave height (in meters, m) and wave period (in seconds, s), measured above sea level (asl). Wind data contains wind speed that initially reported in knots. These values were converted from knots to meter per second (m/s) by multiplying the wind speed by 0.514 [15], [16]. The wind speed at 10 m asl has been calculated using the power law wind profile equation with a power coefficient of 0.11 [17]. These data are based on the Global Forecast System (GFS), which operates at a spatial resolution of 13 kilometres (km). To maintain consistency with RETScreen datasets, the wind speed data were standardized to 10 m asl. The GFS is a global weather prediction model developed by the National Centres for Environmental Prediction (NCEP) [18], a division of the National Oceanic and Atmospheric Administration (NOAA) [19] and the National Weather Service (NWS) of the United States [20]. The model is updated four times daily (at 0:00, 6:00, 12:00, and 18:00 UTC), providing weather forecasts up to 384 hours in advance. Since January 2015, GFS forecasts have been available at a 27 km resolution for prediction periods up to 240 hours.

Additional wind speed data were obtained from RETScreen to increase the density of data points and improve the accuracy of IDW interpolation, especially in areas with limited station coverage. RETScreen provides wind speed data in m/s at 10.0 m asl.

Solar data were also retrieved from RETScreen as Global Horizontal Irradiation (GHI) in kWh/m^2/day, then converted to W/m^2 by multiplying it in (1000/24), a software platform developed by Natural Resources Canada under the Ministry of Natural Resources since 1997. RETScreen integrates real-time data from ground-based weather stations and satellite data from NASA. NASA's satellite systems contribute global meteorological and GHI solar data, with a latency of 3–6 days, ensuring reliable and timely climate inputs for renewable energy assessment.

3.Results

3.1 Developing initial design framework

The methodology described in Section 2.1 has been used in developing the framework for choosing the best location of an Energy Island. This framework can be found in Figure 1. The IDW used in this framework is detailed in Figure 2. The framework provides a structured approach to evaluating the feasibility of using renewable energy to power desalination plants, particularly in remote or island environments. Its main goal is to identify solutions that offer maximum power generation, minimal cost, and low risk. The framework process consists of the below steps.

1- Identifying high-potential sites using global atlases that map solar, wind, and wave energy resources.
2- Once potential sites are identified, the framework screens for any critical interruptions, such as marine traffic, infrastructure conflicts, political constraints, or environmental regulations. Only sites free from major barriers proceed to the next phase.
3- Detailed environmental data is then collected using tools like Windguru and RETScreen, including solar irradiance, wind speed, wave height, and wave period. These inputs are used to calculate energy output using standard engineering equations for wind and wave power as in [21], [22].
4- The data is then analysed in QGIS using the IDW method to visualize spatial variations in energy potential. This allows for the mapping of energy-rich zones and supports site selection that favours maximum renewable energy yield.
5- The framework performs a comprehensive cost analysis, covering capital expenditures (equipment, installation, permitting), operational and maintenance costs (labour, fuel, waste management), and energy-related financial considerations, such as projected savings and demand profiles. This ensures the project remains economically viable.
6- A risk assessment follows, evaluating potential environmental impacts, exposure to natural disasters, social implications, and infrastructure resilience. By addressing these concerns early, the framework minimizes the chance of long-term disruptions, helping ensure project stability and sustainability.
7- With power potential, cost, and risk data in place, the framework utilizes RETScreen software to model technical performance and financial feasibility. RETScreen validates earlier assessments and confirms whether a site is realistically capable of supporting a renewable-powered desalination system.
8- In order to achieve an optimal site selection, the framework accounts for the fact that increased distance from the desalination plant tends to enhance power potential, while simultaneously elevating both cost and risk. Therefore, the objective is to identify a location that offers the best trade-off among maximum power generation, minimal cost,

and reduced risk. To facilitate this, a predefined number of candidate sites are selected at varying distances from the shore. These sites are then evaluated using MCDA, which systematically integrates the key factors to support an evidence-based and balanced site selection process.

9- The decision-making process is guided by MCDA. MCDA is employed to evaluate and prioritize potential locations by integrating key factors such as power output, cost efficiency, and risk into a structured and transparent scoring system. This step ensures that the selected site is not just technically feasible, but also the most balanced and optimal choice across all dimensions.

10- The process concludes with the selection of an "Energy Island" a site capable of reliably generating renewable energy to power desalination plants. By following this structured path, the framework ensures the chosen solution delivers highest power, lowest cost, and minimal risk, supporting long-term, sustainable freshwater production. Importantly, this framework is globally applicable and can be adapted to various geographic and environmental contexts, making it a versatile tool for sustainable water and energy planning worldwide.

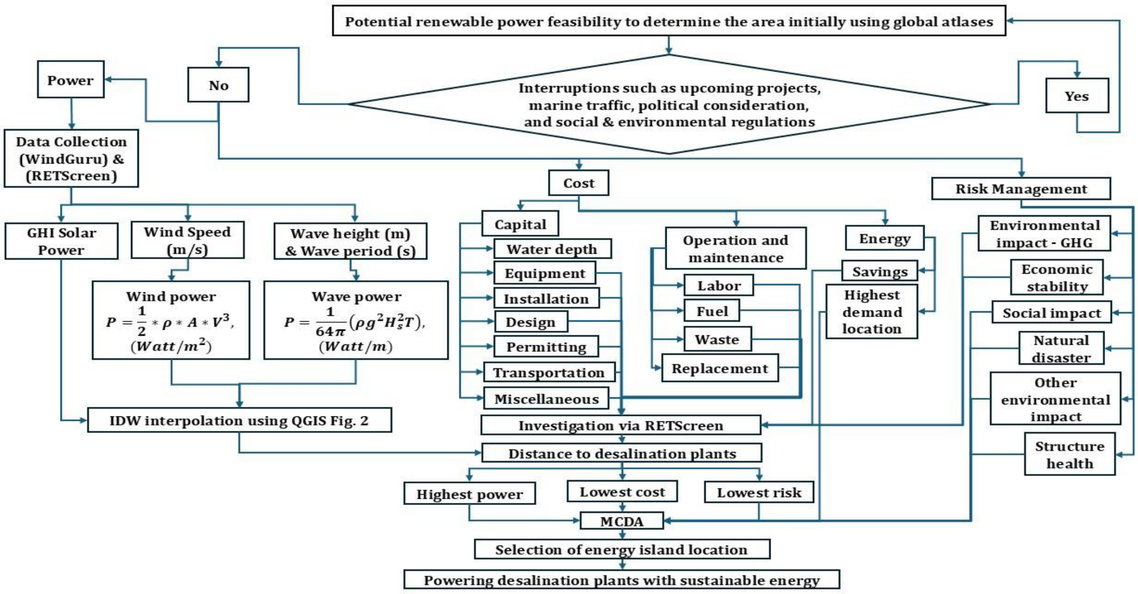


Figure 1. Flowchart explaining the developed framework.

3.2 IDW interpolation

The developed framework has been utilized to develop an energy Island in the Red Sea to power the water desalination plants along the KSA west shore. Figure 3 (a) shows the interpolated wave power while Figure 3 (b) and Figure 3 (c) show the offshore wind and GHI solar power. It can be seen from the figures that wave power is highest in the centre and the north, while the peak of wind power is concentrated in the northern region, and the highest GHI solar power distribution is found in both the northern and southern regions.

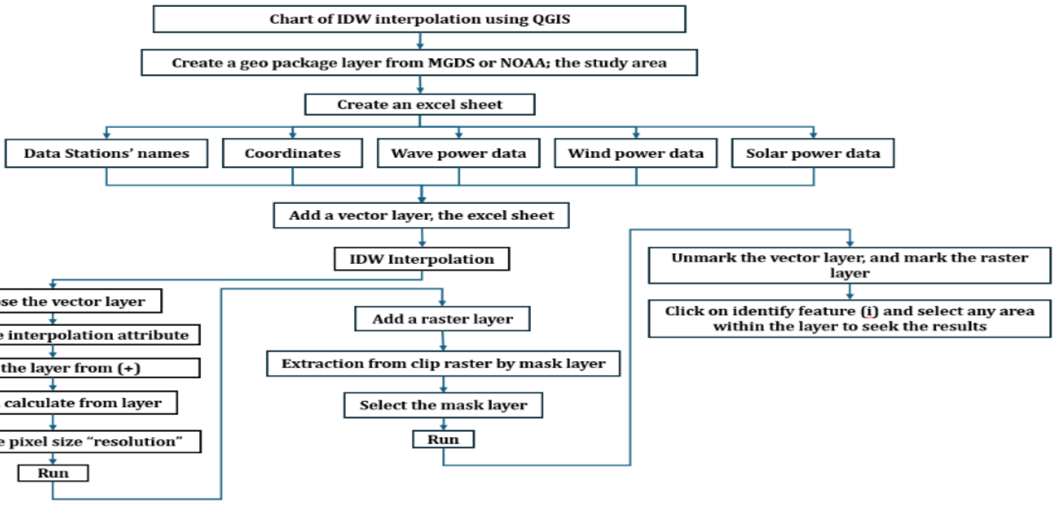
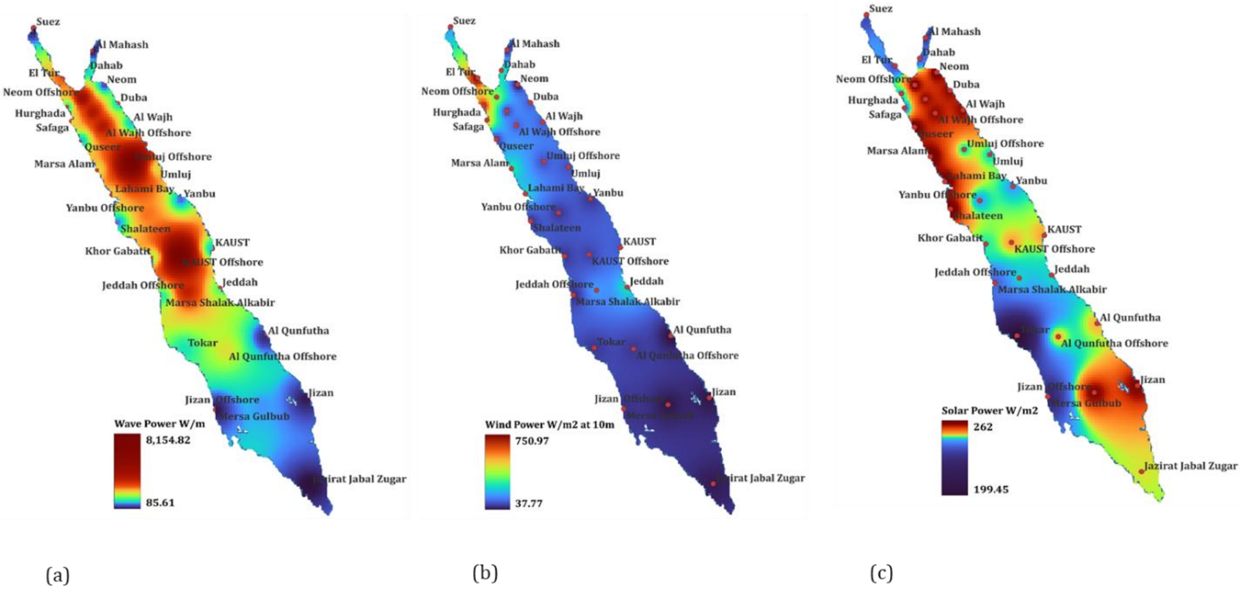


Figure 2. Flowchart explaining the IDW interpolation method.



(a) (b) (c)

Figure 3. IDW interpolation applied for the Red Sea (a) Wave power (b) Wind power at 10m height (c) Solar power (GHI).

3.3 MCDA

Since the study area "the Red Sea" is quite big, MCDA is divided into two parts, one for the region selection (North, Middle, South) and one for the site location. The scoring criteria applied to power, cost, and risk management are unitless values on a scale from 0.0 to 1.0, where 0.0 represents the least favourable option and 1.0 represents the most favourable. These scores are influenced by the distance of each site from the shore. In the MCDA framework, the criteria weights are allocated as follows: 50% for power potential, 25% for economic cost, and 25% for risk mitigation. These weights were determined based on the strategic importance of each factor and are consistent with established practices in the literature. Power potential was given the highest weight due to its critical role in the operation of energy islands, which must reliably generate and supply energy. This emphasis aligns with studies such as [23], which prioritized energy output in PV site selection, and [24], which underscored the importance of affordable and reliable clean energy in sustainability assessments. Economic cost was assigned a weight of 25%, slightly below the 30–35% range reported in comparable studies [25], reflecting its importance for project feasibility without outweighing energy availability. Risk mitigation also received a weight of 25% to account for environmental exposure, structural vulnerability, and regulatory uncertainty, consistent with [26], who highlighted the necessity of resilience in sustainable energy systems. Once the individual criteria scores are established for each site, they are multiplied by their respective weights to generate weighted scores. These weighted scores are then summed to produce an overall score for each site, allowing the site with the highest total score to be identified as the most suitable option. This weighting approach ensures that the evaluation framework balances performance, cost, and reliability, with a clear emphasis on securing a stable renewable energy supply.

3.3.1 Selecting the region

Three geographic areas north, middle, and south are evaluated in the MCDA process using a structured methodology that prioritizes criteria such as power, cost, and risk management, while interruptions serve as a disqualifying factor. The criteria and weights used here are 50% power, 25% cost, 25% risk management, and interruptions (disqualifying if present). The scores are normalized and weighted accordingly and presented in Table 1. MCDA evaluation and results for regions (dimensionless values).. The data can be summarized as:

- Middle region, with a total score of 0.9375, is determined to be the best location for developing offshore renewable energy islands due to favourable ratings in all criteria and the absence of interruptions.
- South region, scores lower at 0.7825 but is still a viable option, ranks second due to less optimal but acceptable scores in all evaluated areas.
- North region disqualified due to the presence of interruptions. This makes it unsuitable for development.

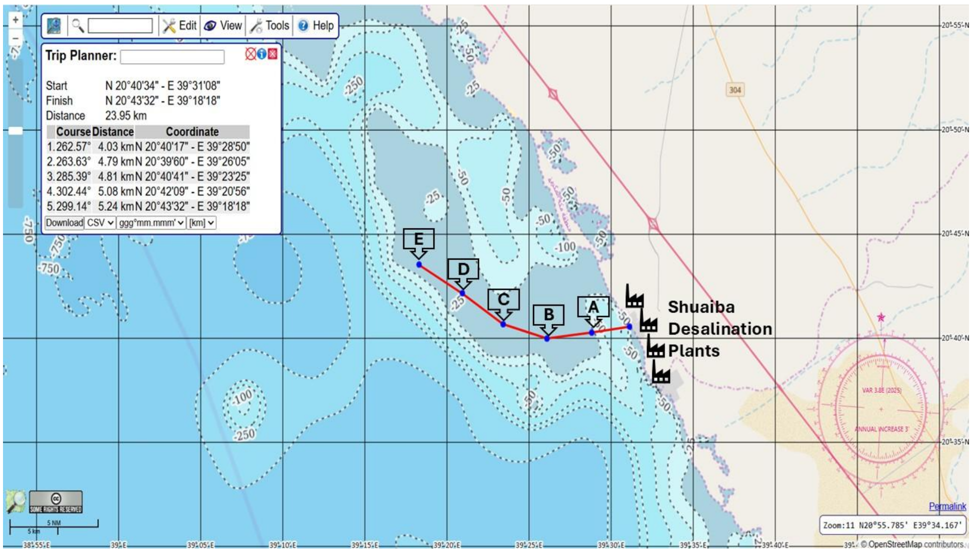
Table 1. MCDA evaluation and results for regions (dimensionless values).

Region	Power	Cost	Risk management	Interruptions	Weighted power	Weighted cost	Weighted risk	Total score
North	1.00	0.95	1.00	Present	Invalid	Invalid	Invalid	Invalid
Middle	0.91	1.00	0.93	None	0.455	0.25	0.2325	0.9375
South	0.74	0.82	0.83	None	0.37	0.205	0.2075	0.7825

Based on these results, the middle region is selected for the development of offshore renewable energy islands as it presents the most balanced approach, offering the highest scores in power, cost efficiency, and risk management, crucial for the sustainable success of the project.

3.3.2 Selecting the site

Five potential sites (A through E) based on power output, cost, and risk management criteria have been evaluated. These factors vary with distance from the shore, influencing the selection of the optimal site for renewable energy production. Site A is located less than 5 km from the coastline, making it the closest and most logistically accessible option. Site B lies between 5 and 10 km offshore, followed by Site C at 10 to 15 km, Site D at 15 to 20 km, and Site E, the farthest, between 20 and 25 km from the shore. This gradation in distance is a critical determinant in the evaluation process, as increasing offshore distance generally enhances wind and wave energy potential but also significantly raises capital and operational costs, complicates maintenance, and exposes infrastructure to harsher environmental conditions. Sites located beyond 25 km were deliberately excluded from consideration due to these escalating technical and economic constraints. Longer submarine cable requirements, higher transmission losses, and elevated structural vulnerability make such distant installations less viable within the scope of this study. As a result, the 25-km threshold represents a practical upper limit, balancing energy potential with financial and operational feasibility in the context of offshore renewable energy deployment. Figure 4 illustrates the locations of the selected sites, with consideration given to water depth and marine traffic. The figure is generated using OpenSeaMap [27]. These sites were carefully identified based on the framework parameters, with a primary focus on the area of highest energy demand for desalination plants along the coast, which is Shuaiba.



Trip Planner:

Start N 20°40'34" - E 39°31'08"
Finish N 20°43'32" - E 39°18'18"
Distance 23.95 km

	Course	Distance	Coordinate
1.	262.57°	4.03 km	N 20°40'17" - E 39°28'50"
2.	263.63°	4.79 km	N 20°39'60" - E 39°26'05"
3.	285.39°	4.81 km	N 20°40'41" - E 39°23'25"
4.	302.44°	5.08 km	N 20°42'09" - E 39°20'56"
5.	299.14°	5.24 km	N 20°43'32" - E 39°18'18"

Download CSV ggg°mm.mmm' [km]

Figure 4. Sites' locations in the Red Sea, 1=Site A, 2=Site B, 3=, Site C, 4=Site D, 5=Site E.

The assumptions used for site evaluations are:

- Solar power remains consistent across all sites due to uniform sunlight availability.
- Wind power increases with distance from the shore, benefiting from better wind conditions.
- Wave power also improves with distance, due to stronger and more consistent wave energy.

The different steps involved within the evaluation process are:

- First step includes the power ratings. The power potential is assessed based on the distance from the shore, with solar power remaining constant and wind and wave power increasing at sites further from the shore.
- The second step involves cost ratings, which includes capital, operational and maintenance (O&M) costs, all of which increase with the distance from the shore due to logistical complexities.
- The last step deals with risk management ratings, which considers environmental impact, economic stability, social impact, natural disasters, and structural health, with greater risks associated with sites farther offshore as shown in. Then, normalize and Weight Scores: Scores are normalized based on maximum values observed across sites

and weighted according to their importance as 50% power, 25% cost, and 25% risk. Table 2. Final Scores for Sites A-E calculates final scores by applying weights to the normalized scores for each criterion.

Based on comprehensive analysis, Site A, located less than 5 km from the coast, emerges as the optimal location. It gets the highest overall score of 0.86 by effectively balancing power potential, cost efficiency, and manageable risk levels. This site's proximity to the shore provides logistical benefits while maintaining favourable attributes for successful offshore energy development. Other sites, particularly those further offshore, exhibit higher power potential but face escalated costs and increased risks, leading to lower overall scores.

Table 2. Final Scores for Sites A-E (dimensionless values).

Site	Power	Cost	Risk Management	Weighted power	Weighted cost	Weighted risk	Final score
A	0.71	1.00	1.00	0.355	0.25	0.25	0.86
B	0.79	0.88	0.88	0.395	0.22	0.22	0.835
C	0.86	0.76	0.76	0.430	0.19	0.19	0.81
D	0.93	0.64	0.63	0.465	0.16	0.16	0.783
E	1.00	0.52	0.51	0.5	0.13	0.13	0.756

3.4 The energy island location

Opting for a single energy island over multiple installations hinges on significant cost efficiencies, operational simplicity, and environmental management benefits. Constructing one island reduces capital and operational expenditures by minimizing the need for duplicative infrastructure and streamlining maintenance and logistics. It also simplifies regulatory compliance and environmental monitoring, as managing one site allows for concentrated efforts in mitigating impacts and adhering to safety protocols. Additionally, a single facility can more effectively optimize resource use and technological integration than multiple dispersed sites, enhancing overall energy production efficiency and reducing environmental disruptions. Therefore, a single energy island presents a more strategic, cost-effective, and environmentally sensitive approach to developing offshore renewable energy resources.

Based on the framework results, Shuaiba, located 40 km south of Jeddah, is the preferred site, taking into consideration the water depth during construction to prevent extravagant costs. Shuaiba has been chosen because it has the highest production of desalinated water on the Red Sea, making it advantageous to construct the energy island nearby. This proximity allows for efficient support of the total electricity consumption of the desalination plants in KSA, which is 42.684 million MWH in 2023, according to the open-source data from the website of the Saudi Water Authority (SWA) [28]. Based on this data, it is expected that about 43.17% of the desalinated water is produced from the Red Sea. It is also assumed that the daily electricity requirement is approximately 2.1 million kW on the Red Sea. As a result of the IDW interpolation, the total hybrid power in Shuaiba is 1998 W/m^2, which requires 1.05 km^2 to power the desalination plants with hybrid clean energy, neglecting the spacing between wind turbines.

4. Conclusion

This study developed an integrated framework combining IDW interpolation MCDA to optimize the selection of sites for renewable energy islands in the Red Sea region. By leveraging the strengths of both methodologies, the framework effectively addressed challenges such as data sparsity and the complexity of offshore renewable energy site selection.

The findings highlight several key insights. First, IDW interpolation demonstrated its ability to provide accurate spatial estimates of renewable energy resources, making it a valuable tool for resource assessment in data-limited regions. Second, the application of MCDA enabled a balanced evaluation of power potential, cost efficiency, and risk management, ensuring a comprehensive and systematic approach to site selection. This dual-method approach allowed for a comprehensive understanding of both spatial and strategic dimensions critical to offshore energy planning.

The analysis identified the Middle region of the Red Sea as the most suitable area for renewable energy development. Within this region, Site A located less than 5 km from the shore emerged as the optimal location due to its favourable proximity, manageable risks, and economic feasibility. The integration of geospatial precision with strategic decision-making produced a replicable model for sustainable energy planning, particularly in regions that face significant environmental and logistical constraints. This framework not only contributes to renewable energy solutions for desalination in Saudi Arabia but also aligns with broader global efforts to mitigate climate change through low-carbon energy systems.

Moreover, offshore renewable energy installations often referred to as energy islands offer the advantage of higher power outputs while requiring smaller spatial footprints compared to their onshore counterparts. These installations support environmental sustainability and can also address social and economic challenges by contributing to resilient infrastructure and energy access in coastal regions.

Future research should aim to expand this framework by incorporating dynamic environmental factors, economic variability, and emerging renewable energy technologies. In areas with limited offshore space, integrating complementary land-based solar installations may offer practical advantages such as reduced maintenance requirements, lower exposure to saltwater-induced corrosion, and enhanced system reliability over time. These improvements would enhance the framework's adaptability and increase its relevance in addressing the complex and evolving challenges of sustainable energy development on a global scale.

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