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ORIGINAL RESEARCH

Spatial modelling and policy evaluation of the offshore wind potential for a small oceanic island: the case of Mauritius

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Abstract

The identification of offshore wind farms necessitates the consideration of multiple factors, including technical, social, economic, and ecological ones, amongst others. In the current study, a multi-criterial model is applied by incorporating wind speed, water depth, grid proximity, tourism activities, and marine spatial constraint factors to determine optimum sites for offshore wind farm placements in the Republic of Mauritius. The North-Eastern region, off the coast of Grand Gaube, has been found to be promising, with an annual electricity potential of 1650 GWh, owing to favourable wind regime of about 7.95 m/s at 100 m height. Moreover, the site location, at an average water depth of 38 m, favours the adoption of conventional jacket foundation. A levelized cost analysis reveals that the electricity generated from the offshore farm would be priced at \$163/MWh, which makes it cost-competitive as compared to heavy fuel oil at \$218/MWh. A scenario looking at the installation of a 608 MW offshore wind plant, which represents the theoretical maximum that may be attained in the optimum region identified, revealed that exploitation of this site has the potential to decrease up to 1.5 times the share of imported fuel oil and diesel for electricity needs. Besides providing guidelines for the implementation of offshore wind technology in Mauritius, the paper reflects on important gaps for adoption, including factors that seek to ease policy uptake.

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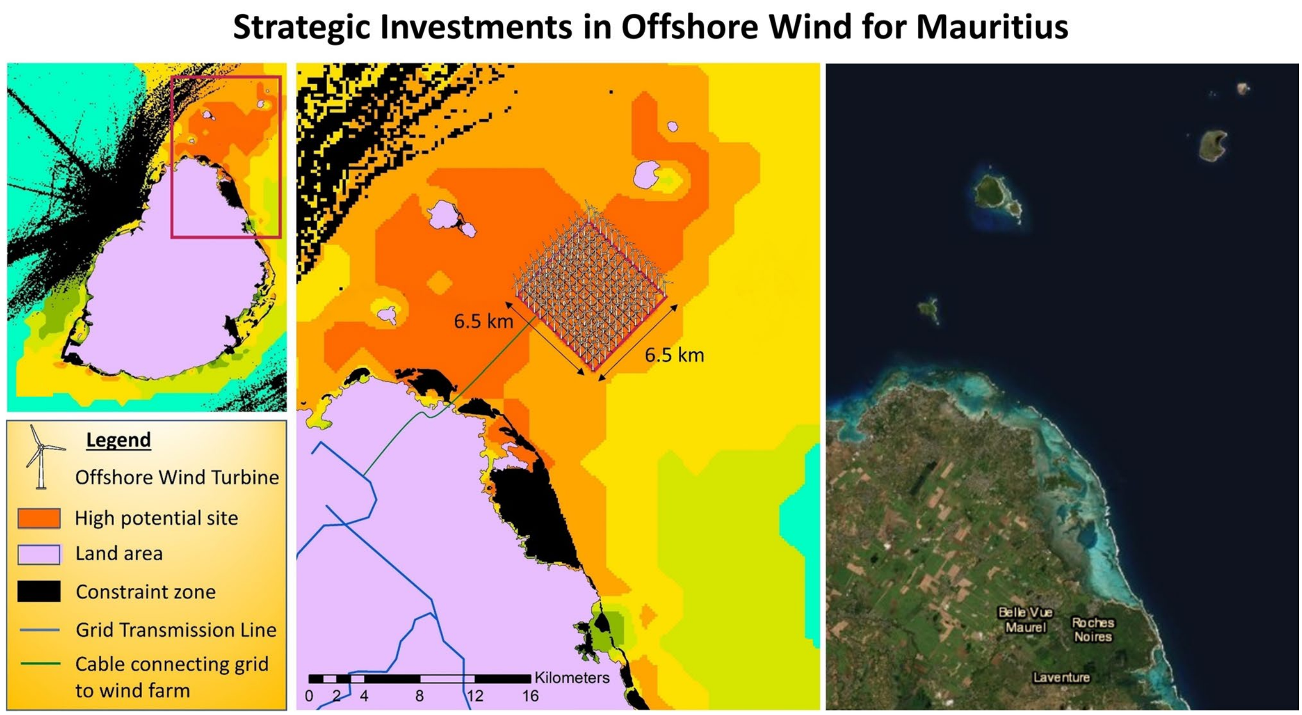
Graphical abstract



Keywords Offshore wind · GIS · MCDA · Decarbonization · Renewable energy · Mauritius

Introduction

Founded on a mixed developing economic system based on the agricultural, tourism, exportation, and financial services sectors, the island of Mauritius is heavily reliant on the importation of fossil fuels to power its economy. An estimated 84% of the primary energy requirement of the country is met by imported fossil fuels, notably oil and coal, with the energy sector alone accounting for nearly 62% of the national greenhouse gas emissions [47]. This heavy dependence on imported fossil fuels is further compounded by the high vulnerability of the country to fossil fuel market dynamics, including price volatility, quality and availability, resulting in unwavering energy security issues. Supply interruptions and shocks in the global energy system, prevalent during the COVID pandemic period, have had significant repercussions in the power and transport sectors of vulnerable fossil fuel-dependent island nations like Mauritius [20]. It is essential for the country to improve its resilience whilst stimulating economic recovery and sustainable development in the post-pandemic period. This requirement has been even more stressed recently, whereby energy prices have soared to unprecedented levels following the ripple effects of the conflict between Russia and Ukraine. An accelerated energy transition through investments in renewable energy would, therefore, help the country in its key endeavour to attain energy security and at the same time contribute to the overarching goal of decarbonizing its carbon-intensive grid in line with its latest Nationally Determined Contribution under the Paris Agreement [9, 49].

Over the past two decades, a panoply of policy instruments and programs has been implemented in Mauritius to boost the renewable energy sector. A Small-Scale Distributed Generation (SSDG) scheme, funded by the Government of Mauritius with UNDP support in 2010, supported the integration of small-scale (< 50 kW) photovoltaic (PV) panels and wind turbines through a targeted Feed-in Tariff (FiT) scheme [15]. Another more recent policy instrument employed includes a net-meting scheme which is benefiting around 2000 small power producers around the island who are generating electricity using PV and wind energy technologies for a total capacity of 5 MW [19]. The recent budget 2021/2022 of Mauritius provides incentives towards sustainable energy generation and proposes the renewable energy sector as a new pillar of economic growth [10]. As part of the measures put forward to ramp up renewable energy generation from 13 to 60% by 2030, a detailed feasibility study is planned to be conducted in order to investigate the offshore wind energy potential for electricity generation [10]. In this vein, the findings of the present paper can support for science-based policy decision-making by guiding the cost-effective implementation of an offshore wind farm, thereby enabling to increase the share of renewables in the energy mix of Mauritius. The electricity generated from renewables was estimated at 688 GWh in 2020, representing a share of 23.9% of the electricity generation mix [39]. Onshore wind, with an electricity generation potential of 18 GWh in 2020, contributed only 0.6% of the electricity requirement of the country [39]. Generating electricity from offshore wind can significantly increase the share of renewables in the mix.

Offshore wind potential assessments of Mauritius have revealed the higher energy resource potentials of the offshore regions of the island as compared to onshore sites. It is estimated that at 80 m height, about 2.3–3.4 times higher wind power densities are yielded near the south-eastern offshore coast, with values attaining 420 W/m^2, as compared to inland regions at 66 m height [38]. The Southern and North-Eastern offshore regions of the island yield 1.8–2.5 times higher wind power densities attaining about 450 W/m^2 at 100 m height as compared to the onshore region at 110 m height [38]. As of 2020, the global offshore wind energy capacity was 34.4 GW, representing an increase of 21.2% as compared to 2019 [21]. The experience gained through the growth of installed offshore wind capacity in addition to material and technological developments has contributed in lowering the upfront investment costs associated with offshore wind turbines. The construction of offshore wind facilities has registered the fastest cost reduction of any renewable energy source in 2019 attaining $78/MWh, which represents a drop in price of 32% as compared to 2018 [1]. In Europe, offshore wind power has become cost-competitive with conventional fossil fuels since 2017 [4]. Projections made by the European Union for offshore wind turbines suggest that a reduction in the capital investment cost of more than 50% and a prolongation of the technical lifetime from 20 to 30 years could be attained by 2050 [23]. In addition to the promising future economic prospects offered by offshore wind facilities, the fact that they are placed at sea is a huge benefit, especially for an island like Mauritius with land scarcity issues.

The suitable planning of offshore wind farms necessitates the consideration of multiple factors, ranging from the climatic suitability of the site pertaining to appropriate offshore wind regimes, geotechnical land properties of the bottom seafloor section, and geospatial constraints associated with shipping routes, amongst others. Multi-Criteria Decision Analysis (MCDA) is a useful tool that allows the structuring of a complex multi-dimensional problem [32]. Schillings et al. [37] resorted to the MCDA technique to investigate the offshore wind potential of the North Sea and to limit conflicts that may arise due to existing sea uses that may interfere with the placement of an offshore wind farm. The offshore wind energy potential of the UK was investigated using a multi-criterial model set up by Cavazzi and Dutton [3] which enables the simulation of technical and economic aspects for proper offshore wind farm planning. An assessment of the offshore wind potential using the MCDA approach in the Gulf of Thailand revealed a technical power potential amounting to 7000 MW, with a generation potential of 15 TWh/year [53]. Mahdy and Bahaj [25] conducted an MCDA to investigate the offshore wind potential of Egypt and was able to identify three highly suitable areas with minimum restrictions, with the capacity to generate 33 GW of wind power.

The innovation of the current study is that it seeks to fill the important gap in literature pertaining to unveiling the techno-economic offshore wind potential of small islands. Such locations have specificities inherent to their physical characteristic and socio-economic contexts—characterized by space and resource limitations, economies that are highly vulnerable to external shocks, reliance on foreign direct investment coming from tourism, which, in turn, is dependent upon fragile ecosystems, amongst others. There are relatively few papers in literature regarding assessments of offshore wind potentials for small islands, and the research presented in this paper aims to address this gap. Moreover, the current paper is amongst the few ones to incorporate tourism activities as an important factor which dictates the placement of offshore wind farms. Being an island, which is heavily dependent on the tourism economy, implies that the inclusion of the tourism activity factor is key for optimum siting of offshore wind power plants in Mauritius.

In the current study, the MCDA technique is adopted to identify highly suitable sites for the constructions of offshore wind farms in the territorial waters of Mauritius. The technical power potential of the farm is revealed, and an economic feasibility assessment is performed to evaluate its economic potential as compared to conventional fossil fuel use for electricity generation. We also reflect on important gaps for adoption, including factors that seek to ease policy uptake.

We begin by contextualizing the research and by describing the area of study. The materials and methodology adopted in the current study are thereafter elaborated. The theoretical foundations underlying the methods used to investigate the offshore wind potential of Mauritius are described in the methodological section. The results of the study are then presented, followed by an in-depth discussion that aims to provide for a scientifically informed guide for the development of offshore wind farms at the identified sites.

Study area

The Republic of Mauritius, situated in the South-West Indian Ocean to the east of Madagascar, has a large Exclusive Economic Zone (EEZ) of 2.3 million km^2 (Fig. 1a).

Since 2012, it shares a joint management area with the Seychelles which extends over 396,000 km^2 of the Continental Shelf. Mauritius Island sits on the Mascarene Plateau (Fig. 1b) which arches about 2000 km across the western Indian Ocean up to the Seychelles, and hosts a rich and diverse ecosystem on the mid-oceanic plateau at water depths of about 100 m [7]. The shallower regions are found on the plateau extending in the Northern offshore waters of the island, in contrast with the deeper sections on the southern latitudes where the bathymetric gradient is steeper. Marine spatial constraints are mainly concentrated within the vicinity of the lagoon (Fig. 1c), enclosed by a near-continuous coral reef, and which comprises of fishing reserves and Marine Parks which are secured under the Fisheries and Marine Resources Act 2007. Inscribed as a UNESCO World Heritage Site, Le Morne Cultural Landscape is protected by a strict legal framework under the National Heritage Trust Fund Act 2004, as delineated in Fig. 1c.

Materials and methods

Framework overview

The framework adopted to investigate the offshore wind energy potential of Mauritius is shown in Fig. 2. Initially, the geospatial constraints prohibiting the construction of an offshore wind facility are identified. The MCDA process begins with the identification of criteria that influence the placement of the offshore wind farm. Analytical Hierarchy Process (AHP) technique is thereafter used to determine the importance of each criterion through a pairwise comparison process which results in the allocation of factor weights. Suitably weighted factors are then combined using the Weighted Linear Combination (WLC) process to identify feasible and unfeasible regions for exploitation. Prohibited regions identified at an earlier stage are then excluded from the analysis to reveal only feasible sites that are graded based on their potential for exploitation. The highest potential regions identified are further probed to determine the technical and economic appropriateness for offshore wind farm implementation.

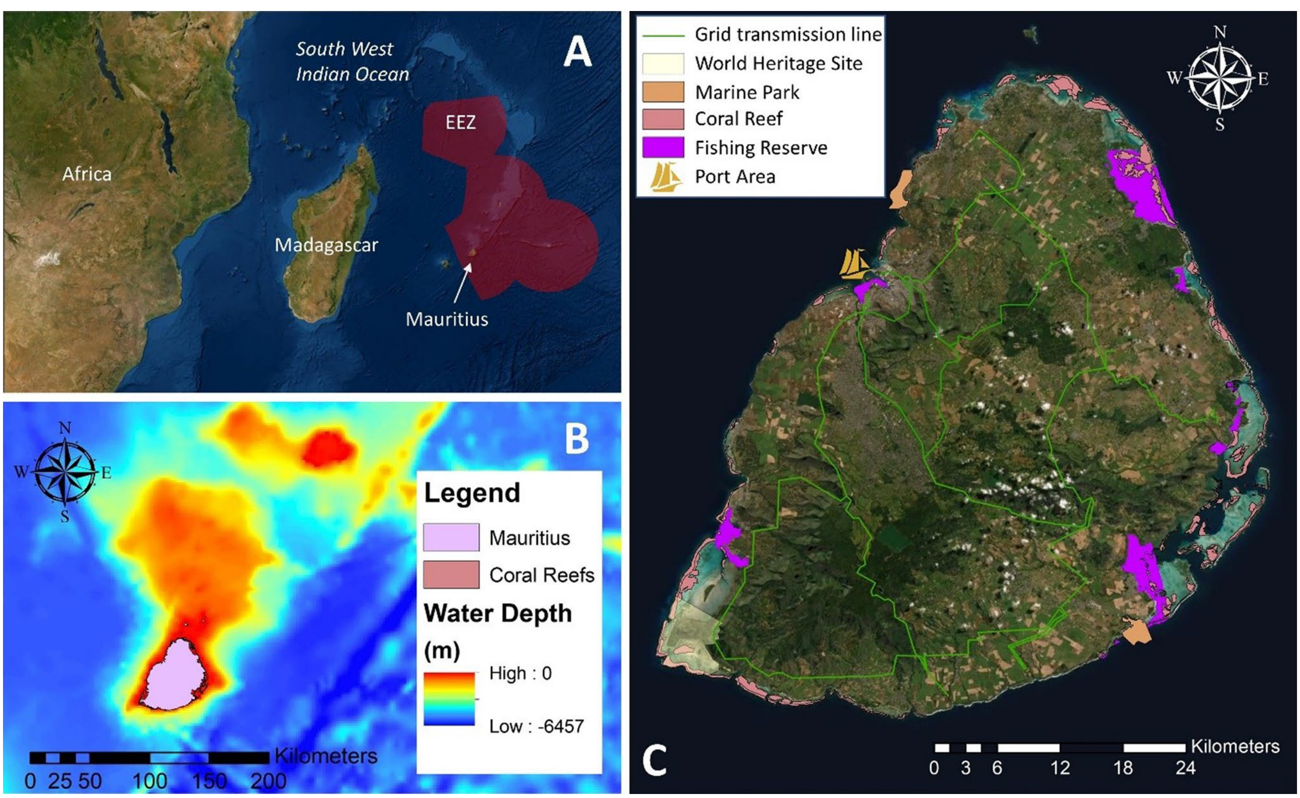


Fig. 1 **a** Location of Mauritius in the South-West Indian Ocean and extent of its Exclusive Economic Zone (EEZ). **b** Bathymetric chart of the South-Western Indian Ocean in the vicinity of Mauritius Island. **c** Location of some nearshore marine spatial constraints for Mauritius

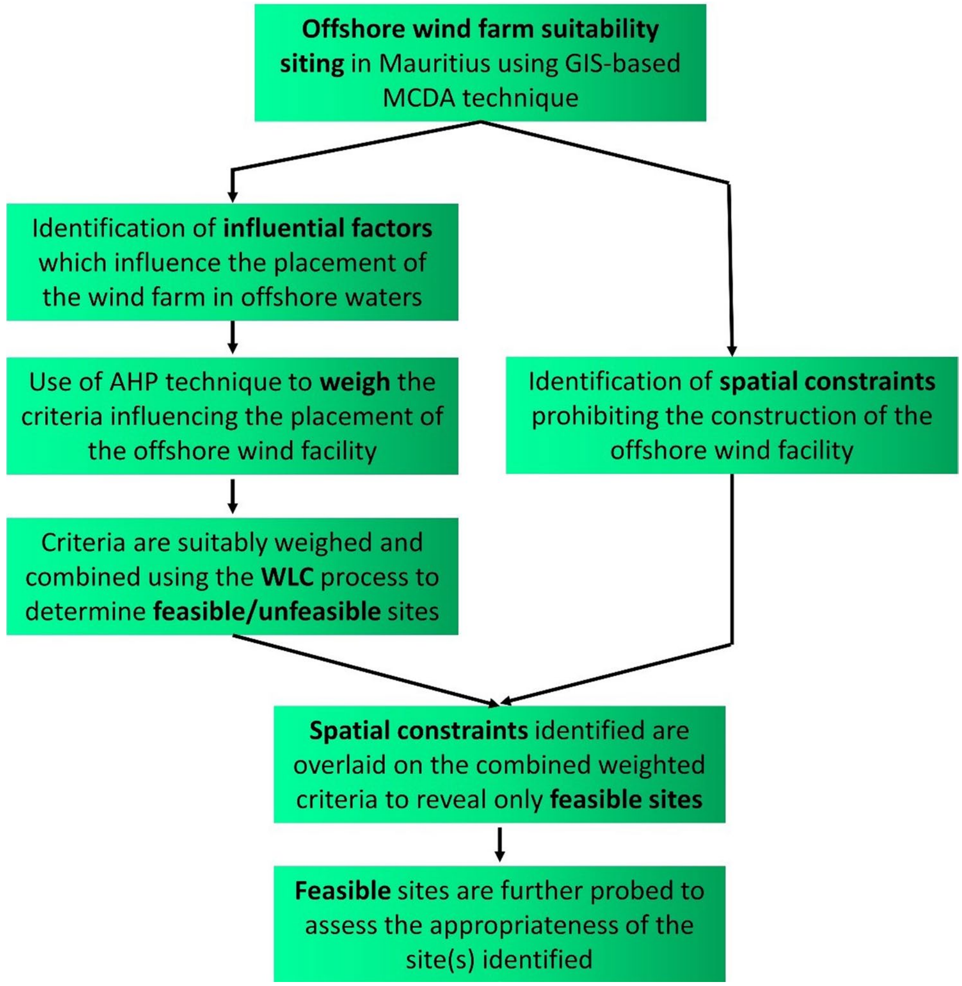


Fig. 2 Methodology adopted to determine the optimum siting and arrangement of an offshore wind facility in waters of Mauritius

Geospatial optimization

GIS-based MCDM

The main processes underlying the GIS-based MCDA approach involve deriving criteria weights through the Analytical Hierarchy Process (AHP) and combining the factors using the WLC process. Both processes are illustrated in the following subsections.

Analytical hierarchy process (AHP) Offshore wind farm siting necessitates the consideration of multiple quantitative and qualitative factors that may influence its placement in the offshore waters. The unstructured nature of the site-suitability analysis confers some degree of complexity to this multi-dimensional problem. Consequently, the AHP approach introduced by Saaty [35] is generally used to reduce the level of complexity through the proper structuring of a decision-making problem into a hierarchical representation. The process involves pairwise comparisons of criteria based on a common scale of measurement, referred to as the Saaty Scale, as presented in Table 1. The result of this pairwise comparison leads to a decision matrix which influences the weights of the elements that make up the analysis, hence giving a structure to the decision problem.

Evaluation matrix A, shown next in Eq. 1, is acquired through the pairwise comparisons of n criteria. The element a_{ij} $(i, j = 1, 2, 3, \ldots, n)$ indicates the quotient of weight.

$$A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix}, a_{ii} = 1, a_{ij} = \frac{1}{a_{ji}}, a_{ji} \neq 0 \quad (1)$$

The relative weights, A_w, of the decision matrix above is calculated using the right eigenvector, w, corresponding to the maximum eigenvalue, $\lambda_{\max}$, as shown in Eq. 2:

$$A_w = \lambda_{\max} w \quad (2)$$

In order to ensure that consistency is maintained in the pairwise comparisons performed, a consistency check is performed, as presented in Eq. 3. The check is performed

Table 1 Saaty's fundamental scale for pairwise comparisons

Intensity of importance	Definition	Explanation
1	Equally significant	Two elements contributing equally to the objective
3	Moderate significance	Experience and judgement slightly favour one element over another
5	Strong significance	Experience and judgement strongly favour one element over another
7	Very strong significance	Activity is strongly favored and its dominance is demonstrated in practice
9	Extreme significance	The evidence favouring one parameter over another is of the highest possible order
2, 4, 6, 8	Intermediate values	Used to represent compromise between priorities listed above

prior to applying the weights to the criteria making up the decision problem. The consistency ratio (CR) measuring the degree of departure from pure inconsistency is derived as follows:

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

where RI represents the consistency of a randomly generated pairwise comparison matrix and CI indicates the consistency index, as expressed in Eq. 4:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

The pairwise comparison test is iterated until CR ≤ 10%, which indicates an acceptable level.

Weighted linear combination (WLC) After deriving the weights through the AHP technique, the different factors are combined through the WLC technique to generate the offshore wind farm suitability map of Mauritius. This aggregation involves assigning derived weights acquired from AHP to individual criterion and then summing them up. The Offshore Wind Suitability Index (OWSI) is given by:

$$\mathrm{OWSI} = \sum_{j=1}^{n} w_j a_{ij} \tag{5}$$

where w_j is the weight of factor j, a_{ij} is the normalized value of area i under factor j, and n is the number of criteria.

Review of offshore wind models

Site suitability analysis for an offshore wind farm requires the consideration of multiple factors We present in Table 2 a synthesis of the influential and constraint factors employed by multiple offshore wind farm studies around the world.

Selected offshore constraint factors

Marine protected areas (MPAs) In view of protecting marine habitats and maintaining biodiversity, MPAs have been set up which consists of six fishing reserves and two marine parks, as illustrated in Fig. 1c. MPAs are secured under strict legal frameworks which would pose a legal constraint to the laying of submarine cables from the offshore wind farm to the shore. The data were made available by UNEP-WCMC and IUCN [48].

World heritage site With the objective to preserve the cultural heritage of Le Morne Brabant, which is regarded as a symbol of marronage during the nineteenth century in Mauritius, strict policy frameworks have been set up and a buffer zone (Fig. 1c) has been traced by the Ministry of Housing and Lands [28]. Georeferencing and digitization of the buffer area was performed using QGIS.

Coral reef Coral reefs are regarded as important ecological habitats for marine organisms and may pose a constraint with regards to the laying of underwater electric cables for the offshore wind farm that may entail significant reef damage [8]. Coral reef distribution around Mauritius was vectorized (Fig. 1c) in QGIS through visual inspection of satellite imageries.

Exclusive economic zone (EEZ) With one of the largest EEZ globally, a key endeavour of the Republic of Mauritius is the promotion of its ocean economy. According to the United Nations Convention on the Law of the Sea (UNCLOS), the country has exclusive rights to implement offshore projects within the limits of its national jurisdiction, as delineated by the EEZ (Fig. 1a). The demarcation of EEZ region for Mauritius was made available by Flanders Marine Institute [13].

Shipping route The location of the offshore wind farm may pose a navigational constraint for marine traffic. The shipping routes around Mauritius were determined from the ship density maps of Marine Traffic from 2019 and 2020 [27]. The map was georeferenced and the ship routes around Mauritius were extracted using QGIS, as illustrated in Fig. 3.

Unfeasible water depths The offshore wind industry has experienced significant growth over the past decade. Monopile foundation has been reported to be the most popular

Table 2 Specifications of offshore wind farm suitability models implemented worldwide

Country	Technique	Constraint	Influential factor and weight	Reference
Egypt	AHP WLC	Military area Natural parks Oil and gas well Shipping routes Cables	Wind power density (54%) Depth (24%) Soil properties (7%) Distance to grid (4%) Distance to shore (11%)	Mahdy and Bahaj [25]
Hong Kong	AHP WLC	Fishing port Restricted areas Fairways Mud disposal Anchorage site Fish culture Recreation zone Artificial reef	Distance to shore (6%) Distance to flora/fauna (3.5%) Distance to recreation zones (3.5%) Distance to port (24%) Distance to fishing areas (5%) Distance to grid (10%) Wind speed (14%) Depth (33%)	Gavériaux et al. [14]
Morocco	AHP WLC	Submarine cables Shipping routes Protected areas Migratory bird route Blue flag beach EEZ	Wind speed (38.5%) Water depth (20.7%) Distance to grid (12.9%) Distance to port (6%) Distance to shoreline (6%) Tourism density (2%) Distance to airport (3.4%) Sediment thickness (10.4%)	Taoufik, M. and Fekri [44]
Brazil	AHP WLC	Low wind speed Unfeasible depth Fishing site Pipeline Conservation site Priority area	Wind speed (53%) Water depth (30%) Distance to shore (11%) Distance to ports (6%)	Vinhoza and Schaeffer [52]
Mauritius (present paper)	AHP WLC	Shipping route Unfeasible depth EEZ Marine protected areas Coral reef World heritage	Wind speed Water depth Distance to grid Tourism density	Doorga et al. [9]

typology with a global market share of 60% [36]. Monopiles are generally used in shallow (0–15 m) and intermediate (15–30 m) depths. Tripod and jacket structures are better suited for transitional water depths between 30 and 50 m [31]. Floating foundations are generally used for deep waters above 50 m and can be implemented in water depths of up to 1000 m based on currently proposed technologies [54]. In the current analysis, we identify and exclude water depths greater than 2000 m using bathymetric data from [16], as shown in Fig. 3.

Selected influential factors

Wind speed Considered as being the most influential factor in offshore wind farm siting studies worldwide, as presented in the offshore wind farm models implemented in Table 2, the wind speed parameter is integrated in the formulated model for Mauritius. The wind speed parameter is directly related to the cost-effectiveness of wind farms [43]. The wind data (Fig. 4) in the vicinity of Mauritius were made available by the Technical University of Denmark (DTU) in collaboration with the World Bank Group. Wind speed values vary from 3.1 to 13.6 m/s at 100 m height, with the strongest wind speeds registered in the Southern and Northern offshore regions, as observed in Fig. 4, and reported by Cunden and Lollchund [5]. Higher scores are given to regions witnessing higher wind speeds and the lower scores are attributed to the regions with the lower wind speeds.

Water depth Due to its influence on the type and cost of foundation necessary to accommodate and offshore wind farm, the bathymetry factor is an important one. Water depth data (Fig. 5) were made available by GEBCO [16]. Higher scores are given to regions lying closer to the shore (0–30 m depth) owing to the popular and cost-effective use of monopiles as compared to the other foundation types.

Proximity to grid The nearness of the offshore wind farm site to the grid transmission line has the benefit of saving on electric cable costs and facilitating the injection of electricity to the grid network. The grid transmission lines of Mauritius were made available by OpenStreetMap [30]. The

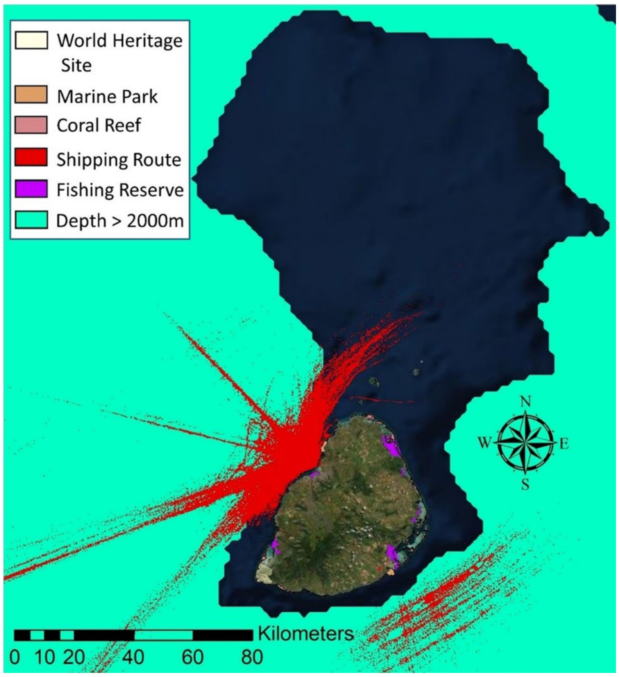


Fig. 3 Geospatial constraints prohibiting the implementation of offshore wind farms in the territorial waters of Mauritius

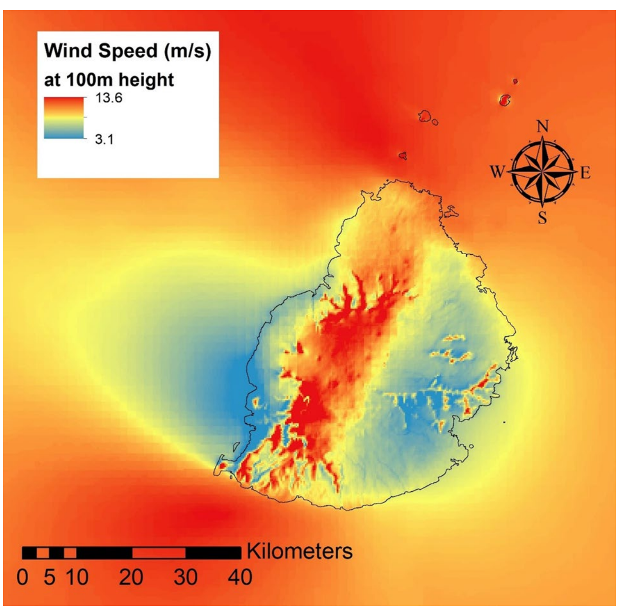


Fig. 4 Map of Mauritius delineating the geospatial variations in wind speeds across the inland and offshore regions of the country

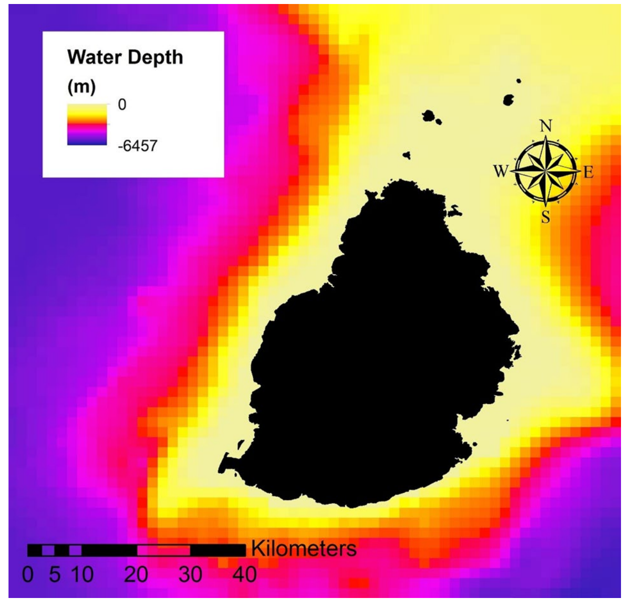


Fig.5 Map of Mauritius delineating the variations in water depths off the coastal areas of the country

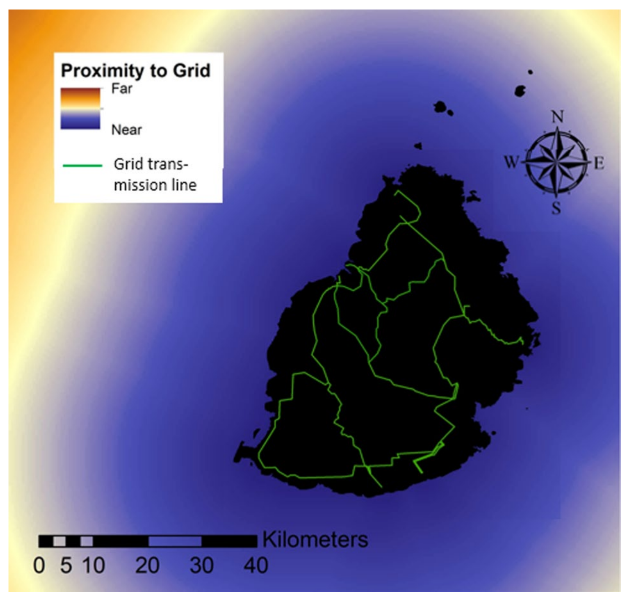


Fig.6 Map of Mauritius delineating the grid transmission network and the proximity of offshore sites to the latter

electricity transmission line data were used to derive the chart illustrated in Fig. 6 which delineate offshore regions around Mauritius which lie nearer and further from the grid network. Higher scores are given to nearshore waters in close proximity to the grid network of Mauritius in order to facilitate injection of electricity from the plant to the electricity grid.

Proximity to popular tourist areas A major inconvenience posed by the implementation of offshore wind turbines is its visibility from the shoreline which decreases the attractiveness of the region where they are installed. Mauritius, being popular touristic destination, whose economy relies on revenues generated from the tourist industry, would necessitate that the offshore wind facility be placed in a region away from tourist activities. The dataset with the main tourist sites on the island (comprising of hotels and popular tourist attractions) was acquired from OpenStreetMap [30] and is presented in Fig. 7. Higher scores are attributed to regions lying far from highly touristic areas in view of dampening the impact of the farm's placement on tourist activities in the region.

Wind energy modelling

A Weibull distribution may be used to represent the probabilistic distributions of wind speeds at a certain region of interest and is given by the probability density function, $f(U)$, as:

$$f(U) = \frac{k}{A}\left(\frac{U}{A}\right)^{k-1} \exp\left[-\left(\frac{U}{A}\right)^{k}\right] \tag{6}$$

where U denotes the wind velocities. The shape factor, k, and the scale factor, A, can be computed using the following equations:

$$k = \left(\frac{\sigma_U}{U_{\text{avg}}}\right)^{-1.086} \tag{7}$$

$$A = \frac{U_{\text{avg}}}{\tau\left(1 + \frac{1}{k}\right)} \tag{8}$$

where σ_U represents the standard deviation whilst the average wind speed is given by U_{avg}.

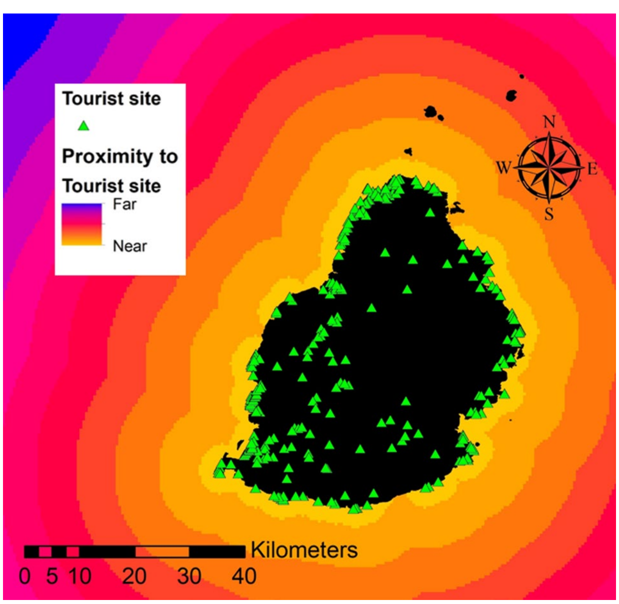


Fig. 7 Map of Mauritius delineating offshore regions around the island lying near and far from tourist sites

The wind energy yield from the turbine may be obtained using the probability density function given next. In Eq. 9, given next, v_c, v_r and v_f are the cut-in, rated and cut-out speeds of the turbine.

$$P(v) = P_r \begin{cases} 0 \text{ for } v < v_c \\ \frac{v^3 - v_c^3}{v_r^3 - v_c^3} \text{ for } v_c \le v \le v_r \\ 1 \text{ for } v_r \le v \le v_f \\ 0 \text{ for } v \ge v_f \end{cases} \tag{9}$$

We assume the use of the wind turbine model: Siemens SWT-3.6-120, rated at 3600 kW, having a 120 m rotational blade diameter and 90 m hub height in the derivation of wind energy yield [55]. We also assume a linear wind flow incident on the wind turbines.

Capacity factor

The capacity factor, CF, defined as the ratio of the actual energy yield (derived from the wind energy model) to the maximum possible electrical energy output from the turbine, is estimated as follows:

$$\text{CF} = \frac{\text{Actual energy yield [MWh]}}{\text{Capacity of turbine \{MW\}} \times 8760\ \text{[h]}} \tag{10}$$

The estimated capacity factor will be used to calculate the levelized cost of electricity associated with the implementation of the offshore wind facility.

Economic modelling

The Levelized Cost of Electricity (LCOE) is defined as the full life-cycle costs of electricity derived from an installed technology per MWh of electricity generated [46]. The advantage of LCOE is that it helps compare multiple technology options to determine the most cost-competitive one. The LCOE [$/MWh] may be estimated as follows, assuming constant annual maintenance costs and energy generation throughout the technology's life-cycle.

$$\text{LCOE} = \frac{K_c K_{\text{RF}} + O_f}{E} \tag{11}$$

where K_c is the capital cost [$], K_{RF} represents the capital recovery factor, O_f indicates the fixed annual operating costs [$], whilst E denotes the annual electricity yield [MWh].

The capital recovery factor, K_{RF}, may be estimated as follows:

$$K_{\text{RF}} = \frac{i(1+i)^t}{(1+i)^t - 1} \tag{12}$$

where i represents the discount rate [%] and t denotes the economic life [years] of the offshore wind technology energy under consideration.

In deriving the LCOE, the main assumptions are that we employ a capital cost value of $3,400,000/MW, a fixed annual and maintenance cost of $95,000/MW, assuming a project lifetime of 20 years and a discount rate of 8%, as suggested by Lazard [24] for offshore wind energy systems.

Results and discussions

Unveiling the techno-economic offshore wind potential

Using the AHP technique, pairwise comparison is performed between a pair of influential factors, yielding the decision matrix shown in Table 3a. Four pairwise comparisons were performed which resulted in an acceptable consistency ratio of 2.6%. The derived weights presented in Table 3b were based on the principal eigenvalue of 4.07. The general order of importance is such that wind speed is attributed the highest weightage owing to its highest degree of importance in determining optimum offshore wind farm sites. Water depth is then attributed the next highest weightage followed by proximity to grid transmission lines and distance to high touristic areas. This order of importance adopted reflects the ones generally employed in various offshore wind farm models implemented worldwide, as shown in Table 2. The factors are then standardized to bring them on a comparable scale prior to applying the derived weights in Table 3b. Combination of weighted and standardized factors then proceeds using the WLC technique which results in the offshore wind farm potential map of Mauritius, shown in Fig. 8. Geospatial constraints identified in Fig. 3 are then overlaid on the map to delineate only regions feasible for exploitation.

Feasible regions around Mauritius are graded from high to low potentials for the implementation of offshore wind energy facilities. From Fig. 8, it can be observed that the regions of highest potentials are found in the Northern, North-Eastern, and South-Western offshore areas which are indicative of locations having high wind velocities, suitable water depths, are located near grid transmission lines, and are adequately situated in zones of fairly low touristic activities. The offshore wind potential map is further probed to

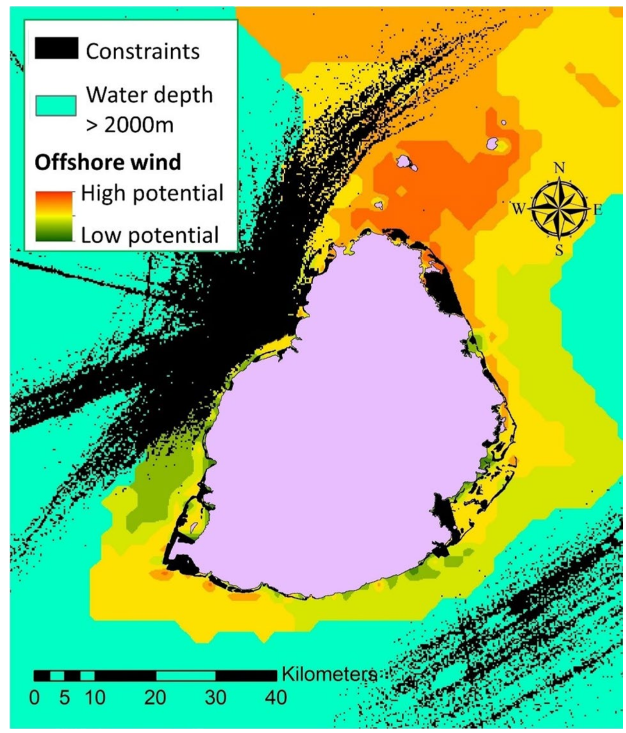


Fig. 8 Map of the maritime zone of Mauritius delineating the offshore wind farm resource potential around the island

Table 3 Results of the AHP method for the **a** decision matrix and **b** factor weights pertaining to the offshore wind farm model

Decision matrix				
	Z_1	Z_2	Z_3	Z_4
Z_1	1	2.00	3.00	3.00
Z_2	0.50	1	2.00	3.00
Z_3	0.33	0.50	1	2.00
Z_4	0.33	0.33	0.50	1

Factor weights			
Cat	Criteria	Weight	Rank
Z_1	Wind speed	44.8%	1
Z_2	Water depth	28.3%	2
Z_3	Proximity to grid	16.4%	3
Z_4	Proximity to touristic sites	10.6%	4

reveal a proposed ideal site in the North East off the coast of Grand Gaube, as illustrated in Fig. 9. Specifications of the proposed site are presented in Table 4. This identified North-Eastern site witnesses high wind speed (7.95 m/s) at 100 m height, whilst being located in an average water depth of 38 m which would favour conventional jacket foundation. Additionally, the site has the added benefit of being located at some distance from the shore (7.2 km), such that the offshore turbines would be practically out of sight from the North-Eastern coast. The relatively lower coral distributions opposite to the farm layout in that region, as illustrated in Fig. 9b, would imply less ecological impacts as the laying of underwater electric cables would not entail significant reef damage. Moreover, the identified site has been strategically located at some distance from Round, Flat, Gunners Quoin, and Ambre Islets which are ecologically sensitive regions and host a rich biodiversity.

Assuming that an offshore wind turbine model: Siemens SWT-3.6-120 with rated power 3,600 kW, 120 m diameter and 90 m hub height [55] is used in the implementation of an offshore wind farm for Mauritius, the annual energy yield may be estimated as presented in Table 4. For an arrangement of 169 turbines proposed at the Northern Eastern site, the estimated annual energy generation potential is around 1650 GWh. The marginal cost for implementing the wind farm in the identified propitious site is estimated at $163/MWh and is even lower than the average LCOE of heavy fuel oil ($218/MWh) in Mauritius [38], making it cost-competitive even without considering energy subsidies. The implementation of an offshore wind farm in the Northern Eastern site can decrease by about 1.5 times, the importation of fuel oil and diesel (1056 GWh in 2020 [39]) to meet electricity demand. Consequently, the investment in an offshore wind farm in a high potential region has the benefit of dampening the reliance on imported fossil fuels for electricity generation and decarbonize the carbon-intensive

Table 4 Specifications of the proposed sites for the implementation of offshore wind farms

	North-east site
GPS locations	− 19.96°; 57.77°
Area	42.3 km^2
Number of wind turbines	169
Offshore wind farm capacity	608 MW
Average water depth at site	38 m
Type of foundation needed	Jacket
Annual mean wind speed at 100 m height	7.95 m/s
Distance to grid transmission line	13.2 km
Visibility of farm/distance to shore	Low/7.2 km
Tourist density near the site	Relatively low
Estimated annual energy yield	1,650 GWh
Capacity factor	0.31
LCOE	$163/MWh
Wave regime	Moderate

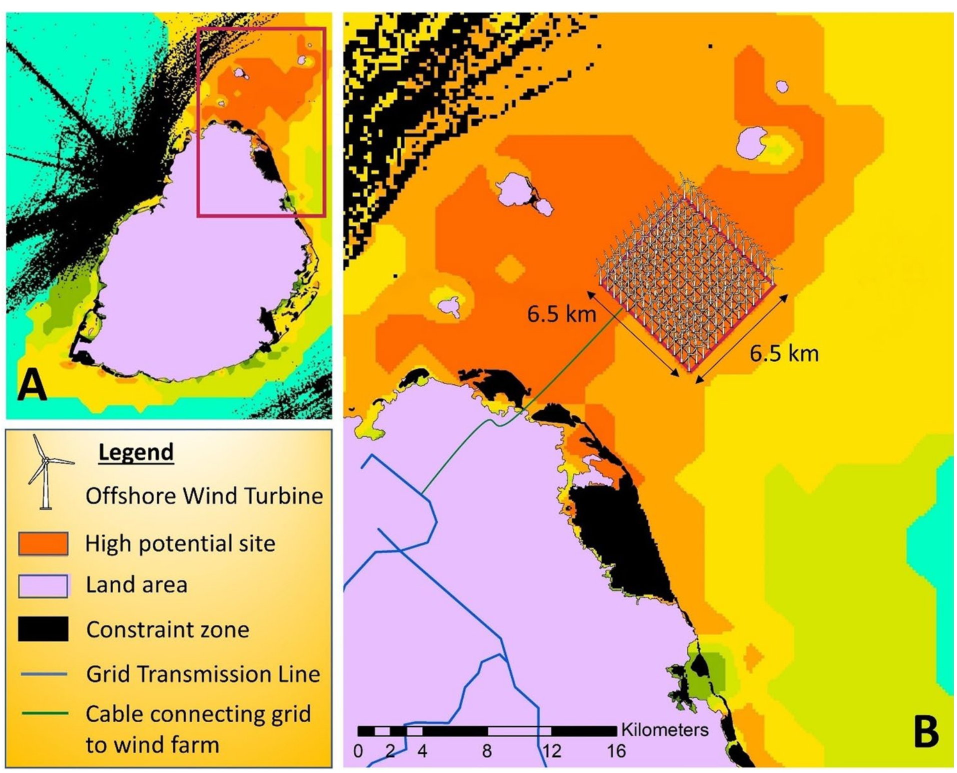


Fig. 9 **a** Location of proposed site identified in the North-East region of Mauritius for the implementation of an offshore wind facility. **b** Offshore wind farm layout comprising of 169 turbines with a 500 m spacing between adjacent turbines and installed in a high potential region identified off the coast of Grand Gaube

power sector whilst yielding long-term economic benefits. Sizing of the farm will be based on energy demand and grid integration capacity.

In comparison with previous studies by Gavériaux et al. [14] for Hong Kong, Mahdy and Bahaj [25] for Egypt, and Vinhoza and Schaeffer [52] for Brazil, which identify sites with higher probabilities for wind speeds occurring in the range of 4–8 m/s, the siting of the proposed offshore wind farm benefits from wind speeds averaging 7.95 m/s. The high wind speed values will be translated into higher energy yields and, therefore, more economic energy generation. However, as also contemplated by other literature studies, the paper considers a range of factors from tourist activities to ecological impacts in order to properly site the wind farm.

The results from the current paper reveal the technical and economic viability of implementing a network of offshore wind turbines in the nearshore north-eastern waters of Mauritius. A network of 169 turbines has been contemplated in the current study to reveal the maximum offshore wind power extraction permissible in a high wind resource area off the coast of Grand Gaube. From this analysis, it was revealed that the installation of typical jacket foundation in water depths averaging 38 m has the technical annual potential of generating around 1,650 GWh, resulting in an LCOE value of about $163/MWh and found to be more economic than fossil fuel oil and diesel. However, based on the energy demand and grid integration capacity of Mauritius, the sizing of a suitable network for offshore wind power turbines in the segment of the optimum site identified that is closer to the shore and that could even favour conventionally used monopiles (intermediate depths of 15–30 m) should be envisaged. The identified site benefits from the ecological advantage of less damage from cable laying due to the lower coral distributions, in addition of the low tourist activities in the vicinity.

Policy uptake and roadblocks

In the Republic of Mauritius, the Department of Continental Shelf, Maritime Zone Administration and Exploration (DCSMZAE) has the legal mandate for Marine Spatial Planning [6]. Such responsibilities include the identification of zones for development of offshore wind farms. However, the DCSMZAE has not yet identified suitable zones for such development (confirmed via email exchanges). Given the national [29] and international commitments [50] taken by Mauritius to develop clean energy, and the fact that the Mauritius Renewable Energy Agency has recently launched an expression of interest from suitable consortiums to develop offshore wind energy in Mauritius [26], not only do the findings of this paper have a high policy relevance, but they are also timely aligned with the country's current ambitions and efforts to unlock the development of offshore wind farms.

However, the transition from scientific assessments to policy uptake is not a straightforward task. For instance, it should be recalled that none of the projects referred to in Table 2 [25], Gavérieux et al. 2019; [44, 52] has been implemented as at-date, although Brazil has registered six environmental impact assessment licences applications for offshore wind as at 2020 [12]. Moreover, at a global level, Zhang et al. [57] infer that global rollout of offshore wind is still in its initial stages, with 6924 wind turbines having been constructed in only 14 coastal nations by 2019 (1 wind farm located in the US, 21 in the UK, 8 in Germany, 8 in Denmark, 7 in China, 2 in Sweden and 3 in the Netherlands).

Whilst this situation may be symptomatic of the recent (and still growing) maturity of research and development on offshore wind technologies that make them cost-competitive with respect to fossil fuel-based energy sources, it also prompts some reflection on the underlying causes accounting for limited diffusion of offshore wind farms as a clean energy source globally, and within the ambit of this paper, utilising those lessons to derive policy implications for the case of the Republic of Mauritius.

In the first instance, this situation could be attributed to a number of gaps in the literature that may have hampered policy uptake across nations involved in offshore wind farm development. For instance, there are currently scarce assessments digging deep into (i) cumulative environmental impacts on marine habitats and species and ecosystem functioning of the benthic community, as well as regulatory risk assessments and other governance and financing challenges [18], [22], (ii) hydrodynamics and hydrographic conditions in the immediate vicinity of sites [51], (iii) impact of offshore wind farms on birds [56] (iv) conducive policy instruments and stakeholder engagement mechanisms [2], (v) potential tourism value-added in terms of 'curiosity trips' [45], (vi) studies on levels of support from island residents [34], (vii) the use of ethnographic studies to inform on the impacts on tourism and recreation around selected sites [40], and the use of integrated strategic planning and a long-term multidisciplinary approach to site selection [42], amongst others.

Given the inherent characteristics of the Republic of Mauritius as a Small Island Developing state, the need for local empirical case studies covering those gaps is heightened. However, with a view to, pragmatically, address national imperatives to decarbonize the energy sector by increasing renewable energy sources to 60% by 2030 [29], it may not be judicious to wait for detailed scientific studies that explore the full-scope of gaps in the literature as previously mentioned. Within this context, this paper provides for an insight of possible sites (Fig. 5) whereby offshore wind farm development is technically feasible, along with a preferred location (Fig. 6) based on an analytically sound methodology ("Materials and methods" section).

Furthermore, scarce diffusion of offshore wind technologies may also reflect a broader limitation of standardized engineering-based assessments of the technical and economic feasibility of technologies. Indeed, another branch of scholarly work posits that technology uptake is essentially path dependent, whereby technology development and diffusion are influenced by a complex interplay between technological and social factors such as user preferences, adequacy of regulatory frameworks, cultural aspects and infrastructure requirements amongst others [17, 33]. These literatures suggest the use of other theoretical frameworks that better integrate socio-technical considerations within analyses that study offshore wind farm development, the lessons of which may better inform policy uptake [11].

Along those reflections, Sovacool [41] calls for energy studies to "become more socially oriented, interdisciplinary and heterogeneous" and "centre on both physical and social processes, include diverse actors and mix qualitative and quantitative methods" so as to better positioned to have a social impact. Comparing the underlying approach adopted in this paper, one may reflect on the reliance on the sole judgement of the authors to choose influential and constraint factors, as well as assign weights that, ultimately, shape the results obtained. To address this gap, the method used and analyses undertaken within this study may be tested with local actors (such as the environment, land use planning, energy ministries, as well as fishermen, NGOs and the public) so as to discuss and agree on most appropriate sites for offshore wind development. To this end, Fig. 5 provides for a basis for such discussions.

Conclusions

In the current study, the feasibility of offshore wind potential is explored for the small island developing state of Mauritius in view of responding to the need to decarbonize the power system and reduce dependence on expensive imported fossil fuel sources for electricity generation. The paper is one of the few for small islands with emphasis on accounting for tourism activities. The marine spatial constraints, such as shipping routes and marine protected areas, are identified and combined with influential factors including wind conditions, water depths, and techno-economic criteria such as proximity to grid transmission lines and tourism density, for proper wind farm planning. The results revealed that the Northern, North-Eastern, and South-Western offshore regions are propitious for offshore wind farm development owing to favourable climatic, economic, and technical conditions.

An in-depth assessment revealed that the North-Eastern site is more suitable for immediate implementation owing to the fact that it is located in an average water depth of 38 m, which would favour the conventionally used jacket foundation. The adequate wind regime of the site, which averages 7.95 m/s at 100 m height over an annual time span, would make it possible to generate up to 1650 GWh of electricity annually. Based on this energy yield, a levelized cost of electricity value of $163/MWh has been estimated for the farm which is found to be cost-competitive as compared to heavy fuel oil ($218/MWh). The highly suitable offshore wind farm site identified in the North-East has a theoretical maximum wind resource potential that can contribute in decreasing up to about 1.5 times the importation of fuel oil and diesel to meet electricity demand whilst catering for the sustainable energy supply of a growing population.

However, this paper also highlights a number of gaps in the literature, covering environmental, policy, regulatory, and methodological factors. The main limitation of the current study is that it has been conducted in a highly academic and siloed approach and without the involvement of other stakeholders. Reflecting on those gaps and with a view to ease policy uptake of the results of this paper, it is proposed to replicate this study with actors having a stake in the development of offshore wind farms.

Suggested avenues for future research should look at sizing of a nearshore wind farm in a segment of the area identified based on (a) the energy demand of the population and grid capacity, as well as on (b) further in-depth ecological considerations pertinent to the site. Moreover, another line of research could focus on the optimum arrangement for wind turbines to increase energy yield in the face of the generated wake effects.

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Authors' contribution JRSD (Corresponding Author) involved in the conception and design of the study, acquisition of data, analysis and interpretation of data, and drafting of the manuscript. ZB contributed in drafting the policy relevance section. TSMC revised the paper for important intellectual content. YC revised the paper for important intellectual content. RK revised the paper for important intellectual content.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval On behalf of all authors, I, Dr Jay Doorga, the corresponding author of this paper wish to assure you that for the manuscript (Feasibility study for the implementation of an offshore wind farm in the nearshore waters of Mauritius: A techno-economic analysis) the following is fulfilled: (1) This material is the authors' own original work, which has not been previously published elsewhere. (2) The paper is not currently being considered for publication elsewhere. (3) The paper reflects the authors' own research and analysis in a truthful and complete manner. (4) The paper properly credits the meaningful contributions of co-authors and co-researchers. (5) The results are appropriately placed in the context of prior and existing research. (6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference. (7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content. The violation of the Ethical Statement rules may result in severe consequences. We agree with the above statements and declare that this submission follows the policies of the Journal of Clean Technologies and Environmental Policy.

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