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Mapping offshore wind potential and spatial trade-offs for marine planning in Caribbean Small Island Developing States

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Offshore wind is a prominent strategic option for decarbonizing power systems and enhancing energy security in Small Island Developing States (SIDS). However, its strategic implementation in the Caribbean is hindered by fragmented spatial data concerning resource availability, technological feasibility, and multi-sectoral trade-offs. This study establishes a reproducible, marine-planning-oriented spatial screening framework that synthesizes wind resource climatologies with critical environmental constraints to delineate opportunity and trade-off zones across the Exclusive Economic Zones (EEZs) of 12 Caribbean SIDS. We first mapped wind speeds at 100 m and integrated country-level technical potentials, including fixed-bottom and floating offshore foundation technologies to facilitate an integrated cross-jurisdictional assessment. A multi-criteria conflict index was subsequently developed from spatial datasets representing Marine Protected Areas (MPAs) and sensitive benthic habitats, specifically coral reefs and seagrass meadows. Our spatial analysis identifies 10.03% of the maritime domain as 'Opportunity' zones—areas where high wind resources align with low ecological and jurisdictional constraints. Significantly, 'Trade-off' zones occupy only 0.36% of the region, revealing a pronounced spatial decoupling between peak wind resources and existing ecological protections. Conversely, 14.88% of the area is classified as 'Avoid' zones, predominantly concentrated in nearshore environments. By integrating resource potential, foundation technologies, and constraint layers into a transparent workflow, this study provides a rigorous evidence base to transition from national-level aggregates to actionable, sub-EEZ siting strategies in the Caribbean.

KEYWORDS
blue economy, Caribbean SIDS, floating offshore wind, Marine Spatial Planning (MSP), multi-sectoral conflict

1 Introduction

Small Island Developing States (SIDS) contend with a nexus of energy insecurity and climate vulnerability. Despite contributing less than 1% of global greenhouse gas emissions (IPCC, 2022), SIDS are disproportionately vulnerable to climate change impacts such as sea-level rise and extreme weather events, while remaining heavily dependent on imported fossil fuels for electricity generation (~80%) (Copping et al., 2020). Renewable energy transitions in these contexts offer multiple co-benefits, including reduced fuel import costs, improved energy security, and local economic development (David et al., 2021). However, evidence suggests that the pace of energy transition in SIDS is constrained less by resource availability than by institutional, financial, and technical limitations (Cherp et al., 2021). Although several Caribbean nations have established ambitious renewable energy targets, achieving these goals requires coordinated planning frameworks and context-specific implementation strategies (Atteridge and Savvidou, 2019; Havea et al., 2024; Surroop and Raghoo, 2018). The compounding fiscal strain of imported fossil fuels necessitates a rapid transition, which creates persistent foreign exchange drains and high electricity tariffs that stifle local development (Dominković et al., 2018; Kousksou et al., 2015). Considering the significant lead times required for offshore infrastructure, proactive spatial planning is essential for establishing energy sovereignty and macroeconomic resilience in the region (Timilsina and Shah, 2016).

In this context, offshore wind energy has emerged as a promising option for Caribbean SIDS, where land availability is limited but marine areas are extensive. The Caribbean Sea is influenced by the easterly Caribbean Low-Level Jet (CLLJ) (Cook and Vizy, 2010), resulting in strong and persistent trade winds across much of the region. Climate reanalysis and observational studies indicate high wind power densities, typically ranging from 200–600 W/m², with peak values in the core CLLJ zone (Bethel, 2021; Timilsina and Shah, 2016; World Bank, 2019; Dutton et al., 2019). Regional assessments and site-specific studies further confirm the technical feasibility of offshore wind deployment, including in areas surrounding Trinidad and Tobago and the Greater Antilles (Chadee and Clark, 2014; Weiss et al., 2018). At a global scale, offshore wind potential is estimated to exceed 70 TW, with a substantial share located in deeper waters suitable for floating technologies (IRENA, 2024; World Bank, 2019; Dutton et al., 2019). Given their large Exclusive Economic Zones (EEZs), Caribbean SIDS may host a significant portion of this untapped resource.

Globally, offshore wind has entered a phase of rapid acceleration as a cornerstone of the blue economy and national decarbonization strategies. However, its expansion introduces inevitable spatial competition with established ocean uses and ecologically sensitive areas. To address these multi-sectoral challenges, Marine Spatial Planning (MSP) has emerged as a critical governance framework, integrating ecological, social, and economic objectives into spatial decision-making (Depellegrin et al., 2024; Singh et al., 2025). While these global MSP approaches have been effectively supported by remote sensing and *in situ*-based planning, their application in Small Island Developing States (SIDS) remains constrained (Al-Nassar et al., 2019; Azzellino et al., 2019; Dhunny et al., 2019; Spijkerboer et al., 2020). In these contexts, the transition from theoretical resource mapping to practical implementation is uniquely hindered by extreme land-scarcity, intense dependence on marine ecosystems (e.g., tourism and fisheries), and fragmented spatial evidence (Díaz and Soares, 2021; Kim et al., 2016; Havea et al., 2024). Consequently, a transnational integrated assessment—one that embeds techno-economic wind modeling directly within an MSP framework—is not merely a technical exercise but a strategic necessity to navigate the unique trade-offs of the Caribbean seascape.

Within MSP and access permitting, the resolution of spatial conflict is a key focus. Marine spatial models often use GIS-based multi-criteria decision analysis (MCDA) to screen areas for offshore wind development – combining criteria such as wind speed, depth, proximity to grid, and exclusion zones (MPAs, coral reef buffers, seagrass beds, fisheries grounds) to identify preferred sites (Al-Nassar et al., 2019; Azzellino et al., 2019). Recent work has employed ensemble MCDAs and spatial clustering to make such planning more robust and equitable (Dhunny et al., 2019; Martinez and Iglesias, 2024; Spijkerboer et al., 2020). Likewise, frameworks have been proposed to evaluate ecosystem service trade-offs (e.g. wind compare to fisheries or tourism) and to identify low-conflict zones (Díaz and Soares, 2021). Empirical reviews of MSP measures indicate common resolutions such as spatial reservations, multi-use zones, ecosystem-based management and compensation schemes to mitigate conflicts (Kim et al., 2016). These insights demonstrate that any Caribbean offshore wind plan must systematically account for coral reef and seagrass habitat protections, MPA boundaries, shipping routes and traditional fishing areas, all of which impose constraints on suitable wind development zones.

In addition to resource availability and spatial conflicts, physical constraints such as water depth further influence offshore wind feasibility in the Caribbean. Much of the region is characterized by steep bathymetric gradients, limiting the applicability of fixed-bottom foundations to nearshore shallow waters (<50 m) (Shea and Ramgolam, 2019). Floating offshore wind technologies, while currently less mature, provide access to deeper waters and are expected to become increasingly cost-competitive in the coming decades (World Bank, 2019; Dutton et al., 2019). The coexistence of these two technological pathways introduces additional spatial trade-offs, particularly in relation to environmental sensitivity and marine use intensity.

To address these gaps, this study develops a spatially screening framework for offshore wind energy planning in Caribbean SIDS. The framework integrates remote sensing-derived wind resources, bathymetric data, and spatial layers representing marine environmental and socio-economic constraints within a GIS-based analytical approach. Specifically, the study aims to: (1) Map the spatial heterogeneity of 100m wind resources using high-resolution climatologies across the selected Caribbean SIDS. (2) Evaluate environmental and socio-economic trade-offs by constructing a Conflict Index based on ecologically-critical marine habitats. (3) Identify opportunity zones that align technical wind potential with specific depth constraints.

By linking offshore wind resource assessment with MSP, our study develops a transparent, reproducible screening framework specifically for data-limited and ecosystem-dependent contexts. Unlike global assessments that often overlook local socio-economic nuances, this research integrates technological foundation pathways (fixed vs. floating) directly into a conflict-proxy model. Moreover, this study provides the first harmonized, multi-national offshore wind assessment across twelve Caribbean SIDS, bridging the gap between fragmented national datasets and the need for basin-scale energy coordination. This research provides not only a localized evidence base for Caribbean policy development but also a scalable model for sustainable ocean governance in SIDS worldwide. This approach directly addresses the increasing global demand for spatially explicit, data-driven management in regions where planning capacity remains traditionally constrained.

2 Materials and methods

2.1 Study area

We defined the study domain as the marine jurisdictions of twelve Caribbean SIDS (Table 1), represented by EEZs, bathymetry and jurisdictions were mapped within a regional Caribbean context. The Gridded Marine Bathymetry Data are retrieved from GEBCO Seabed 2030 Project (2024) and extracted using the EEZ boundaries of the Caribbean Sea region, to generate a continuous wind speed surface across Caribbean jurisdictions (Figure 1).

2.2 Offshore wind resource data and preprocessing

We synthesized local Caribbean site data with raster collections to determine spatial wind resource gradients. The primary wind data source of this study are 100 m wind speed raster from Global Wind Atlas (Davis et al., 2023), offshore wind potential data from World Bank (2020) and coastal electricity grid infrastructures retrieved from Open Street Map (OSM) with a voltage above 52 kV. Wind speed at 100 m was selected because it aligns with standard hub-height approximations used in global and regional wind assessments and to maintain consistency with international offshore wind screening products. The Protected Areas, distribution of seagrasses and coral reefs in Caribbean are retrieved from UNEP World Database on Protected Areas (2026). We screened all raster datasets for potential data gaps along coastlines and tile-edge artifacts. Where multiple sources were integrated, we re-computed layer statistics post-mosaicking to maintain consistent range rendering across the regional ocean.

TABLE 1 List of Caribbean SIDS in study area.

Caribbean SIDS in research region	
Antigua and Barbuda	Barbados
Belize	Cuba
Dominica	Grenada
Guyana	Haiti
Jamaica	Saint Kitts and Nevis
Saint Vincent and the Grenadines	Trinidad and Tobago

2.3 Technical potential assessment

To analyze technology-conditioned offshore wind potential, we mapped spatial layers representing technical potential for fixed-bottom and floating foundations. These layers were treated as indicative "technical potential" surfaces that summarize feasible resource under assumed technology constraints (e.g., depth, distance, and technical exclusions as embedded in the source product). Fixed-bottom and floating datasets were processed consistently to maintain interpretability and avoid conflating the two technology classes. For mapping, fixed-bottom and floating potential were displayed using continuous graduated color-scheme, with class breaks shown in the legend to match the visual conventions used in regional marine spatial planning documents and to enable consistent cross-figure comparison (Rusu and Onea, 2019).

The fixed-bottom and floating "technical potential" layers were derived from the World Bank/ESMAP offshore wind technical potential framework (2020), which applies consistent global screening criteria to enable cross-country comparability. In this framework, technically viable areas are defined as offshore locations within 200 km of shore and with annual mean 100 m wind speeds exceeding 7 m s^{-1}. The 50 m depth threshold was specifically adopted to maintain alignment with the World Bank/ESMAP offshore wind technical potential framework in Caribbean region (2020), which provides a harmonized global standard for cross-country comparability in emerging markets. Foundation class is assigned based on bathymetry: floating potential is restricted to waters between 50 m and 1,000 m, while fixed-bottom potential is restricted to waters shallower than 50 m. We explicitly report these thresholds because they condition the partitioning of potential between fixed and floating classes and therefore underpin valid cross-jurisdiction comparisons. These depth limits reflect current commercial and pre-feasibility screening conventions rather than a hard physical constraint; deeper waters (>1,000 m) may become relevant under future technology innovation, but are excluded here to maintain consistency with the underlying technical potential dataset and its assumptions.

2.4 Country-level wind potential compilation

Variables representing technical potential for fixed-bottom and floating foundations (GW) were extracted. Country names were standardized using the "Territory" field in the source table, and the analysis was restricted to Caribbean SIDS with available wind potential statistics. We generated comparative bar charts that display fixed-bottom and floating technical potential side-by-side for each country. Countries were ordered by total technical potential (fixed + floating) to facilitate cross-country comparison and to highlight the extent to which national potential is driven primarily by one foundation class. This national-level synthesis provides a complementary perspective to the spatial potential maps by summarizing scale differences across SIDS and clarifying the relative contribution of fixed-bottom versus floating potential.

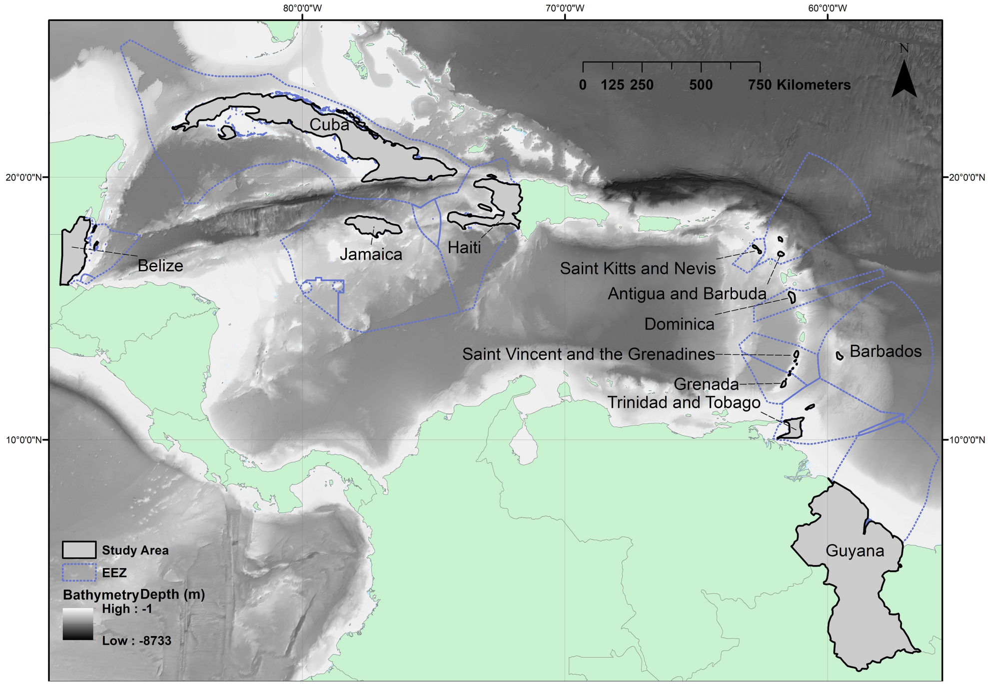

FIGURE 1
Geographical scope and maritime jurisdictional boundaries of the studied Caribbean SIDS.

2.5 Marine planning constraints and conflict index construction

To represent MSP-relevant constraints, we assembled spatial layers capturing protected and sensitive marine features, including (1) marine protected areas (MPAs) retrieved from UNEP-WCMC-The World Database on Protected Areas (WDPA) and (2) shallow-water habitats (coral reefs and seagrass) retrieved from Global Distribution of UNEP-WCMC Coral Reefs and seagrass datasets. These constraints were selected not only for their ecological sensitivity but because they represent the primary natural capital sustaining the tourism and artisanal fisheries of Caribbean SIDS (Dominković et al., 2018; Scobie., 2016). Where constraint layers were provided as vector polygons, they were converted to raster format at a consistent analysis resolution. Each constraint layer was encoded as a binary surface (presence = 1, absence = 0) to produce a transparent, conservative representation of potential environmental constraints. We then constructed a conflict index as the unweighted additive sum of the binary constraint rasters:

$$CI(x,y) = \sum_{\{k=1\}}^{K} C_{k(x,y)}$$

Where $C_{k(x,y)}$ is the binary raster for constraint K at grid cell (x, y), and K is the number of constraint layers included. Under this definition, higher values of CI indicate a greater concentration of mapped constraints within the same location. The index is intended as an early-stage screening proxy for potential planning trade-offs, rather than a definitive measure of regulatory exclusion or social conflict.

Prior to raster algebra, all raster used in the conflict index were aligned to a common grid (extent, cell size, and origin) to avoid misalignment artifacts with this principle adapted from Martinez and Iglesias, 2022b. When datasets originated as separate national tiles, those statistic points were divided into a single regional raster per layer before analysis. Where required, we used a consistent masking method corresponding to the regional EEZ domain to ensure that index values were computed over comparable off-shore space.

2.6 Wind–conflict screening and quadrant classification

To further incorporate wind resources and constraints into a planning-relevant synthesis, we developed a weighting methodology combining wind speed and other marine users' conflict index three-dimensional wind–conflict typology (Table 2). In the baseline implementation, "high" and "low" conditions are defined using median values of the wind surface W and the conflict index CI within the analysis domain, receiving a balanced partition that is appropriate for cross-jurisdictional comparison and communication in early-stage MSP.

- High wind: $W(x,y) > median(W)$
- Low wind: $W(x,y) \leq median(W)$
- High conflict: $CI(x,y) > median(CI)$
- Low conflict: $CI(x,y) \leq median(CI)$

Moreover, median splits may not coincide with decision-grade thresholds. Offshore wind viability is often framed using minimum wind-speed (or power-density) requirements, while regulatory constraints may involve hard exclusions (e.g., legally designated no-go areas) rather than distribution-based cutoffs. To address this,

TABLE 2 Multi-criteria framework for offshore wind potential categorization.

Zone category	Definition & logic	Specific spatial criteria & constraints
Opportunity	High wind/Low conflict	Wind speed ≥ 8.0 m s^{-1} at 100 m AND $CI = 0$ (Located outside all exclusion areas).
Trade-off	High wind/High conflict	Wind speed ≥ 8.0 m s^{-1} at 100 m AND $CI \geq 1$ (Overlapping with at least one restrictive layer).
Low priority	Low wind/Low conflict	Wind speed ≥ 2.0 m s^{-1} at 100 m and< 8.0 m s^{-1} at 100 m AND $CI = 0$ (Located in non-restricted areas).
Avoid	Low wind/High conflict	Wind speed ≥ 2.0 m s^{-1} at 100 m and< 8.0 m s^{-1} at 100 m AND $CI \geq 1$ (Overlapping with least one restrictive layer; highest development resistance).

we implement and report alternative, policy- and feasibility-informed thresholding schemes in sensitivity analyses. Specifically, we evaluate (1) a wind viability cutoff $W^{\backslash *}$ ($W^{\backslash *}$=8 m s^{-1} at 100 m), (2) a constraint cutoff $CI^{\backslash *}$ that reflects regulatory or conservation priorities and (3) key ecological features like marine protected areas and large habitat patches were treated as absolute exclusion zones. Bathymetric data was used to segment technical potential into Fixed-bottom (0–50 m) and Floating (50–1000 m) foundation classes. Areas exceeding 1000 m in depth were excluded as technically infeasible. Under this framework, the four classes are defined analogously, replacing medians with $W^{\backslash *}$ and $CI^{\backslash *}$, and we examine the persistence of "opportunity" and "trade-off" patterns across threshold choices.

$$Category = \begin{cases} \text{Opportunity}, & W(x) \geq T_W \wedge CI(x) < T_C \\ \text{Trade}-\text{off}, & W(x) \geq T_W \wedge CI(x) \geq T_C \\ \text{Low priority}, & W(x) < T_W \wedge CI(x) < T_C \\ \text{Avoid}, & W(x) < T_W \wedge CI(x) \geq T_C \end{cases}$$

$W(x)$. is the wind speed at grid cell x, $CI(x)$ is the calculated Conflict Index, T_W represents the wind viability threshold (8.0 m s^{-1} at 100 m hub height), and T_C represents the critical conflict index threshold ($T_C = 1$, representing the presence of at least one environmental constraint).)While the additive sum $CI(x, y) = \sum C_k(x, y)$ quantifies the multi-layer constraint intensity of conflicts, a binary thresholding scheme $CI = 0$ *vs* $CI \geq 1$ was implemented in the final screening matrix (Table 2) to conservatively flag any grid cell containing mapped environmental sensitivities.

This screening is designed to support early-stage MSP discussions by identifying where strong wind resources coincide with relatively low mapped constraints (candidate opportunity areas) and where potential development would likely face substantive planning trade-offs (Martinez and Iglesias, 2024). In this research we emphasize that these classes do not represent formal suitability or exclusion; rather, they could provide a transparent synthesis for prioritization and for targeting follow-up analyses (e.g., stakeholder consultation, higher-resolution ecological data, shipping and fisheries governance, grid connection feasibility, and cost modeling).

2.7 Visualization

All cartographic outputs were produced in ArcMap (v10.2) modelled using Python 3.12. We used consistent base layers (EEZ boundaries, land boundaries, and marine bathymetry) to ensure visual comparability across figures. Wind and potential layers were displayed using continuous color-scheme, and the wind–conflict screening map was rendered as a categorical raster with a four-class legend designed to communicate marine planning implications (opportunity/trade-off/avoid/low priority). Insets adopted where necessary to enhance legibility for smaller island groups and fragmented EEZ geometries.

3 Results

The Caribbean SIDS region presents a highly fragmented archipelagic–continental setting in which national EEZs form a mosaic of adjacent jurisdictions embedded within a strongly heterogeneous seafloor (Figure 1). Bathymetry indicates a sharp contrast between (1) broad, relatively shallow banks and shelves around parts of the northern Caribbean (For instance, Bahamas platform and shelf-influenced margins), and (2) steep bathymetric gradients and deep basins across much of the central basin. This jurisdiction–bathymetry coupling is a first-order constraint for offshore wind siting because foundation feasibility and cable routing are conditioned by depth and seabed slope, while governance and permitting are mediated by EEZ boundaries and trans-boundary adjacency.

The 100 m wind-speed surface exhibits a significant spatial gradient across the Caribbean domain, with higher winds concentrated in a broad corridor from the south–southeastern portion of the mapped area and lower winds prevailing across more sheltered or inland-sea portions of the basin (Figure 2). The mapped wind speeds range from ~2.79 to ~12.59 m s^{-1} in the displayed extent, indicating substantial intra-regional variability relevant to energy yield and project bankability. More importantly, the highest-wind areas are not uniformly distributed along coastlines; instead, they form coherent offshore "belts" and localized hotspots, implying that national opportunity space is likely to be spatially clustered rather than evenly available across national EEZ.

The spatial distribution of technical potential is characterized by concentration within distinct coastal corridors, a pattern driven primarily by bathymetric thresholds (Figure 3). Bathymetry dictates a clear partitioning of space: fixed-bottom potential is restricted to near-shore shelf areas, while floating technology significantly expands the developable envelope into deeper EEZ waters. This intra-jurisdictional variability reinforces the need for sub-regional spatial prioritization over national-level aggregates.

National-level assessments reveal significant heterogeneity across the twelve SIDS (Figure 4). A dominant regional trend is the prevalence of floating potential over fixed-bottom foundations, driven by the steep bathymetry identified in the regional context (Figure 1). The varying balance between these technology classes across jurisdictions suggests that foundation choice is a primary

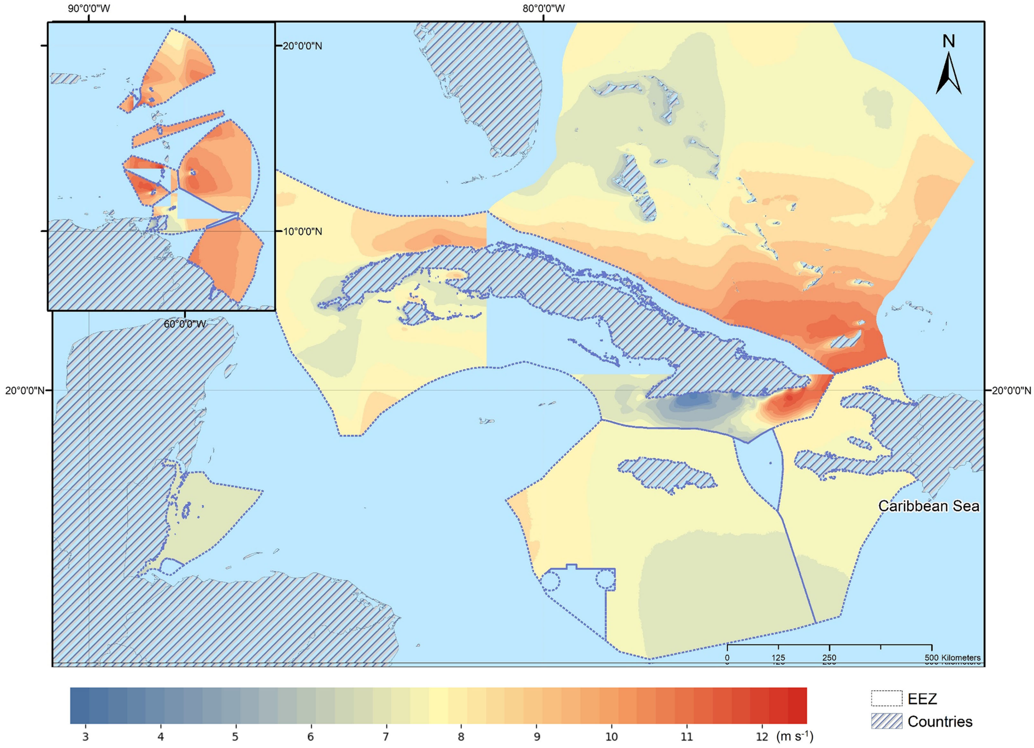

FIGURE 2
Offshore wind power at 100m in study area.

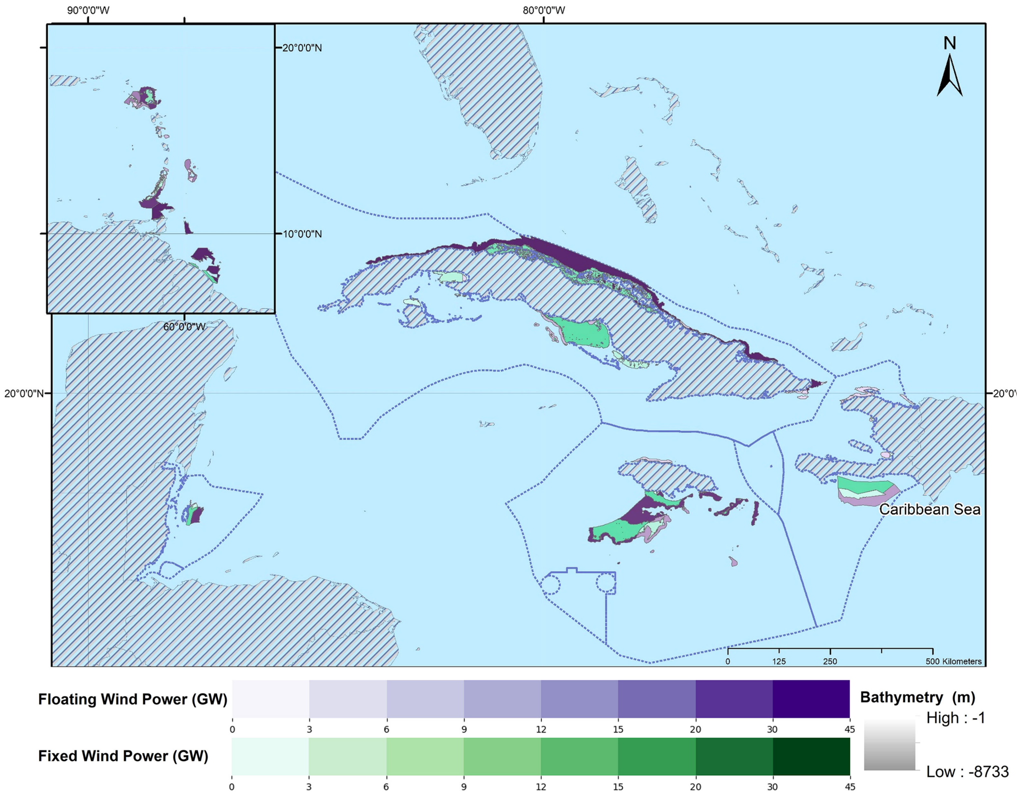

FIGURE 3
Bathymetry-driven heterogeneity in offshore wind technical potential. The spatial distribution highlights the depth-mediated partitioning between fixed-bottom and floating foundation pathways across the Caribbean seascapes.

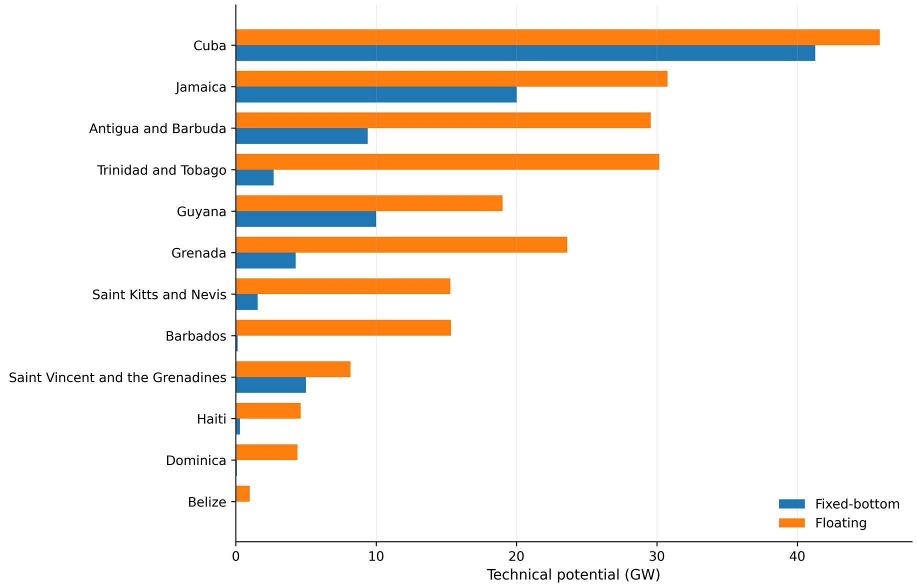

FIGURE 4
National-level offshore wind potential across 12 Caribbean SIDS.

strategic determinant for offshore wind roadmaps in the Caribbean, rather than a secondary technical detail.

The wind–conflict typology (Figure 5) categorizes the maritime space into four planning-relevant zones. 'Opportunity' areas emerge where high wind speeds coincide with minimal ecological and use overlaps. The screening results indicate that high-wind corridors are often fragmented into discrete 'opportunity' and 'trade-off' segments, illustrating that resource abundance alone does not guarantee capacity for development. This classification provides a transparent basis for targeting subsequent stakeholder engagement in high-value but contested waters.

To provide an in-depth quantitative basis for marine spatial planning, a cell-based statistical analysis was conducted on the 15,279 grid cells within the study domain (Table 3; Figure 5). The

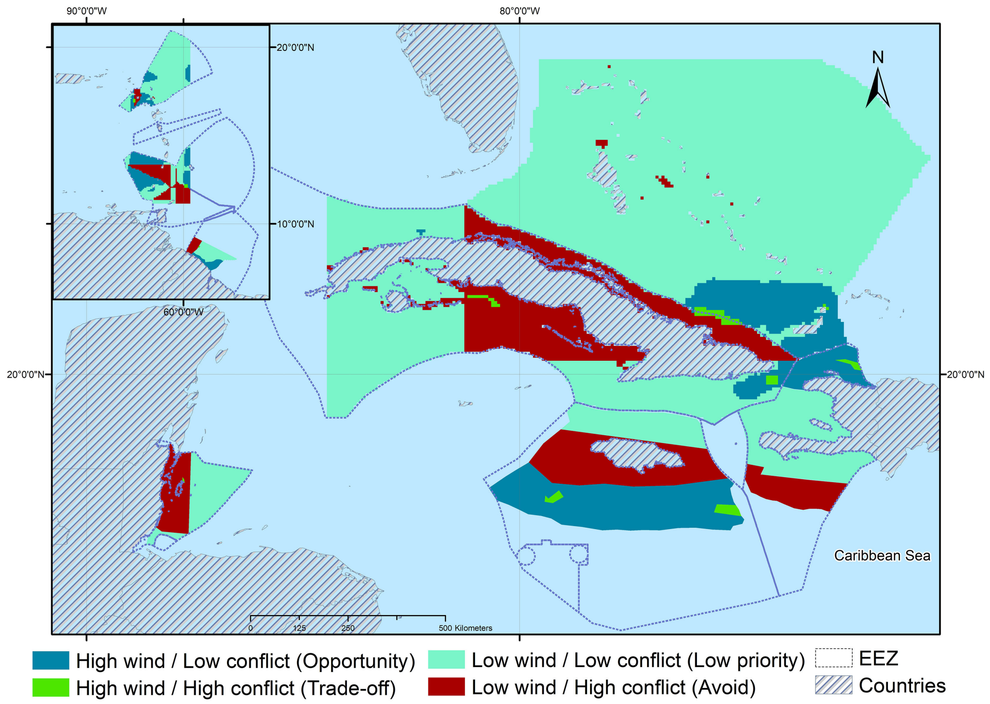

FIGURE 5
Spatial typology of offshore wind and multi-sectoral maritime conflicts.

screening framework reveals that 'Opportunity' zones (high wind/low conflict) constitute 10.03% (1,533 cells) of the total maritime space. These areas represent 'low-regret' corridors where superior wind resources align with low ecological and jurisdictional constraints, making them prime candidates for early-stage feasibility studies.

The 'Trade-off' zones (high wind/high conflict) occupy a remarkably small fraction of the region (0.36%, 56 cells). This indicates that the most productive wind resources across the Caribbean SIDS are largely spatially decoupled from currently mapped marine protected areas (MPAs) and sensitive habitats (coral reefs and seagrass). Conversely, 'Avoid' zones (low wind/high conflict) account for 14.88% of the area, primarily clustered in nearshore environments where ecological sensitivity is highest but wind speeds are lower due to coastal sheltering. The vast majority of the analyzed EEZ space (74.71%) is classified as 'Low Priority', emphasizing that while the technical potential is vast at a country level, the actionable planning space is highly concentrated. These findings underscore the necessity of a sub-regional, MSP-oriented approach to prioritize the identified<10% opportunity corridors for sustainable energy transition.

4 Discussion

Our results underscore a core planning reality for Caribbean SIDS: offshore wind opportunity is present at basin scale, yet the fraction of developable resource is strongly mediated by bathymetry and jurisdictional geometry. The sharp shelf-to-basin transitions that characterize much of the region compress fixed-bottom feasibility into narrow nearshore bands, while large portions of EEZ space quickly shift into depths where floating technology becomes the dominant pathway. This depth-mediated partitioning provides a concrete explanation for the systematic "floating premium" observed in the country-level technical potential comparisons (Figure 4): in many SIDS settings (Dornan and Shah, 2016; Lucas et al., 2017; Kuang et al., 2016), the wind resource might be adequate, but the seafloor constrains which foundation class could still realistically access the wind resource. Because fixed-bottom and floating potentials are computed under distinct bathymetric windows (<50 m vs 50–1,000 m), the observed "floating-dominant" pattern across many Caribbean SIDS should be interpreted as a depth-conditioned feasibility signal rather than a pure wind-resource effect.

Although a single "economically viable" wind-speed threshold (e.g., a minimum hub-height wind speed) is sometimes used in project screening, applying such a universal cut-off across Caribbean SIDS can be misleading at the regional scale because (1) turbine technology, array losses, and wake assumptions differ across assessments; (2) the same wind speed can imply different capacity factors under different turbulence and stability regimes; and (3) early-stage MSP questions typically require relative prioritization within each jurisdiction rather than a binary bankability decision. We therefore adopted a median split of $W(x)$ and $C(x)$ to yield a balanced partition that is distribution-robust, comparable across highly heterogeneous EEZ geometries, and explicitly aligned with the objective of producing a communicable screening typology rather than a site bankability filter. Importantly, this choice does not imply that cells above the median are economically viable, nor that cells below the median are unviable; it only indicates relative position within the regional surface.

A practical implication for marine planning is that offshore wind should be treated less as a single-sector expansion issue and more as a technology-conditioned zoning challenge. In Caribbean where fixed-bottom options are spatially limited, early MSP dialogues could more productively focus on (1) identifying candidate floating corridors compatible with existing marine uses and (2) the enabling infrastructure and permitting steps required for deeper-water deployment. Conversely, in shelf-rich settings where fixed-bottom potential is extensive, MSP could prioritize delineating nearshore development zones that minimize conflicts and optimize cable routing and construction logistics (Martinez and Iglesias, 2022a; Zheng et al., 2016).

The divergence between country-level technical potential and the mapped distribution of potential highlights an important interpretive caution: national aggregates cannot simply be used to predict the spatial concentration of opportunity. Even where the overall technical potential of a country is substantial, the resource is often clustered into specific coastal segments or offshore belts (Liu et al., 2018; Leal Filho et al., 2022). For MSP, the actionable unit is therefore not the country total per se but the sub-EEZ opportunity structure—the size, continuity, and proximity of candidate zones relative to ports, grid nodes, and sensitive habitats (Wickliffe et al., 2024).

This observation also has high relevance with the energy system strategy. SIDS are typically small but fragile, and large offshore wind projects may exceed near-term absorption capacity. Where opportunity is spatially clustered, planners could more readily assess whether a small number of candidate corridors could support phased buildout (e.g., single or multiple projects) without triggering extensive multi-use conflicts across the entire EEZ (Petzold and Magnan, 2019). In this context, mapping of marine user-conflicts in

TABLE 3 Distribution of offshore wind planning categories based on cell-based spatial quantification.

Planning category	Cell count	Percentage (%)	Planning implication
High wind/Low conflict (Opportunity)	1,533	10.03%	Immediate priority for feasibility studies
High wind/High conflict (Trade-off)	56	0.36%	Requires targeted stakeholder negotiation
Low wind/Low conflict (Low priority)	11,416	74.71%	Secondary consideration for long-term expansion
Low wind/High conflict (Avoid)	2,274	14.88%	Strict exclusion for biodiversity conservation
Total	15,279	–	–

SIDS provides an operational bridge between "technical potential" and "implementable potential."

We define the conflict index as a proxy for screening constraints, noting it identifies potential planning friction rather than establishing absolute regulatory exclusion (Klöck and Nunn, 2019). While direct monetary valuation is omitted, this framework treats ecological integrity as a key socio-economic proxy. In the Caribbean, coral reefs and seagrass beds are the primary natural capital for tourism and artisanal fisheries—sectors forming the backbone of national GDPs. By identifying 'low-conflict' zones relative to these habitats, the framework inherently minimizes potential economic opportunity costs and reduces the risk of administrative delays or compensation claims.

The classification of "High Conflict" versus "Low Conflict" zones in this study is rooted in the intersection of technical feasibility and the preservation of essential marine ecosystems. The primary constraints identified—MPAs, coral reefs, and seagrass—represent the "avoidance" criteria due to their critical role in sustaining Caribbean national GDPs through tourism and fisheries.

A key finding is the spatial decoupling of wind resources and ecological constraints. High-conflict "Trade-off" zones account for only 0.36% of the analyzed cells, occurring only where the Caribbean Low-Level Jet's high-wind corridor directly overlaps with mapped sensitive habitats or protected boundaries. In contrast, "Opportunity" zones (10.03%) represent areas where the steep bathymetry of the Caribbean allows for high-yield wind development (particularly floating) in deeper waters that are naturally distant from the ecologically dense nearshore banks.

Consequently, a zone is considered "High Conflict" not just due to the presence of a single constraint, but as development within these clusters triggers complex multi-sectoral trade-offs between renewable energy imperatives, biodiversity conservation, and socio-economic dependencies. This distinction allows planners to transition from broad national targets to sub-EEZ prioritizations, focusing on "low-regret" corridors where ecological friction is minimized.

However, users and policy-makers in SIDS should note that constraint layers (MPAs, habitats) vary in resolution and completeness across jurisdictions; unmapped areas are not necessarily "no-conflict" zones. Furthermore, the index does not capture dynamic factors such as shipping density, submarine cables, or site-specific geotechnical conditions. These considerations motivate a staged planning workflow, where this initial screening prioritizes candidate areas for subsequent high-resolution assessments and deep stakeholder engagement (Sokoloski et al., 2018).

The median-threshold Wind and other user conflict classification provides a communicable first-pass decision support layer by translating heterogeneous datasets into four interpretable planning classes. However, it should be interpreted as a screening tool rather than a definitive siting recommendation. Two critical considerations matter in this study:

First, the conflict index is constructed from layers that have different epistemic model logic—formal protections (MPAs), ecological distributions (coral reefs, seagrasses), and activity proxies (fishing effort). While aggregating heterogeneous spatial layers into a unified index is an effective strategy for early-stage prioritization, this process inherently compresses diverse normative and legal constraints into a singular numerical scale (Kerr et al., 2015). In practice, the regulatory weight of Marine Protected Areas (MPAs) varies significantly across jurisdictions; they may function as absolute 'no-go' zones in some contexts while serving as negotiable zoning categories in others. Furthermore, habitat datasets often exhibit discrepancies in spatial completeness and temporal relevance. Consequently, the 'trade-off' classification should be interpreted as a critical signal for targeted due diligence and multi-sectoral negotiation rather than a definitive spatial exclusion.

Second, thresholding by the median produces a balanced quadrant partition that is robust for communication, but it is not invariant to data resolution and distribution. In cases where wind or conflict distributions are highly skewed, alternative thresholds (e.g., quantiles or policy-defined cut-offs) might better align with planning needs. A straightforward extension is to compare the median-based typology with quantile-based or "minimum viable wind" thresholds and report sensitivity of mapped opportunity shares across EEZs (Ghigo et al., 2020; Satir et al., 2018).

Despite being an initial screening exercise, the combined results suggest several governance-relevant insights for Caribbean MSP.

1. Prioritizing 'low-regret' opportunity areas for initial feasibility studies could reduce early-stage social and ecological friction, because they are more likely to receive lower social and ecological friction (Figure 5). This does not eliminate the need for EIA-level studies, but it improves the efficiency of planning effort (Scobie, 2016).
2. Anticipating where negotiation is unavoidable, Trade-off zones is capable to identify where the energy yield incentive is strong enough that negotiation may be warranted. These are the candidate areas where co-location design, seasonal restrictions, compensation mechanisms, or spatial reconfiguration might be considered to reconcile uses.
3. The strong contrast between fixed-bottom and floating envelopes implies that MSP discussions should explicitly incorporate technology choice. Floating options may shift development into deeper areas that either reduce or exacerbate conflict depending on the spatial distribution of uses and habitats.
4. The juxtaposition of adjacent EEZs within a shared basin-scale wind regime points to opportunities for regional learning and potentially shared infrastructure planning (e.g., port upgrades, supply chain hubs, common environmental baselines), particularly for SIDS that individually face limited project pipelines (Wickliffe et al., 2024; Wolf et al., 2016).

Our results indicate that offshore wind technology pathway is not a secondary engineering detail but a primary determinant of where offshore wind can plausibly be developed in most Caribbean SIDS. The country-level comparison of technical potential shows that floating foundations frequently represent the dominant share of offshore wind potential, consistent with the regional bathymetric context and the spatial separation of fixed-bottom and floating envelopes. In many small island settings, depth increases rapidly beyond nearshore banks, compressing fixed-bottom feasibility into narrow coastal corridors while shifting most of the remaining opportunity space into depths where floating platforms are required (Atteridge and Savvidou, 2019). This depth-mediated partitioning has direct MSP implications. Fixed-bottom candidates tend to cluster closer to shore, where overlap with nearshore fisheries, tourism uses, coastal navigation, and sensitive habitats is commonly greatest. Floating candidates, by contrast, expand the feasible envelope into deeper waters that may reduce some nearshore conflicts but introduce different spatial interactions, including larger mooring and human footprints, dynamic cable corridors, and potential navigation considerations associated with tow-out, installation and maintenance logistics (Rogers et al., 2019). Therefore, the same windy corridor can present fundamentally different trade-off profiles depending on whether the development concept is fixed-bottom or floating—even before socio-economic considerations are introduced. This underscores the need for MSP processes to explicitly separate technology classes in early zoning and to treat "opportunity space" as technology-conditioned rather than generic.

Benthic Habitats and fishing effort proxies vary in observation period and may not represent current or future conditions, especially under climate-driven ecosystem shifts or evolving fisheries patterns. Similarly, wind resource layers are modeled climatologies rather than measurement-based project site assessments (Meschede et al., 2022; Scandurra et al., 2018). The workflow requires raster alignment, resampling, and masking across inputs. While this is standard practice, it introduces interpolation and edge effects. Because our aim is screening rather than micro-siting, we prioritize interpretability and regional consistency, but we emphasize that project development would require higher-resolution metocean data and site-specific geotechnical assessments. Our composite index is intentionally simple to avoid over-fitting assumptions, but it does not encode legal hierarchies, enforcement intensity, seasonal dynamics, or cultural values. The index is best understood as a "pressure overlay" rather than an impact assessment.

5 Conclusion

Caribbean SIDS face several challenge of rising energy needs and intensifying spatial competition in coastal seas, yet the region's offshore wind opportunity remains unevenly translated into planning-relevant options. Here we map basin-scale wind resources and technology-conditioned technical potential, showing that bathymetry sharply constrains fixed-bottom feasibility while floating platforms substantially expand developable space across many EEZs. Moving beyond national aggregates, we demonstrate that opportunity is spatially clustered within jurisdictions, making sub-regional EEZ prioritization essential for actionable marine spatial planning. By integrating wind layers with mapped ecological and use constraints into a transparent offshore wind power and other users conflict typology, we identify where "low-regret" opportunities are most plausible and where high resource value implies unavoidable trade-offs. Together, these results provide a transferable screening framework to accelerate evidence-based offshore wind zoning in data-limited island contexts and to target the next round of stakeholder engagement and site-specific assessment.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

XW: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Resources, Supervision. XT: Funding acquisition, Project administration, Resources, Writing – review & editing, Supervision. DJ: Funding acquisition, Project administration, Resources, Writing – review & editing. XX: Data curation, Software, Validation, Writing – review & editing. QZ: Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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