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Assessing the impacts of spatial constraints on the techno-economic potential of offshore wind energy: A case study of the Caribbean Sea, Colombia

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ABSTRACT

Offshore wind resources may be affected by multiple constraints, including technical, environmental and socio-economic factors. The available area for wind energy development can be significantly reduced if these constraints are treated as strict exclusion zones, affecting the potential energy output, the feasibility of project development and in some cases increasing the cost of deployment. This study introduces a framework to evaluate the impact of spatial constraints on the techno-economic potential of offshore wind energy. It demonstrates its application through a case study of the Caribbean Sea in Colombia, a tropical region that unlike most tropical areas, is exceptionally windy and offers promising offshore wind opportunities.

We formulated three scenarios with different levels of spatial restrictions and potential offshore activity co-existence, and estimated available area, technical potential, and deployment costs per scenario. Annual energy production maps were generated using wind speeds from ERA5 reanalysis data and a 15 MW IEA reference wind turbine. We also estimated a spatially explicit levelised cost of energy (LCOE) per scenario, considering water depth and distance to shore as key variables.

The results show that up to 105 TWh/year could be generated at an LCOE below $100/MWh, exceeding 88% of Colombia's projected electricity demand by 2039. However, constraints reduce the viable areas for development, leading to a 46% decline in energy generation potential between the least and most space-restrictive scenarios. This framework provides a replicable blueprint for guiding offshore wind assessments in emerging economies, where customised studies are essential for policy decisions, marine spatial planning and infrastructure investment.

1. Introduction

Coastal regions are experiencing rapid urbanisation, population growth, and the concentration of energy-intensive industries and infrastructure along coastlines [1,2]. This demographic and economic expansion is expected to increase energy demand. In this sense, offshore wind energy represents an opportunity to supply clean energy to these regions, diversify economies reliant on fossil fuel extraction, stimulate new employment and industrial activities across the offshore wind value chain, and attract foreign investment. However, as an emerging technology, offshore wind development remains costly, and deployment is mainly concentrated in developed countries. Furthermore, most techno-economic assessments of offshore wind potential have concentrated on high-income regions, resulting in a limited understanding of opportunities and challenges in developing countries [3].

While global studies (e.g., [4–7]) are useful for identifying high-potential regions, large-scale assessments often rely on generalised spatial constraints that do not account for region-specific complexities. These assumptions may overlook technical, environmental and socio-economic conditions, reducing their accuracy and applicability for regional and national planning. Given the significant potential of

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Nomenclature

AEP	Annual Energy Production
CAPEX	Capital Expenses
CF	Capacity Factor
CRF	Capital Recovery Factor
GIS	Geographic Information Systems
Do	Rotor Diameter
DR	Discount rate
EEZ	Exclusive Economic Zone
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LCOE	Levelised Cost of Electricity
LT	Lifetime
O&G	Oil and Gas
OPEX	Operational Expenses
OWF	Offshore Wind Farm
OWRM	Offshore Wind Road Map
PWD	Power Wind Density

focused on developing economies to ensure that offshore wind energy strategies and plans are grounded in the specific conditions of each region.

The Caribbean region in Colombia is of particular interest. This region is an industrial and commercial hub, occupying a strategic geographic position connecting the country to the global market (See Fig. 1). The projected energy demand for 2039 in this region is the highest in the country, reaching 35,363 GWh, compared to 22,489 GWh and 13,027 GWh for the Oriente and Nordeste regions, respectively [9]. Additionally, Guajira (one of the region's departments) has the lowest energy coverage, approximately 60%, compared to a national average of 96% [10]. In contrast, the potential for offshore wind energy in that region seems to be high. In the Global Wind Atlas [11], the area is characterised by excellent wind conditions, with annual mean wind speeds above 9 m/s (at 150 m hub height) over most of the area. This indicates an opportunity to develop offshore wind energy to supply electricity to the residential and industrial sectors in the Caribbean region and potentially to the country.

While wind speed is a critical parameter for estimating the technical potential of wind energy, the estimation of offshore wind resources and the deployment of this technology are influenced by multiple additional constraints, including technical, environmental and socio-economic

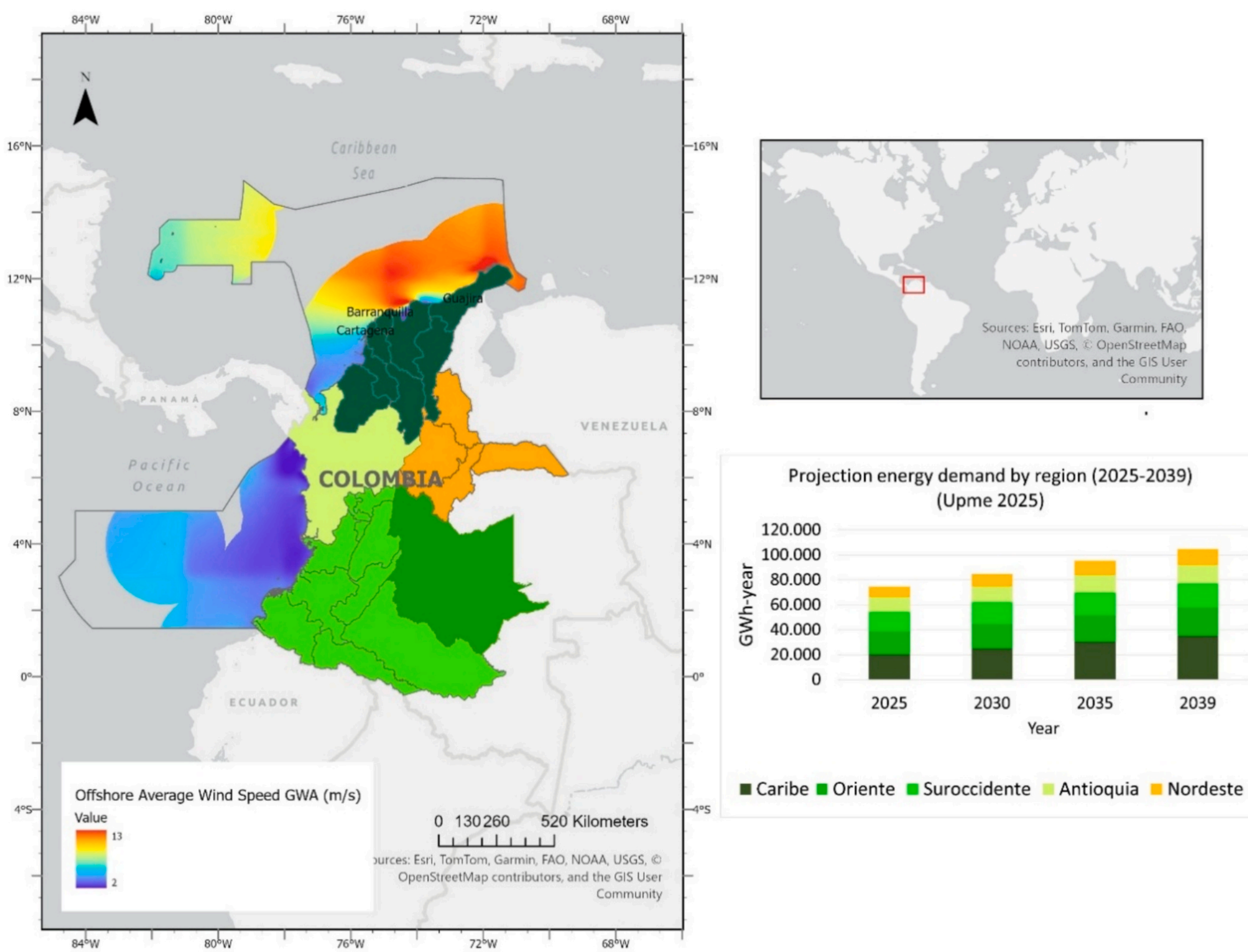


Fig. 1. Location of the study area. The projected energy demand by region is based on [9].

offshore wind energy to support sustainable energy transitions in developing countries [3,8], it is relevant to conduct regional assessments factors. The available area for wind energy development can be significantly reduced if these constraints are treated as rigid exclusion zones, posing challenges for marine spatial planning, affecting the potential energy output, the feasibility of offshore wind farm (OWF) projects and in some cases increasing the cost of deployment.

Existing studies evaluating the wind energy potential of the Caribbean Sea in Colombia exhibit wide variability in the types of constraints, scale of analysis (from regional to local), and spatial and temporal resolutions of datasets used. For example, Franco [12] carried out a regional assessment of the Caribbean Sea, considering natural parks and a water depth limit of 60 m as the only constraints. They used reanalysis data from North American Regional Reanalysis (NARR) with a 3-hour temporal resolution from 1979 to 2013 and a spatial resolution of 32.4 km. This study highlights the locations with the highest potential for energy generation based on average wind speeds but does not quantify the potential energy generation.

Carvajal-Romo et al. [13] focused on a local scale and assessed the wind energy potential for onshore and offshore Guajira. The study estimated a combined potential of approximately 996 TWh per year, considering 100% use of the department's land and sea area. This study did not incorporate key constraints such as bathymetry, environmentally protected areas, traditional offshore activities, or distance to the coastline. The study references wind speeds from [14,15], but the datasets used in the energy generation evaluation are not specified.

Ruiz et al. [16] used high-resolution 10-minute wind data from 13 meteorological stations along the Caribbean coastline of Colombia, with records spanning between one and six years. The dataset is compared with ERA5 reanalysis data. The Wind Power Density (WPD) and Annual Energy Production (AEP) at each station are calculated using both observational and modelled sources, revealing that the stations with the highest WPD and AEP values are found in La Guajira. Although the temporal resolution is high, the limited spatial resolution (restricted to 13 stations) introduces limitations when assessing the full wind energy potential across the region, as it may not adequately capture localised wind patterns and offshore variability.

The Offshore Wind Road Map (OWRM) for Colombia [17] evaluated wind energy potential in the Caribbean offshore (regional scale) and estimated a potential installed capacity of 50 GW using the wind speed data from the Global Wind Atlas (GWA) [11]. The study included some restrictions such as annual average wind speeds below 7 m/s, water depths exceeding 1,250 m and legally protected environmental areas. This study also outlined several constraints, but they were not incorporated into resource estimations. Notably, some exploratory zones identified by the study overlap with environmentally sensitive areas or do not account for buffer zones along the coastline, raising questions about the feasibility of project development in these locations.

The current variability in the scale of analysis, constraint selection, and data resolution across studies constitutes a knowledge gap for the Caribbean region. It limits the consistent classification of wind resources (e.g., theoretical, technical or economic potentials) and diminishes the reliability of such assessments for informing policy-making and investment decisions. Moreover, existing studies in the Colombian Caribbean Sea do not examine how varying spatial management strategies may impact offshore wind energy potential.

An additional knowledge gap for the study area relates to the economic analysis of offshore wind energy and the absence of spatially explicit evaluations. The LCOE of offshore wind power is affected by site-specific factors such as wind speed, water depth and proximity to onshore connection. A global assessment of LCOE from offshore wind [18] presents a spatially resolved LCOE, in which wind resources, bathymetry and distance to the coast are key variables in the model cost. However, as noted above, such global assessments fail to capture regional factors, limiting their applicability for specific regions.

A comprehensive economic assessment for the Caribbean offshore in Colombia is presented in the OWRM. [17]. This study includes low and high-deployment cases based on national energy plan projections. However, the study does not assess offshore wind energy LCOE in a spatially explicit manner nor provide supply cost curves, which limits its ability to capture location-specific cost variations and assess what share of the technical potential could be developed competitively.

To approach the aforementioned knowledge gaps, this paper proposes a region-specific methodological framework for assessing the techno-economic potential of wind energy in the Caribbean Sea, in Colombia. To address the first gap and ensure that the entire region is analysed with the same constraint criteria, the country's exclusive economic zone (EEZ) was selected and technical, environmental and socio-economic constraints were mapped. These constraints were categorised as either hard or soft, based on the degree of flexibility they allow with respect to the technical feasibility or regulatory compliance. Three scenarios were formulated with varying levels of spatial restrictions and potential coexistence of offshore activity. Finally, the available area for offshore wind energy deployment for each scenario was estimated.

To address the second gap, the spatially explicit techno-economic potential was assessed. Wind speed data from the ERA5 reanalysis data [19] and a 15 MW IEA reference wind turbine [20] were used to estimate the capacity factor and annual energy production (AEP) maps. The cost structure was developed based on recent literature, where water depth, distance to onshore connection, and turbine rating are the key variables influencing the CAPEX and OPEX components. Finally, multi-scenario supply curves were generated to understand the impact of various space management options and financial parameters on wind energy potential.

Our study is novel in the following aspects:

i) Regionalisation and refinement of spatial constraints that are highly aggregated or absent in global studies. These include the differentiation of multiple categories of environmentally sensitive areas specific to the Colombian context, the inclusion of both artisanal and industrial fisheries, and the consideration of existing offshore infrastructure (e.g., oil and gas infrastructure).
ii) The formulation and comparison of three spatial planning scenarios, which explore trade-offs between competing marine uses under alternative constraint assumptions and go beyond a single "static" potential estimate commonly reported in global assessments. This scenario-based approach aids in the anticipation of potential conflicts with environmental conservation, oil and gas activities, shipping and fishing and also allows us to quantify how planning choices influence techno-economic outcomes.
iii) Given the lack of spatially explicit techno-economic studies in developing countries and in particular for the study area, and considering that the first stage in offshore wind planning involves identifying technically feasible and economically viable areas, our study focuses on establishing a robust and transparent spatially detailed techno-economic baseline. Our analysis identifies high-potential areas, providing insights to inform emerging policies, zoning, and planning aligned with national energy goals. Our results are particularly timely, as policy and regulatory frameworks are currently being discussed in the country.
iv) Finally, when comparing the results of our study with those obtained by extracting Colombia as a subset from global studies, we observe significant differences in available capacity and cost estimates. These discrepancies arise precisely from the simplifications and generalised assumptions required in global analyses and reinforce the need for regional-scale assessments to better align offshore wind energy strategies with the specific technical, economic, and environmental conditions of regions

2. Methods

The methods used to assess the impact of spatial constraints on the techno-economic potential of wind energy in the Caribbean Sea can be grouped into three parts. In the first part, the main technical, environmental, and socio-economic constraints were mapped. Based on these

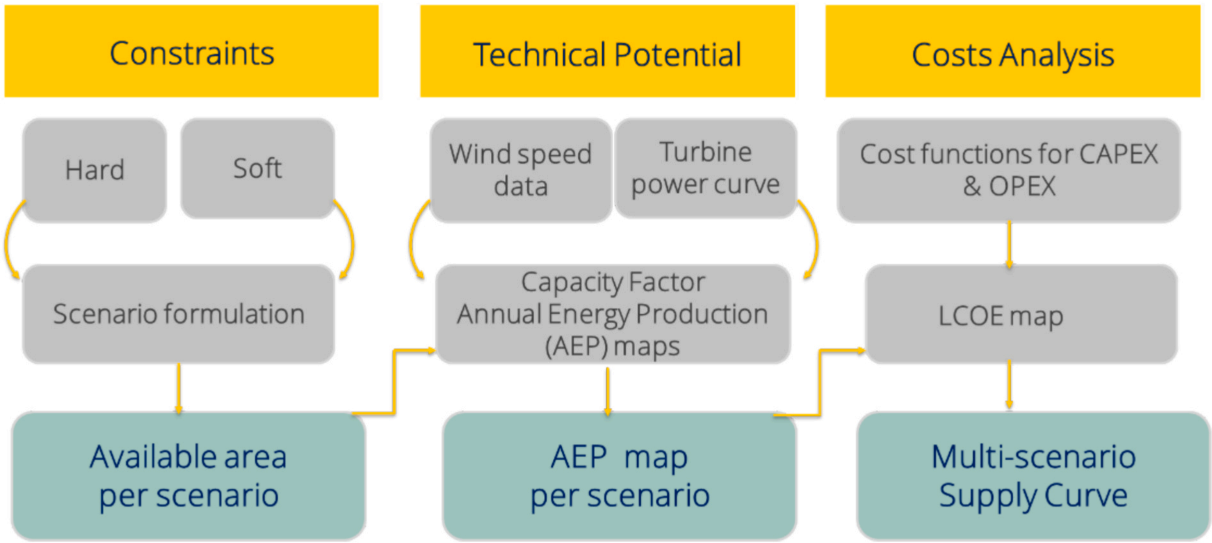


Fig. 2. Methodology flowchart. The proposed framework consists of three steps: (i) mapping constraints, (ii) estimating the technical potential and (iii) analysing the cost of technology deployment.

Table 1
List of constraints assessed in this study.

Constraint			Data type	Processing	Source/reference
Hard	Technical	Wind speed (≤7 m/s) [a]	Raster	Clipping according to threshold and area of analysis (EEZ Caribbean Colombia)	[11]
	Technical	Bathymetry (>1000 m)	Raster	Clipping according to threshold and area of analysis Interpolation to a 2.4 km pixel size	[38]
	Socio-economic	Shipping density (2)	Raster	Classification of values (5 classes) Polygonise (raster to vector)	[39]
	Socio-economic	Subsea cables (3)	Vector	Buffer zone 500 m on each side	[40]
	Socio-economic	O&G discoveries & production areas (3)	Vector	Clipping to EEZ Caribbean Colombia	[41]
	Environmental	Marine protected areas	Vector	Clipping to EEZ Caribbean Colombia	[42]
Soft	Environmental	Key biodiversity areas	Vector	Clipping to EEZ Caribbean Colombia	[43]
	Environmental	Conservation areas	Vector	Clipping to EEZ Caribbean Colombia	[43]
	Environmental	Important bird areas	Vector	Clipping to EEZ Caribbean Colombia	[43]
	Environmental	Biosphere reserve	Vector	Clipping to EEZ Caribbean Colombia	[42]
	Socio-economic	O&G exploration areas (4)	Vector	Clipping to EEZ Caribbean Colombia	[41]
	Socio-economic	Industrial fishing	Vector	Polygonise (raster to vector)	[44]
	Socio-economic	Artisanal fishing	Vector	Polygonise (raster to vector)	[44]
	Socio-economic	Distance to coastline	Raster	Buffer zone 10 and 22 km	Generated from [45]

(1) At 150 m hub height, annual average. (2) Shipping density higher than 5 million boats from 2015 to 2022. (3) Subsea cables, oil and gas (O&G) production fields and new gas discoveries are considered exclusions due to the installed offshore infrastructure that cannot be co-located with offshore wind development [22]. (4) Exploration leases are considered soft constraints because the potential overlap between OWF areas and O&G exploration regions may change over time since exploration contracts are shorter than production contracts. Upon expiration, exploration areas are often partially or fully relinquished.

constraints, three scenarios with different levels of restrictions and potential offshore activity co-existence were formulated, and the available area per scenario was estimated. In the second part, the technical potential for electricity generation from OWFs was calculated for each scenario. The third part included generating a spatially explicit LCOE map per scenario and multi-scenario supply curves to analyse the variation of cumulative energy generation vs LCOE. Fig. 2 illustrates the methodological approach in a flow diagram.

The first part analysed Colombia's EEZ in the Caribbean Sea, which covers about 390,000 km^2. The second and third parts estimated the area remaining after applying a bathymetric cut-off of 1000 m, which is assumed to be the technical threshold for offshore wind energy deployment [4].

2.1. Mapping constraints and defining scenarios

Geospatial data were collected from diverse sources related to technical, environmental and socio-economic constraints (See Table 1). Geographic Information Systems (GIS) were used to visualise and integrate the data layers and estimate the available area. Constraints were classified into two categories: hard and soft. Hard constraints are those areas considered fixed exclusions because they i) impact the wind resource potential (e.g. wind speed below a cut-off), ii) are legally protected areas (e.g. National parks), iii) represent challenges for project

Table 2
Constraints considered exclusion areas by scenario.

Constraint			Scenario 1	Scenario 2	Scenario 3
Hard	Technical	Wind speed (≤7 m/s)	Exclusion	Exclusion	Exclusion
	Technical	Bathymetry (>1000 m)	Exclusion	Exclusion	Exclusion
	Social/ Offshore activities	subsea cables	Exclusion	Exclusion	Exclusion
	Social/ Offshore activities	Shipping density	Exclusion	Exclusion	Exclusion
	Social/ Offshore activities	O&G discoveries & production areas	Exclusion	Exclusion	Exclusion
	Environmental	Marine protected areas	Exclusion	Exclusion	Exclusion
Soft	Environmental	Key biodiversity areas	Multiple uses	Exclusion	Exclusion
	Environmental	conservation areas	Multiple uses	Exclusion	Exclusion
	Environmental	important bird areas	Multiple uses	Exclusion	Exclusion
	Environmental	Biosphere reserve	Multiple uses	Exclusion	Exclusion
	Social/ Offshore activities	O&G exploration areas	Multiple uses	Multiple uses	Exclusion
	Social/ Offshore activities	industrial fishing	Multiple uses	Multiple uses	Exclusion
	Social/ Offshore activities	artisanal fishing	Multiple uses	Multiple uses	Exclusion
	Social	Distance to coastline	No constraint	>10 km	>22 km

feasibility (e.g. deep water) or iv) may pose operational risks (e.g. high-density shipping, existing offshore infrastructure).

Soft constraints are treated as flexible areas that may depend on future policy and regulation. Soft constraints can also include areas of multiple use, where regions allocated to traditional offshore activities or of environmental conservation interest may coexist with wind developments. Table 1 outlines the constraints and the processing and sources of data layers used in this study.

Based on the mapped constraints, three scenarios were formulated, each reflecting different levels of restrictions and potential offshore activity co-existence. Since Colombia is currently developing the policy and regulations for offshore wind development, scenario analysis can be useful in understanding how different levels of spatial restrictions affect the techno-economic potential of offshore wind energy. Table 2 summarises the constraints for each scenario.

Scenario 1 is the least restrictive, only considering hard constraints as exclusion areas. This scenario assesses the area availability when wind development coexists with traditional offshore activities and areas of environmental conservation interest. Scenario 2 has a moderate level of restriction. In addition to the hard constraints, soft constraints related to environmental areas such as the biosphere reserve, key biodiversity areas, conservation areas, and areas of importance for birds are considered exclusion zones. Furthermore, the distance to the coastline is fixed to 10 km in this scenario [21]. Scenario 3 is highly restrictive. This scenario considers all the exclusions of Scenarios 1 and 2 and adds O&G exploratory blocks and fishing areas as restrictions. It also includes a buffer area of 22 km distance to the coastline, as is the case of the Netherlands and the UK [4,22].

Table 3
Technical parameters to estimate CF and AEP.

Technical parameters information from [20,21]	
Turbine model	IEA 15 MW
Power rated (MW)	15
Hub height(m)	150
Cut-in wind speed (m/s)	3
Rated wind speed (m/s)	10.6
Cut-out wind speed (m/s)	25
Rotor diameter (D_o)(m)	240
Turbine spacing	10 D_o x10 D_o
Wake efficiency	0.88
Availability factor	0.9
Transmission efficiency [(1)]	0.93

[(1)] This factor was estimated as an average for distances between 20 and 70 km based on [21].

2.2. Technical energy potential

The technical potential was estimated for the area covering Colombia's EEZ across the Caribbean Sea, and water depths up to 1000 m. We used wind speeds (derived from the U and V components) from the ERA5 reanalysis dataset [19] covering 2000 to 2023. The wind speed at 150 m was obtained by vertical interpolation of the wind speed on the native level as described in [23]. This dataset has an hourly temporal resolution and a spatial resolution of 0.25° × 0.25°. The 15 MW IEA wind turbine model [20] (See A 1) with a hub height of 150 m above ground level (AGL) was selected for the capacity factor (CF) calculation. This conceptual turbine is widely used in offshore wind literature as a state-of-the-art model for performance and cost assessments under moderate-to-high wind speed conditions [17,18,21].

The capacity factor (CF) for each grid cell is estimated according to Eq. (1)

$$CF = \frac{1}{\boldsymbol{N}}\sum_{i=1}^{\boldsymbol{N}}\frac{\boldsymbol{P}(\boldsymbol{U}_i)}{\boldsymbol{P}_{\boldsymbol{w}}} \tag{1}$$

where $\boldsymbol{P}(\boldsymbol{U}_i)$ is the power produced by the wind turbine at every hour. $\boldsymbol{P}(\boldsymbol{U}_i)$ is estimated with the turbine power curve of the selected model (See Table 3 and **A 1**) as a function of the wind speed full-time series $\boldsymbol{U}_i$ at 150 m. $\boldsymbol{P}_{\boldsymbol{w}}$ is the turbine power rated (15 MW), and N = 24 (hours/day)* 365 (days/year)* 24 (years).

The capacity factor raster map was interpolated using the inverse distance weighting method to a cell size of 2.4 km × 2.4 km to fit one turbine per raster pixel, considering a turbine spacing of ten rotor diameters ($10D_oX10D_o$) [18,21] and a rotor diameter of 240 m for the 15 MW IEA turbine.

The Annual Energy Production (AEP) for each grid cell was estimated according to Eq. (2)

$$\boldsymbol{AEP} = \boldsymbol{CF}^{*}\boldsymbol{Pw}^{*}8760 \tag{2}$$

The AEP map is multiplied by a factor f (see Eq. (3)) to account for the availability factor (*af*), and wake and transmission efficiencies (*eff*) (see Table 3). After this step, the AEP raster was clipped by the polygons that define the available areas per scenario.

$$\boldsymbol{AEP}_{af\&eff} = \boldsymbol{f}^{*}\boldsymbol{AEP} \tag{3}$$

2.3. Spatially-explicit LCOE estimation

Similar to the AEP map, the LCOE map was estimated for the country's EEZ across the Caribbean Sea, and water depths up to 1,000 m. Posteriorly, it was clipped using the polygons corresponding to the available areas per scenario. The LCOE is estimated for each grid cell based on Eqs. (4) and (5):

Table 4
List of CAPEX and OPEX functions.

CAPEX and OPEX Components[(1)]			Variable
CAPEX	Turbine and tower		Rated power, rotor diameter and hub height
	Balance of system	Offshore structure	Water depth and rated power
		Power transmission	Distance to onshore connection[(2)] and rated power
		Permits & engineering	Water depth and rated power
		Personnel equipment	Constant
		Scour protection	Rated power
		Port staging, transport & installation	Water depth
	Non-hardware		Water depth and rated power
OPEX	Variable		Annual Energy Production (AEP)
	Fixed		Rated power

[(1)]Each component is considered in a spatially explicit way. [(2)] Euclidean distance from each pixel to onshore connection points.

$$\boldsymbol{LCOE} = \frac{\boldsymbol{CRF}^*\boldsymbol{CAPEX} + \boldsymbol{OPEX}}{\boldsymbol{AEP}_{\boldsymbol{af\&eff}}} \quad (4)$$

$$\boldsymbol{CRF} = \frac{\boldsymbol{j}^*(1+\boldsymbol{j})^{\boldsymbol{T}}}{(1+\boldsymbol{j})^{\boldsymbol{T}} - 1} \quad (5)$$

CAPEX : *Capital expenses*

OPEX : *Operational expenses*

CRF : *Capital recovery factor*

j : *discount rate*

T : *lifetime*

The cost function for each component of CAPEX and OPEX was generated as a raster map with the same spatial extent, spatial resolution and coordinate reference system as the AEP raster map (see section 2.3). Instead of using factors per rated power, the cost structure was built based on [18,21], with water-depth and distance to onshore connection as the key parameters of the cost functions. This approach allows for the inclusion of site-specific factors, reflecting cost variations across different locations.

The components of CAPEX are the costs of turbine and tower, balance of system and non-hardware (See Table 4). The balance of system consists of offshore structure (for fixed or floating turbines, depending on water depth), power transmission, permits and engineering, personnel, scour protection, port staging, transport and installation. Non-hardware costs [24] include commissioning, decommissioning, contingency, construction finance, and insurance.

Offshore structure costs depend on water depth. The same classification as [18] was followed, distinguishing between fixed and floating turbines: foundations are fixed for water depths shallower than 25 m. Jacket foundations are used for depths between 25 and 55 m, while the structures are floating for depths greater than 55 m.

The transmission cost function was adapted from [18] and [21], based on OWFs rated power between 500 and 1,000 MW (roughly 33 to 66 turbines, assuming a turbine capacity of 15 MW), and includes switchgear, transformer, and substation costs. High Voltage Alternating Current (HVAC) system is used for distances under 50 km, while High Voltage Direct Current (HVDC) is considered for distances exceeding 50 km. The onshore connection points (see location in Fig. 4) were assumed to be situated near existing substations [25], under the assumption that these facilities could be expanded or that new substations could be constructed nearby to serve adjacent energy demand centres.

Table 5
Areas per constraint [(1)].

Constraint			Area (km^2)
Hard	Technical	Wind speed (≤7 m/s at 150 m hub height)	51,587
	Technical	Bathymetry (>1000 m)	334,291
	Offshore activities	Subsea cables	1,514
	Offshore activities	Shipping density [(2)]	4,175
	Offshore activities	O&G discoveries & production areas	15,625
	Environmental	Marine protected areas	62,090
Soft	Environmental	Key biodiversity areas	7,830
	Environmental	Conservation areas	2,217
	Environmental	Important bird areas	1,932
	Environmental	Biosphere reserve	85,838
	Offshore activities	O&G exploration areas	24,921
	Offshore activities	Industrial fishing [(3)]	8,086
	Offshore activities	Artisanal fishing	7,468
	Social/visual impact	Distance to coastline (>10 km)	12,655
	Social/visual impact	Distance to coastline (>22 km)	26,386

[(1)] Some constraints overlap; therefore, the sum of constraint areas is bigger than the total analysed area (390000 km^2 for the EEZ); [(2)] The shapefile was cleaned out by removing polygons with areas lower than 5 km^2. [(3)] Dispersed points were not included in the estimation.

The distances from offshore locations to a connecting point were estimated as Euclidean distance and stored as a raster map with the same extent and resolution as the AEP map. Using Euclidean distance limits the estimation accuracy; however, accounting for detours due to seabed restrictions may be more practical for smaller-scale analyses. The Euclidean distance raster is the input to estimate transmission cost as a function of rated power and distance to onshore connection. Table 4 shows the variables to build the CAPEX and OPEX raster files. The detailed formulation of each component, based on [21], is presented in A 2.

All costs are in US$ and the reference year is 2024. To maintain consistency in indexation, the same database [26] referenced by [21] was used. Discount rates (DR) of 6, 8 and 10% and lifetimes (LT) of 20, 25 and 30 years were considered to examine how these financial parameters influence cost-competitiveness across the supply curve for each scenario.

Detailed turbine spacing modelling is beyond the scope of this study; however, its impact on AEP and LCOE was tested across three specific locations. For this analysis, a medium-sized wind farm (350 km^2) was considered, with the centroid defined by the coordinates of each location. The number of turbines at each location was estimated based on three different spacing configurations. Wake efficiency for each turbine array was derived from [27] (see A 3). Using these wake efficiency values, the AEP was calculated for each wind farm. CAPEX and OPEX were extracted from raster maps specific to each location (see Table 4), and subsequently, the LCOE was determined for each turbine spacing scenario and location.

3. Results

3.1. Available areas

Bathymetry represents the most critical constraint, with 334,291 km^2 of excluded area (about 95% of the EEZ). This is because the region with water depths shallower than 1,000 m forms a narrow strip along the coast, limiting the suitable area for offshore wind development. This finding contrasts with other regions, such as the North Sea, where water depths are relatively shallow in most of the continental platform. After bathymetry, environmental constraints and areas with average wind speeds lower than 7 m/s represent large potential restrictions,

Table 6
Available areas per scenario.

Scenario	Total excluded area (km^2)	Total available area (km^2)	Total available area (%)	Available area with water depth <55 m (km^2)
1 Low restriction	372,544	18,046	4.6	8,219
2 Mid restriction	379,263	11,404	3.0	4,442
3 High restriction	383,295	7,441	1.9	1,936

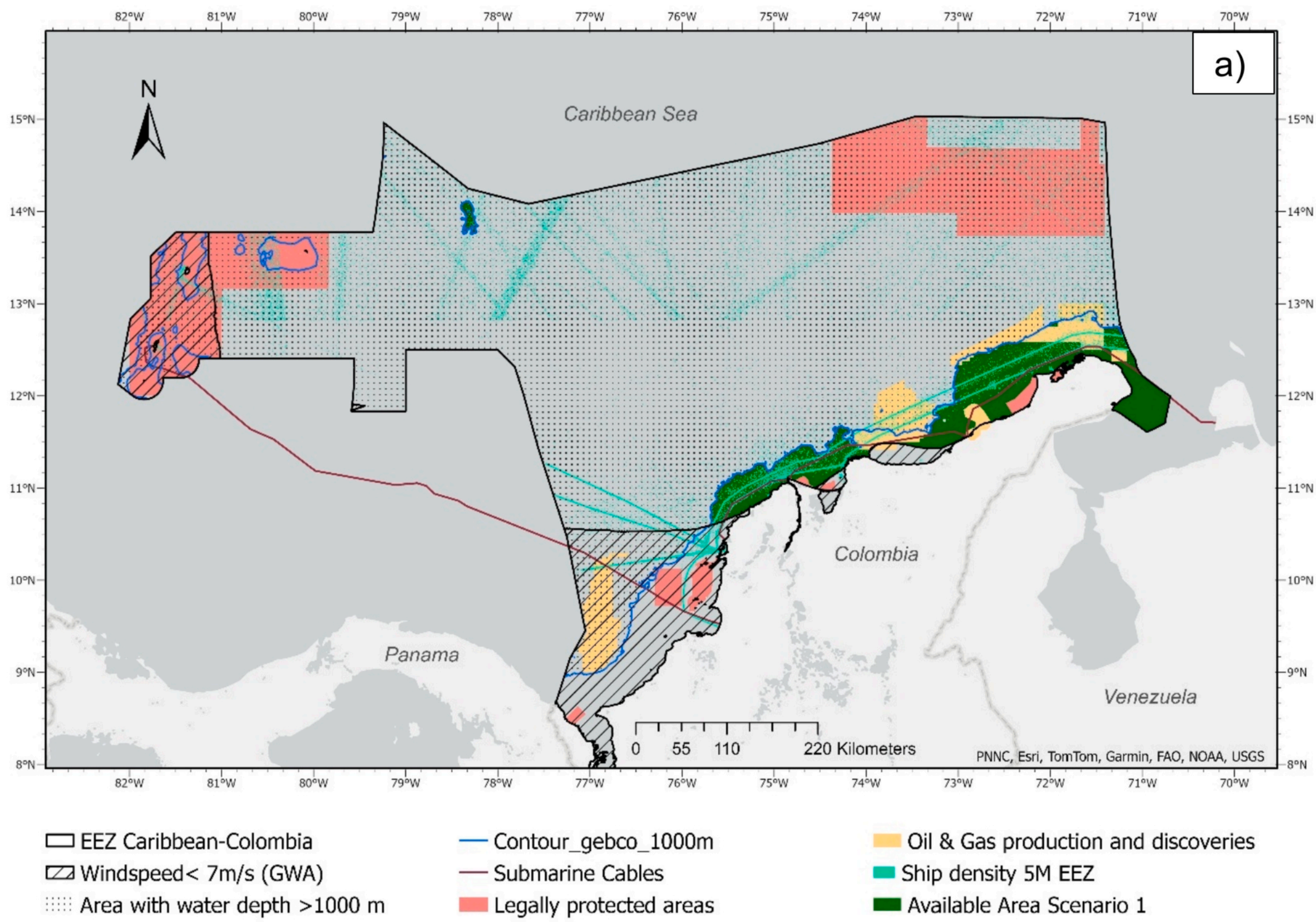


Fig. 3. (a–c) Maps of spatial restrictions and available areas per scenario. (a) Scenario 1 is the least restrictive and only considers hard constraints as exclusion. (b) Scenario 2 has a moderate level of restriction. In addition to the hard constraints, soft constraints related to environmental areas such as biosphere reserve, key biodiversity areas, conservation areas, and areas of importance for birds are considered exclusion zones. A 10 km buffer area from the coastline is included. c) Scenario 3 is highly restrictive. This scenario considers all the exclusions of Scenarios 1 and 2 and adds O&G exploratory blocks and fishing areas as restrictions. It also includes a buffer area of 22 km from the coastline.

accounting for 159,907 and 51,587 km^2, respectively, although some overlap with bathymetric exclusions occurs. A summary of the areas excluded per constraint is presented in Table 5.

Even under the least restrictive scenario, only 4.6% of the studied area would be available for OWFs deployment. As restrictions increase, the available area drops to only 1.9% in the high-restriction scenario, a 59% reduction in space. The area with shallow waters (<55 m) presents a steeper decline, from 8,219 km^2 in the low scenario to only 1,936 km^2 in the high-restriction scenario, a 76% reduction in areas suitable for fixed bottom OWFs. This trend indicates that, as restrictions increase, floating turbines become more suitable for available areas. Table 6 presents the available areas per scenario. Fig. 3 shows the distribution of available area under each scenario and highlights the impact of restrictions on area availability.

3.2. AEP and LCOE maps

The areas with the highest energy potential are concentrated in the eastern and northern offshore Guajira (see Fig. 4), where average wind speeds exceed 10 m/s. In this zone, the estimated AEP reaches approximately 71 GWh per pixel (12,400 MW/km^2/year). In contrast, lower AEP values are observed towards the north of Riohacha, Barranquilla and Cartagena due to lower wind speeds ranging between 7 and 8 m/s. The AEP maps for Scenarios 2 and 3 are similar to Scenario 1, with the only difference being the available area, which is affected by the clipping process based on the restrictions applied in each scenario (see A 4).

Areas with higher AEP generally exhibit lower LCOE values (see Figs. 4 and 5), indicating the most cost-effective locations for development. Moreover, in some regions with shallow waters and near the coastline, LCOE remains high (ranging from 200 to 300 $/MWh) due to

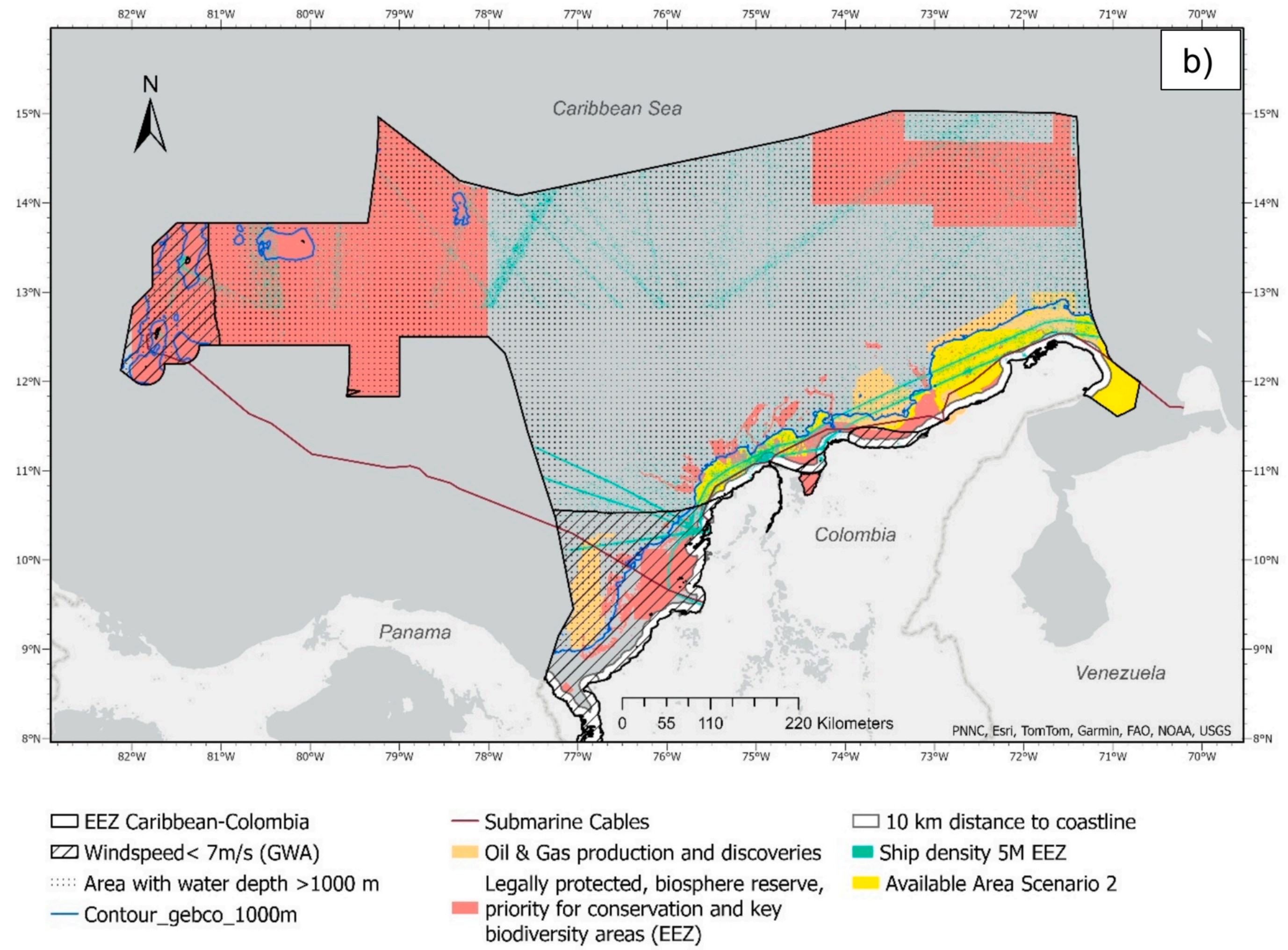


Fig. 3. (*continued*).

relatively low AEP, suggesting that AEP is a key factor influencing LCOE variations. For scenarios 2 and 3, the LCOE maps differ based on the available area, which is affected by the clipping process according to the restrictions applied in each scenario.

CAPEX components were plotted for three specific locations to compare their contribution to total CAPEX (see Fig. 6). The turbine and tower have the highest share for all the locations. For Location 3, offshore structure and transmission (cables) costs are higher than for Locations 1 and 2 due to greater water depth and distance from the coastline. However, the LCOE is lower because of higher AEP conditions. The share of transmission costs for these three locations is about 10% of the total cost (average). This relatively low share is mainly because the maximum distance to the shoreline is 70 km.

3.3. Multi-scenario supply curves

The multi-scenario supply curves for cumulative energy generation versus LCOE are useful in understanding the impact of various space management options and financial parameters on wind energy potential and what percentage of the potential can be developed in an economically competitive way. Across all scenarios, the supply curves show the typical trend of increasing LCOE with cumulative capacity, as lower-cost resources are allocated first (See Fig. 7). The shape of the curves is similar, but the cumulative energy supply and the LCOE values expand differently depending on the scenario and the financial parameters used. The convergence of three curves in each scenario is explained by the fact that the available area is limited and the most expensive units of capacity are associated with sites that are either remote to onshore connecting points, located in relatively low wind-speed zones (about 7 m/s), situated in deep waters (close to 1000 m) or subject to a combination of these factors. These conditions lead to a steep increase in LCOE, exceeding 500 $/MWh in some areas (See Fig. A4 3).

Scenario 1 presents the flattest curve and the highest energy generation potential. For a DR of 6% and an LT of 30 years, the supply curve expands to 105 TWh below 100 $/MWh and an additional 85 TWh between 100 and 200 $/MWh. The potential generation in Scenario 3 is the lowest, with a cumulative energy supply of 55 TWh below 100 $/MWh and an additional 31 TWh between 100 and 200 $/MWh for the same DR and LT. When using an LCOE benchmark of $200/MWh, and the same DR and LT mentioned above, the energy potential declines by 46%, from 190 TWh in Scenario 1 to 86 TWh in Scenario 3.

The progressive reduction of energy generation from Scenario 1 to 3 is consistent with the spatial extent in each scenario (see Table 7). Despite the decreasing area and total production, the mean CF progressively increases from Scenario 1 (67%) to Scenario 3 (73%). This trend can be attributed to the fact that the available areas in Scenarios 2 and 3 contain a higher proportion of sites with more favourable wind speed conditions. Installed capacity also declines across scenarios, from 41 GW in Scenario 1 to 17 GW in Scenario 3, reflecting the spatial reduction and higher capacity factors.

The highest generation potential is associated with floating OWFs (see Fig. 8). At a 6% DR and 30-year LT, OWFs with fixed turbines have a

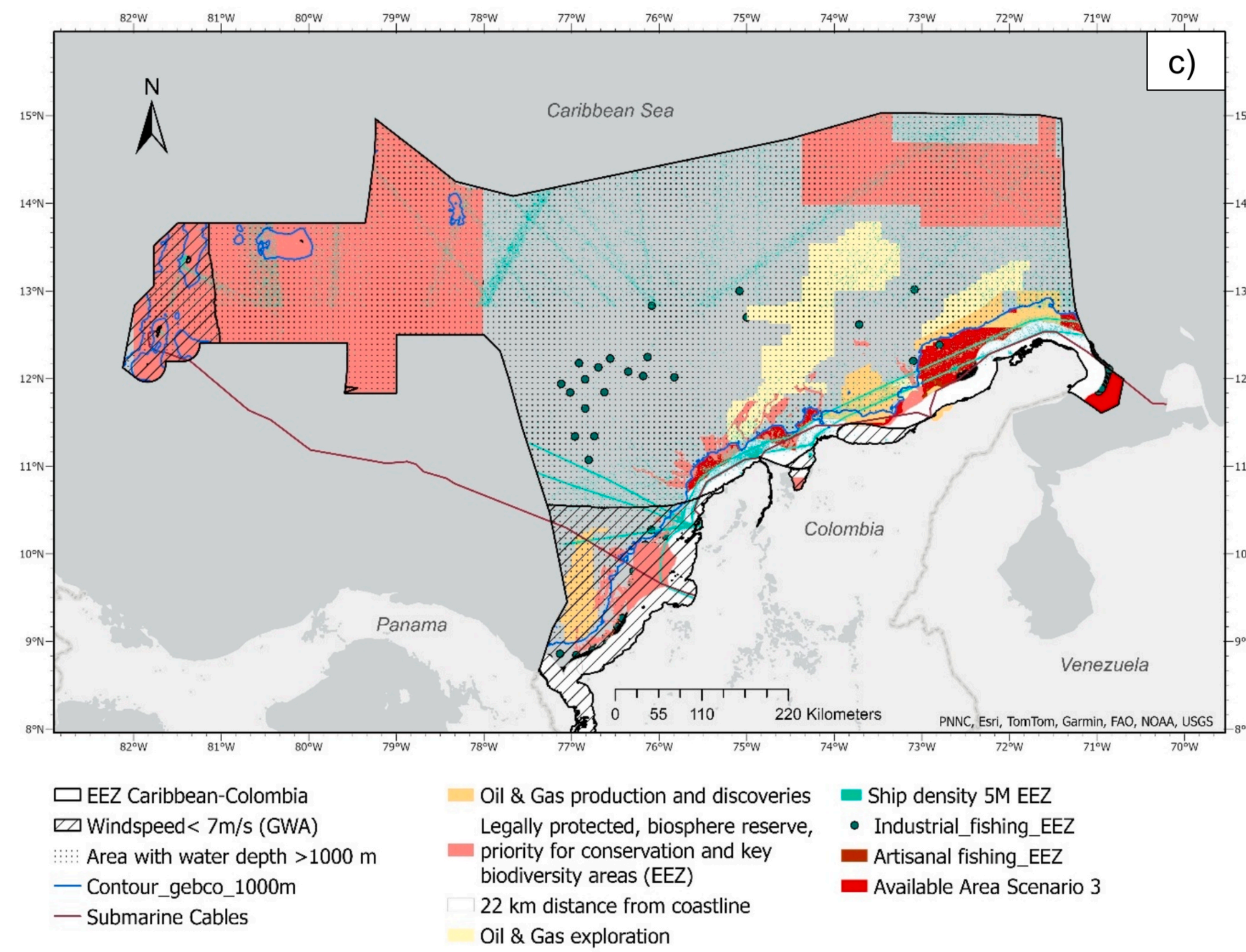


Fig. 3. (*continued*).

cumulative energy potential of 44 TWh per year at a LCOE below 100 $/MWh and 29 TWh per year at LCOE between 100 and 200 $/MWh. In comparison, OWFs with floating turbines can produce 61 and 56 TWh per year under the same LCOE thresholds. Additionally, LCOE for floating OWFs appears cost-competitive, with values similar to those of fixed turbines for the first 47 TWh and LCOEs lower than those of fixed turbines, beyond 47 TWh. This result can be attributed to more favourable wind speed conditions in deep-water areas, which lead to higher annual energy output.

Turbine spacing affects wake efficiency and consequently impacts the AEP and LCOE. A 10.5 D_o turbine spacing provides the lowest LCOE across the three tested locations (see Fig. 9). As the spacing between turbines is reduced to 7 D_o or 5.25 D_o, the number of turbines that can be installed increases, leading to a higher AEP.

However, this can also lead to a higher LCOE. While installing additional turbines increases CAPEX and electricity production, the resulting increase in LCOE is not driven solely by higher investment costs but primarily by increasing wake losses, which reduce the marginal gains in annual energy production and thereby limit improvements in LCOE. This indicates that although reducing turbine spacing can increase technical potential, the $10D_o$ spacing used in this study is adequate to balance energy production with economic efficiency.

4. Discussion

4.1. Relevance and contribution

This study uses a region-specific methodological framework to present the first spatially explicit techno-economic assessment of wind energy potential in the Caribbean Sea, Colombia. Our methodology addresses the limitations of global studies by providing an analysis that captures regional conditions. It also fills the gap of current regional studies by ensuring consistency in constraint criteria and considering spatial variations across the region.

The scenario analysis provides insights into how different levels of spatial restrictions can affect the techno-economic potential of offshore wind energy. This information allows for identifying trade-offs between maximising area availability and minimising conflicts. For instance, Scenario 1 prioritises wind energy, offering the largest area and potential, but requiring strong stakeholder coordination. In contrast, Scenario 3 limits wind development by prioritising other uses, resulting in much less available area and energy potential.

The spatially explicit LCOE assessment highlights areas with the greatest techno-economic potential for offshore wind development. Given that the policy and regulatory framework for offshore wind is still under development in the country, with ongoing discussions following the first offshore wind auction round [28], in which only a single bid was submitted, the LCOE maps can play an important role in informing

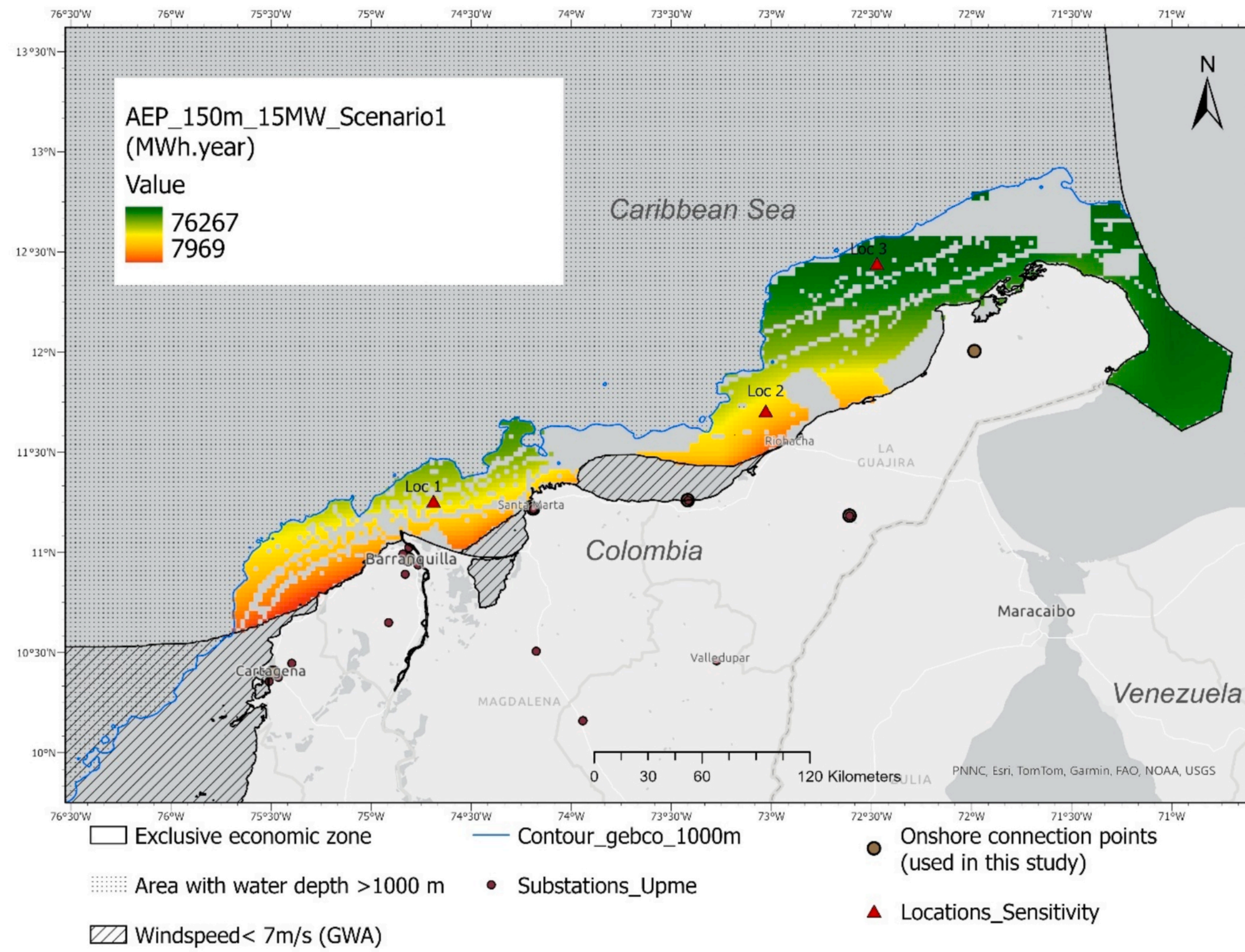


Fig. 4. Annual Energy Production (AEP; MWh) map for Scenario 1.

zoning regulations, spatial planning frameworks, and financial incentive schemes that can attract greater investment in future bidding rounds.

The results show that up to 105 TWh/year could be generated at an LCOE below \$100/MWh, exceeding 88% of Colombia's projected 2039 electricity demand. Moreover, up to 190 TWh/year could be generated at an LCOE below 200 \$/MWh. This higher potential represents approximately 30% of the country's total annual energy demand [29] and approximately 156% of the projected annual electricity demand by 2039 [9]. Carvajal-Romo et al. [13] estimated a significantly higher potential (996 TWh per year) over a smaller area. This discrepancy is explained by i) the lack of spatial and technical constraint analysis in their assessment and ii) the fact that they did not account for wake effects, transmission losses or availability factor.

The OWRM study [17] estimated a technical potential of 50 GW within selected "exploration polygons". While our analysis covers essentially the same region, the estimated potential, expressed in installed capacity, is lower, at approximately 41 GW in the least restrictive scenario. This difference can be attributed to OWRM's inclusion of areas with water depths up to 1250 m. Furthermore, their estimate was based on a nominal power density of 4 MW/km^2, an assumption that may overlook wind speed variability and wake losses.

When disaggregating by country in the global assessment done by Bosch et al. [4], the estimated potential for Colombia is 502 TWh. As expected for a global approach, their spatial analysis did not provide a detailed treatment of constraints. Furthermore, their study included areas with wind speeds below 7 m/s in both the Caribbean and the Pacific regions; therefore, the total assessed area was larger.

Regarding the economic analysis, our results show that about 54% (average of the three scenarios) of the technically available area has an LCOE lower than 100 \$/MWh (see Table 7), considering a DR of 6% and a 30-year LT. As the DR increases and the project LT decreases, the LCOE rises, making it less competitive. The differences relative to the OWRM study [17] are not directly comparable, as their analysis incorporates learning curves to project LCOEs for 2030, 2040, and 2050, whereas our study does not include future cost projections.

Bosch et al. [18] estimated an average LCOE of \$301/MWh for offshore wind in Colombian waters with depths less than 25 m. When categorised by LCOE bands, over 60% of the estimated potential falls in zones where the LCOE exceeds \$175/MWh, suggesting that much of the technically available resource remains relatively expensive to develop. Since their analysis included both the Caribbean and Pacific coasts and considering that the Pacific region features mean wind speeds below 4 m/s and deep water depths, these results obscure the more favourable conditions found in the Caribbean. This finding reinforces the need for regional-scale assessments to better align offshore wind energy strategies with the specific technical, socio-economic, and environmental conditions of regions.

Project viability and competitiveness can be significantly influenced by financing conditions. When the DR and LT change from 6% and 30 years to 10% and 20 years, the LCOE increases by approximately 57% (see Fig. 7). In developing countries, where higher discount rates reflect greater perceived risk and limited access to affordable financing,

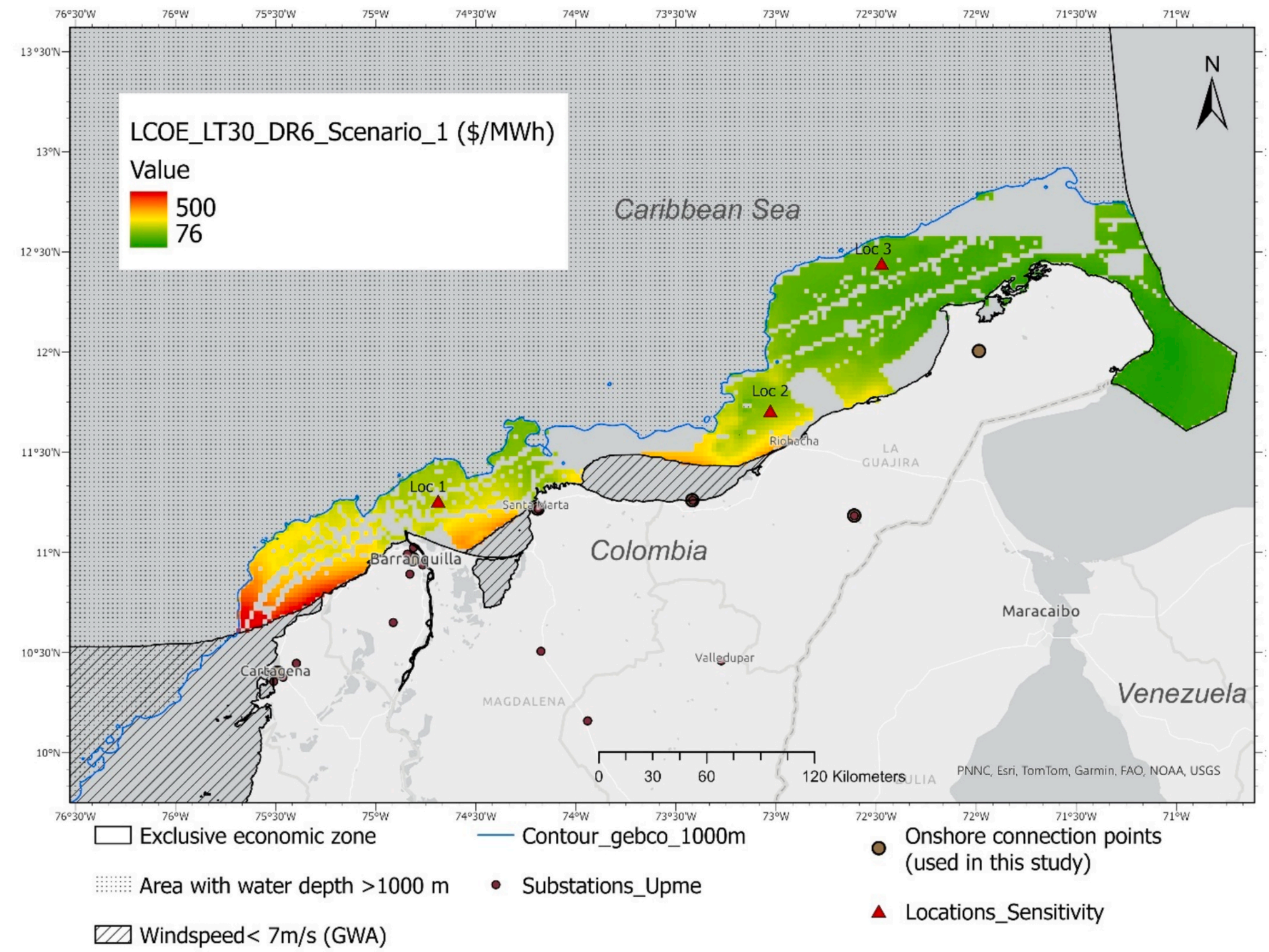


Fig. 5. Levelised cost of electricity (LCOE, $/MWh) map for Scenario 1.

implementing risk-mitigation strategies, securing low-interest rates through concessional finance, and establishing stable policy frameworks are important steps for the economic feasibility of OWF projects. Given the considerable resource availability, offshore wind energy in the Caribbean could play a key role in meeting regional and national electricity demand in the future. Ongoing technological learning has shown its potential to enhance competitiveness in offshore wind markets [30,31], which can, in turn, boost market confidence and reduce the DR. Additionally, economies of scale driven by the adoption of larger rotor diameters and higher hub heights are expected to lower turbine CAPEX [7]. These cost reductions would help to decrease the LCOE, increasing project viability and enabling the development of a larger offshore wind sector in Colombia.

4.2. Limitations and future research

While this study provides relevant insights into the offshore renewable energy potential in the study area, some limitations should be noted. From a technical point of view, we acknowledge that local measurements (e.g., LiDAR buoys or coastal masts) could improve model calibration and reduce uncertainty. However, given the regional scale of the analysis, the ERA5 dataset provides a consistent and widely accepted basis for assessment. ERA5-derived wind data have been widely used in the literature for offshore and coastal wind resource evaluations. Koberle et al. (2022) [32] have demonstrated that this dataset provides the most accurate global reanalysis currently available for wind resource estimation, especially with enhanced low-level jets [23,33,34] often found in the Colombian Caribbean Sea.

Marine geotechnical data (sediment type, rock presence, liquefaction risk) can limit the accuracy in estimating foundation and anchoring costs. This type of data is highly specialised and its acquisition is expensive (high-resolution 3D seismic, shallow boreholes, electromagnetic measurements, etc.) and not publicly available for the entire Caribbean region. A detailed geotechnical characterisation of the marine seabed in the study area would represent a valuable topic for future research, but it falls outside the scope of the present spatial techno-economic assessment.

Turbine space optimisation and wake modelling were not comprehensively approached in our work. To avoid overestimating energy yield, we followed the approach proposed by Langer (2024) [21], and a wake efficiency factor of 88% was applied. Additionally, for three specific locations, different turbine spacings were tested to evaluate their impact on LCOE. It was observed that a $10.5D_o \times 10.5D_o$ array has the lowest LCOE in OWFs.

Our study focused on regions with wind speeds above 7 m/s, a threshold that may be restrictive, but provides a more realistic appraisal of areas where offshore wind is currently technically and economically viable. However, assessing the potential of low-to-moderate wind speed areas can still be valuable for capturing the full picture of energy potential, particularly considering ongoing technological advancements that could make currently marginal areas viable in the future. Our methodology can be easily adapted to allow for more flexible wind speed

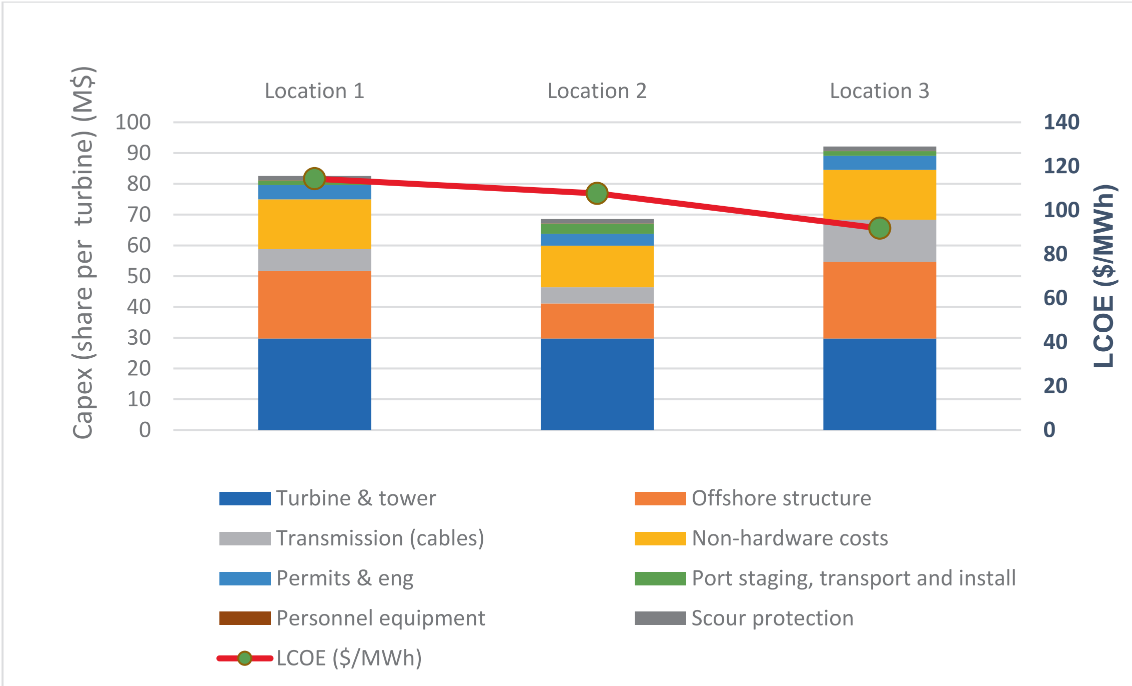


Fig. 6. CAPEX components and their contribution to the total CAPEX. (See location points on Fig. 5).

thresholds in this context.

Regarding the economic analysis, since there are currently no offshore wind deployments in Colombia, the cost structure used in this study was based on existing literature applied in Indonesia. This assumption introduces limitations: it may not account for factors such as local supply chain constraints, labour costs, or logistical challenges. The OWRM study [17] considers that the expansion of a local supply chain is closely tied to policy commitments and anticipated market volumes, with multi-gigawatt project pipelines generally needed to justify the large capital investments required for cost-competitive, state-of-the-art supply chains. The same study analyses a low growth scenario in which existing ports such as Cartagena and Barranquilla could support offshore wind staging and marshalling with only minor upgrades. In contrast, a high growth scenario would justify dedicated port facilities and moderate investments in upgrades, mainly quayside reinforcement and, in some cases, channel deepening, with initial activities focused on Cartagena and Barranquilla and secondary options in Santa Marta [17].

Cost components such as subsea cabling, port renovation or new construction and the expansion of onshore infrastructure (transmission and substations) are beyond the scope of this study. It is recommended that future research assess transmission capacity expansion to determine the practical feasibility of integrating this electricity into the grid. While the estimates of this study provide a practical approximation and should be interpreted as baseline estimates, the actual costs may vary significantly once concrete regulatory mechanisms are in place and domestic implementation begins.

Our study did not include cultural constraints, such as the religious beliefs and cosmogonies of Indigenous communities living along coastal areas. These factors may represent significant barriers to project feasibility, particularly in regions where the sea has a spiritual and cultural value. In the case of Guajira-onshore wind projects, for example, consultation processes involving more than 235 communities have led to substantial delays in project initiation and development [35]. As mentioned in reference [36] it is recommended to incorporate culturally sensitive planning and early stakeholder engagement into offshore wind development strategies. The results of our study can inform these future analyses aimed at identifying zones with high social returns or minimal conflict.

Finally, future research could explore integrating offshore wind energy with green hydrogen production to optimise infrastructure and enhance efficiency. Moreover, studies should evaluate the role of offshore wind in supporting grid stability, especially alongside the country's dominant hydroelectric resources, whose seasonal complementarity [37] can strengthen system reliability and support a resilient clean energy strategy.

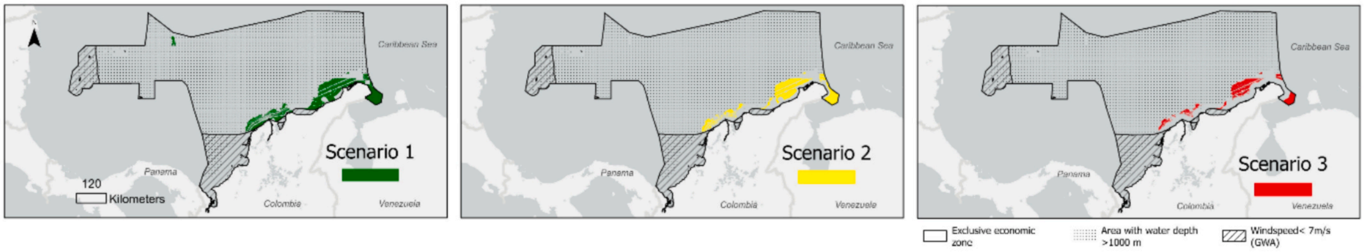
5. Conclusions

This study presents a comprehensive regional-scale assessment that allows us to understand how spatial constraints impact the techno-economic potential of offshore wind energy. It demonstrates its application through a case study in the Caribbean Sea, Colombia, one of Latin America's most promising yet understudied regions for offshore wind energy.

Bathymetry represents the most significant constraint (about 95% of the EEZ), with 334,291 km^2 of the excluded area. Environmental constraints also contribute substantially to the exclusions, with a total affected area of 159,907 km^2, although some overlap with bathymetric exclusions occurs. For Scenario 1, the least restrictive scenario, 4.6% of the total studied area would be suitable for OWFs deployment. As restrictions increase, the available area drops to only 1.9% in the high-restriction scenario.

When using an LCOE benchmark of 100 $/MWh, a 6% DR and a 30-year LT, technical potential reaches 105 TWh-year in Scenario 1. This potential represents approximately 88% of the projected annual electricity demand by 2039 [9]. The estimated generation capacity declines by 46% from Scenario 1 to Scenario 3, highlighting the significant impact that spatial restrictions can have on resource availability. Floating farms have the highest generation potential, with 61 MWh-year versus 44 MWh-year associated with fixed OWF, for the same LCOE, DR and LT mentioned above.

Turbine and tower represent the highest share of total CAPEX, followed by offshore structure. Transmission costs account for about 10%; however, if the method is applied to other regions where depths and distances to onshore connection may be greater, transmission costs can become an important component of the total CAPEX. DR and LT



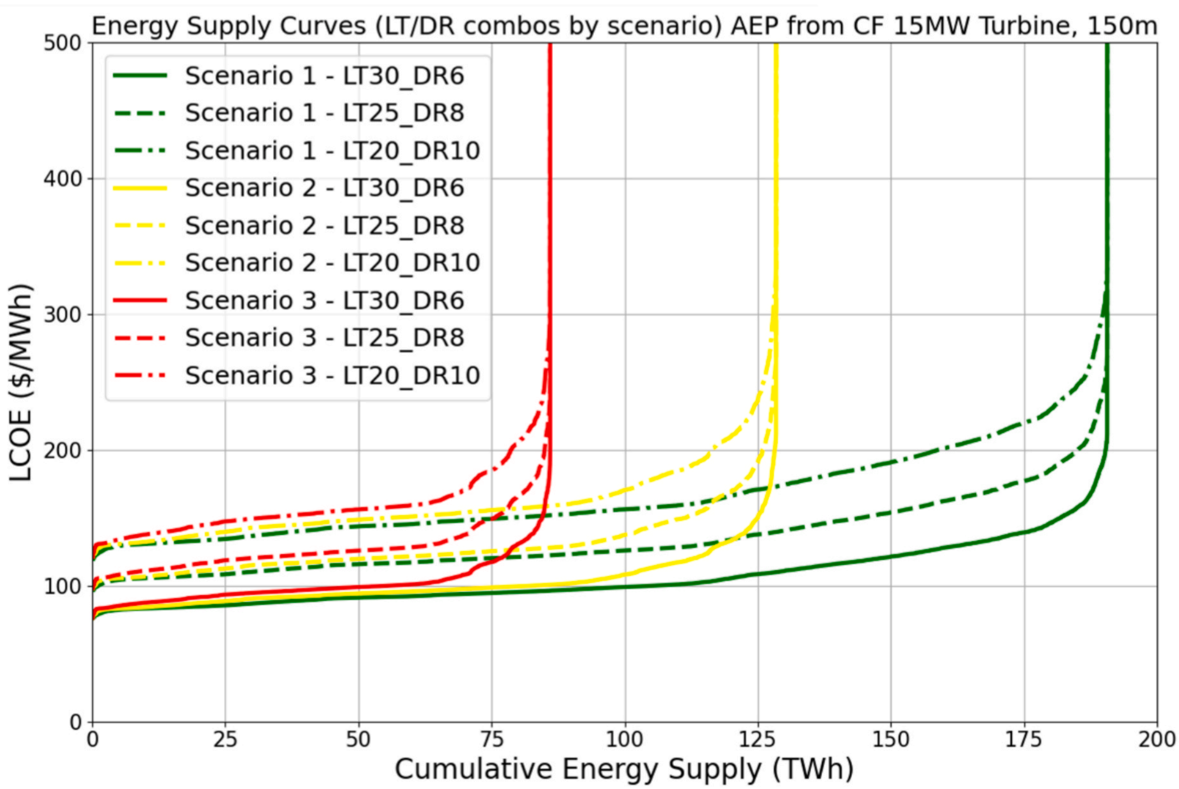


Fig. 7. Multi-scenario supply curve of cumulative energy supply vs LCOE. Each colour corresponds to one of the available-area scenarios. For each scenario, three representative combinations of discount rate (DR) and lifetime (LT) were applied (6%–30 years, 8%–25 years, and 10%–20 years) to provide a high, medium and low-potential estimate for each scenario.

Table 7
Summary of available area, installed capacity, LCOE and AEP per scenario*.

Scenario	1	2	3
Available Area (AA) (km^2)	18,046	11,404	7,441
CF (mean)	0.67	0.71	0.73
Installed Capacity (GW)	41	26	17
AA with LCOE below 100 $/MWh ($km^2$)	8,305	6,531	4,400
AA with LCOE below 100 $/MWh (%)	46	57	59
AA with LCOE between 100 and 200 $/MWh ($km^2$)	3,969	4,752	3,000
AA with LCOE between 100 and 200 $/MWh (%)	22	42	40
Cumulative AEP (TWh-year) with LCOE below 100 $/MWh	105	82	55
Cumulative AEP (TWh-year) with LCOE between 100 and 200 $/MWh	85	46	31

*For this table, the discount rate and lifetime are 6% and 30 years, respectively.

significantly impact project competitiveness. Increasing the DR from 6% to 10% and reducing the LT from 30 to 20 years raises the LCOE by approximately 57%. LCOE is also sensitive to turbine spacing arrays. It is observed that a $10.5D_o \times 10.5D_o$ configuration gives the lowest LCOE, and it increases by about 29% when considering a $5.25D_o \times 5.25D_o$ array.

This study highlights spatial and sectoral trade-offs, aiding in the anticipation of potential conflicts with environmental conservation, oil and gas activities, shipping, fishing, and tourism. The spatial LCOE analysis identifies high-potential areas, providing insights to inform emerging policies, zoning, and planning aligned with national energy goals. These findings are particularly timely, as policy and regulatory frameworks are currently being discussed in the country. Moreover, the proposed framework provides a replicable blueprint for guiding offshore wind assessments in emerging economies, where regional studies are essential for policy decisions, marine spatial planning and infrastructure investment.

CRediT authorship contribution statement

Lorena Suarez Bermudez: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andre Faaij:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Edgar Yañez:** Writing – review & editing, Methodology, Conceptualization. **Andrea N. Hahmann:** Writing – review & editing, Validation, Methodology, Data curation. **Luis Ramirez Camargo:** Writing – review & editing, Supervision, Methodology, Conceptualization.

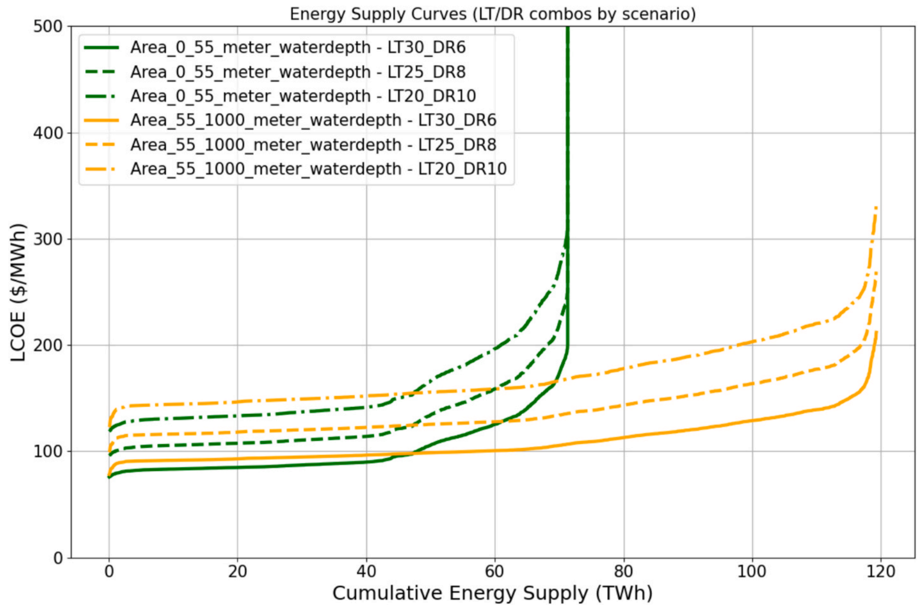


Fig. 8. Multi-scenario supply curve of cumulative energy vs LCOE for fixed and floating wind turbines. The available area within two water depth ranges (0 to 55 m for fixed and 55 to 1000 m for floating) was used to estimate the potential in each case.

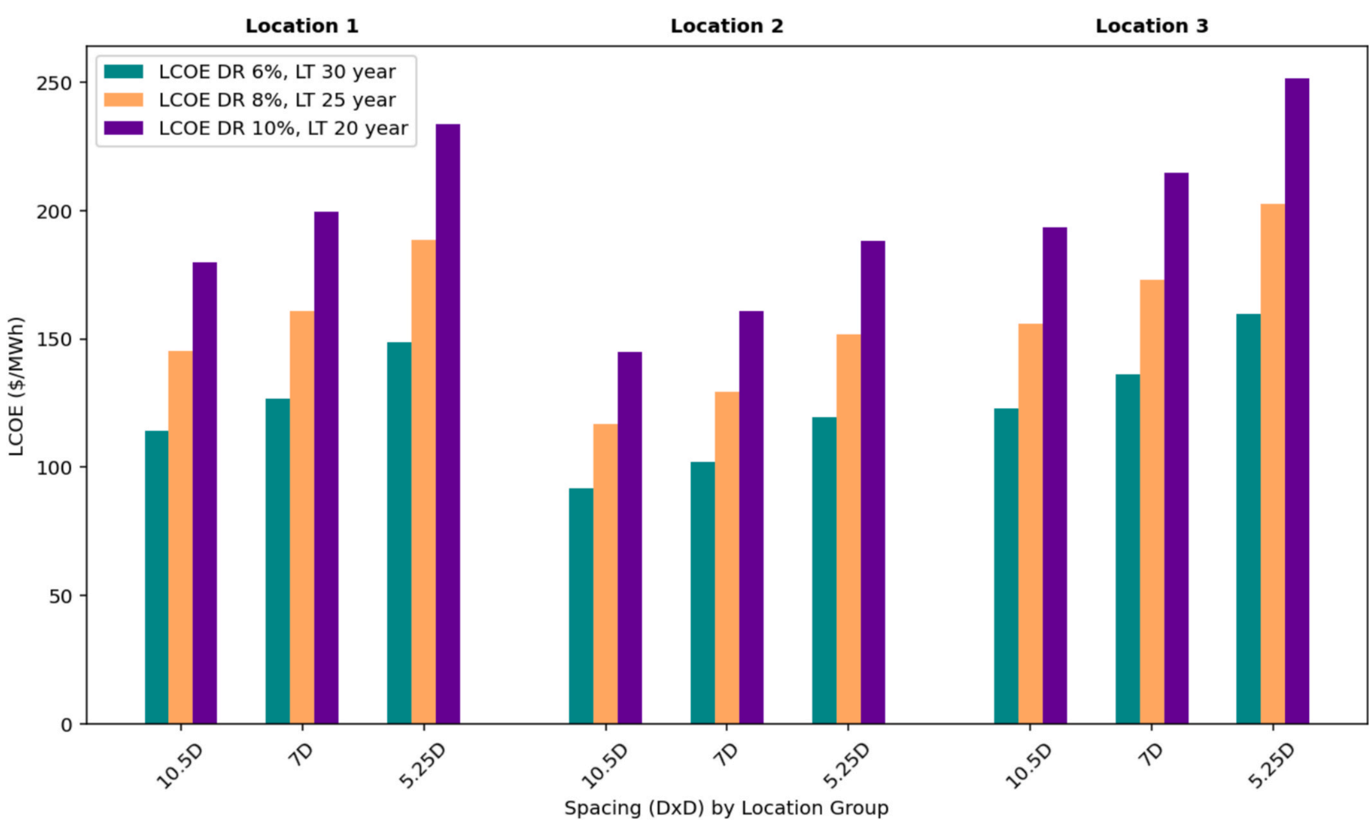


Fig. 9. Sensitivity of LCOE to turbine spacing for three locations (see location points on Fig. 5).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

A loan-scholarship was awarded to the first author from Ecopetrol S. A. to pursue PhD studies. The views expressed in this paper do not necessarily reflect those of Ecopetrol S.A.

Appendix

A 1. Reference turbine power curve used in this study

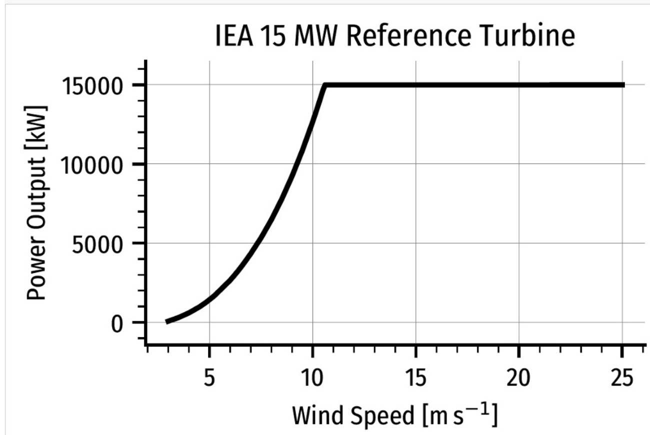


Fig. A1. Power curve IEA 15 MW reference turbine [21].

A 2. Cost functions for CAPEX component

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Table A2.1
Components of Capex and their respective cost functions. All values and functions are based on [21].

Raster file		Cost function based on	Value US$	Formula
Turbine and tower		Constant	29,742,501	
Balance of system	Offshore Structure	Water depth and rated power		**If z ≤ 25 m Monopile** (0.201*z2 + 0.613*z+411.464)**Prated**1.11 * 1.30 **If 25 m < z ≤ 55 m Jacket** (0.114*z2 − 2.270*z+531.738)* *Prated**1.11 * 1.30 **If 55 m < z ≤ 1,000 m Floating** (0.774*z+680.651)* *Prated**1.11 * 1.30
	Power Transmission	Distance to onshore connection and rated power		**If l ≤ 50 km HVAC** (8.5*l+56.8)* *Prated**1.11 * 1.30 **If l > 50 km HVDC** (2.2*l+387.8)* *Pated**1.11 * 1.30
	Permits& Engineering	Water depth and rated power		**Fixed-bottom turbines:** 208**Prated**1.23 **Floating turbines:** 250**Prated**1.23
	Personnel Equipment	Constant	60000*1.7	
	Scour Protection	Rated power		55**Prated**1.70
	Port staging, transport & installation	Water depth		**Fixed-bottom turbines:** 2,688,000 * 1.23 **Floating turbines:** 1,212,000 * 1.23
Non-hardware		Water depth and rated power		**Fixed-bottom turbines:** 733**Prated**1.23 **Floating turbines:** 878**Prated**1.23

A 3. Parameters used for the 3 types of turbine spacing

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Table A3.1
Parameters for turbine spacing sensitivity.

Rotor diameter (m)	240	240	240
Wind farm area (km2)	350	350	350
Spacing (rotor diameter)	10.5	7	5.25
Spacing (km2)	6.35	2.82	1.59
# turbines	55	124	220
Wake efficiency (1)	0.91	0.82	0.7

(1) Derived from [27].

A 4. Additional AEP and LCOE maps

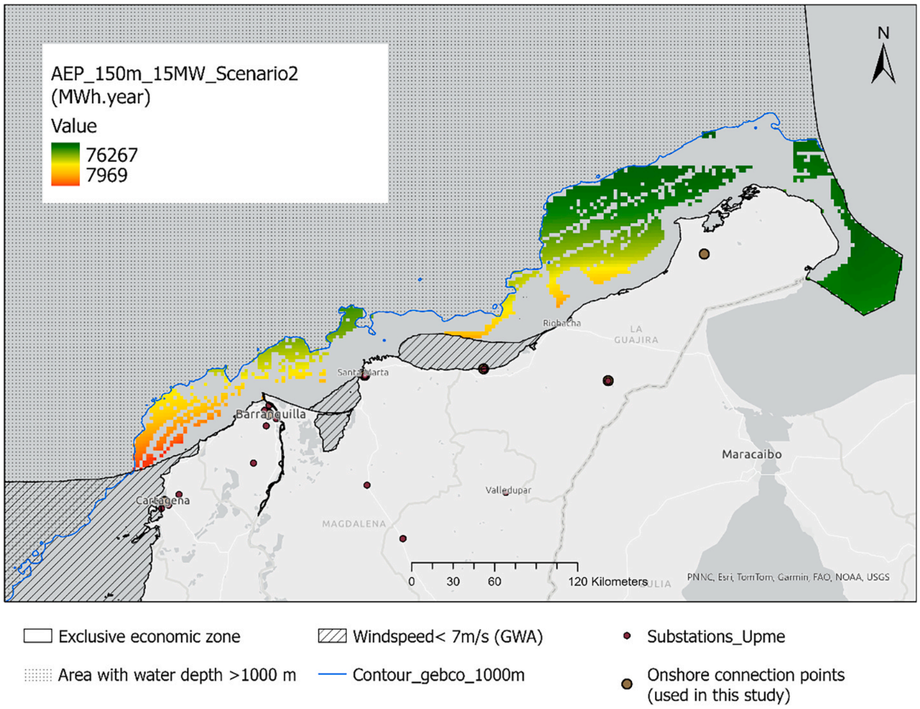

Fig. A4.1. AEP map scenario 2.

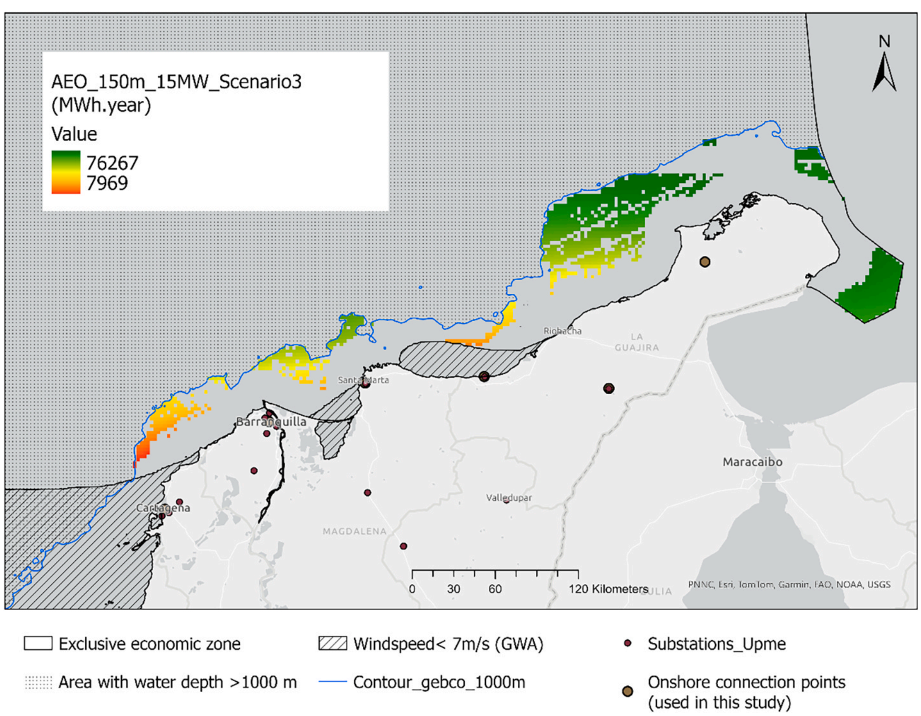

Fig. A4.2. AEP map scenario 3.

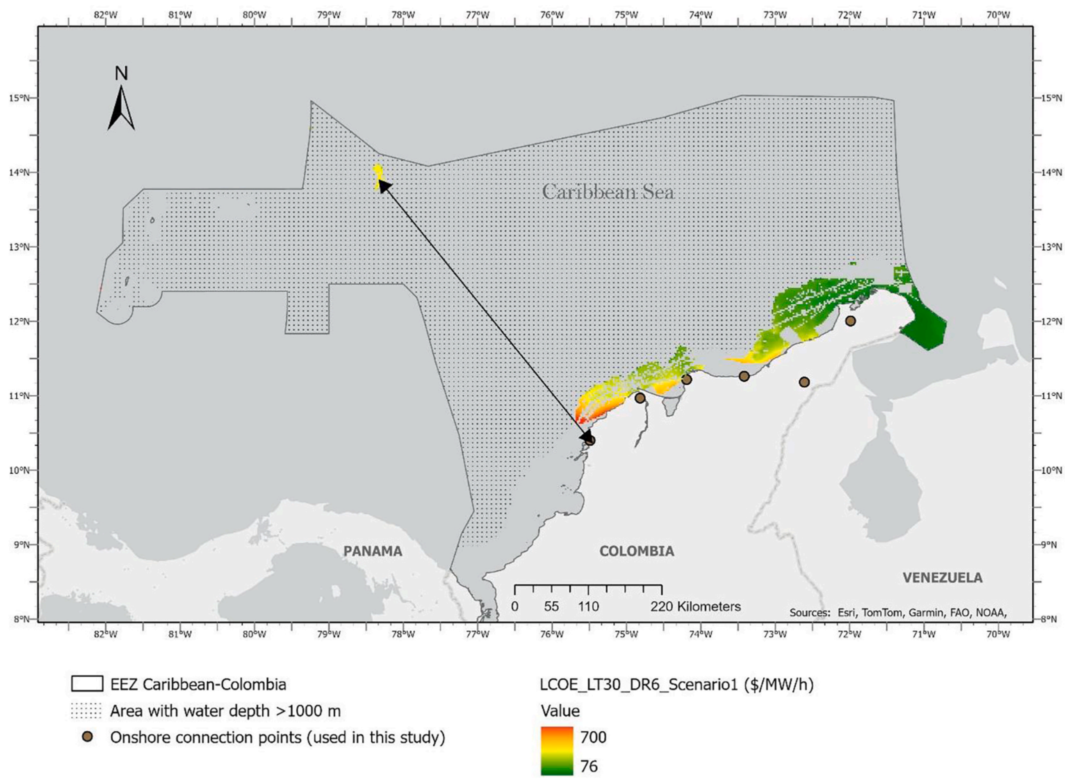

Fig. A4.3. LCOE map total EEZ scenario 1.

Data availability

Data supporting the findings of this study come from publicly available sources and are referenced in Table 1 and Appendix of the paper. The outputs of this study are openly available in **10.5281/zenodo.18804468**.

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