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STRATEGIC PLANNING FOR OFFSHORE WIND ENERGY: A METHODOLOGICAL FRAMEWORK FOR INCREASING ITS SUSTAINABILITY

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“*As simple as possible but no simpler*.”
Albert Einstein

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PLANEJAMENTO ESTRATÉGICO PARA A ENERGIA EÓLICA OFFSHORE: UM MARCO METODOLÓGICO PARA INCREMENTAR SUA SUSTENTABILIDADE

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A energia eólica offshore atingiu 75,2 GW de capacidade total instalada com projetos operacionais na Asia, Europa e Norte América até 2023, aproximadamente 7,5% da capacidade de geração instalada global. China e a União Europeia são os líderes no desenvolvimento desta tecnologia. A Colômbia e o Brasil são mercados em inovação onde está se consolidando o marco regulatório e a Colômbia se posicionou um passo na frente lançando a primeira rodada de concessão de áreas para aproveitamento de eólicas offshore em dezembro de 2023, dentro de um contexto industrial e político diferente ao do Brasil. Os países líderes utilizaram sistemas de apoio à tomada de decisão baseados em tecnologias GIS no processo de planejamento estratégico da energia eólica offshore (Avaliação Ambiental Estratégica ou Planejamento Espacial Marinho). No Brasil, ainda estão sendo definidas as metodologias e procedimentos de tomada de decisão que guiarão a expansão do parque de geração renovável relacionado com energia eólica offshore. Este trabalho propõe um marco metodológico composto por quatro componentes, incluindo um sistema GIS de apoio à tomada de decisão com abordagem baseada em dados para aprimorar o processo de planejamento estratégico e ajudar aos *stakeholders* na definição e priorização de áreas para o desenvolvimento de parques eólicos offshore mais sustentáveis e procurando sua a integração vertical dentro do marco de formulação das políticas públicas até a implementação destes projetos. A metodologia considera a integração de diferentes métodos de análise multicritério aplicando técnicas de modelagem geoespacial parametrizadas para materializar o planejamento por meio de cenários estratégicos. O Estado do Ceará foi selecionado como estudo de caso e as análises exemplificadas para um Cenário de Otimização Sustentável. Os resultados mostraram que a zona costeira do Ceará tem potencial para definir pelo menos 10 Áreas Eólicas Offshore Sustentáveis cobrindo 2.647 km^2 estabelecendo uma meta clara de 10,7 GW de capacidade instalada total para o Estado, o que representa 11% da meta nacional no cenário de desenvolvimento Ambicioso (96 GW) definido pelo Banco Mundial no horizonte até 2050.

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STRATEGIC PLANNING FOR OFFSHORE WIND ENERGY: A METHODOLOGICAL FRAMEWORK FOR INCREASING ITS SUSTAINABILITY

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In 2023, Offshore wind energy reached a total installed capacity of 75.2 GW, representing approximately 7.5% of the global wind installed capacity, with operational projects in Asia, Europe, and North America, led by China and the European Union. Colombia and Brazil emerge as innovation markets, with Colombia taking a step ahead by launching the first round of concessions for offshore wind utilization areas in December 2023, amidst a distinct industrial and political context from Brazil. Decision support systems based on GIS technologies have been employed by leading countries to aid in strategic planning for offshore wind energy, implementing tools such as strategic environmental assessment and marine spatial planning. This research proposes a methodological framework comprising four components, including a GIS-based decision support system and a data-driven approach, to enhance strategic planning and assist stakeholders in defining and prioritizing areas for offshore wind development, with a focus on coastal project sustainability and vertical integration from policy formulation to project implementation. The methodology integrates various multicriteria analysis methods, employing geospatial modeling techniques parameterized to realize planning through strategic scenarios. The state of Ceará serves as a case study, prioritizing the Sustainable Optimization Scenario, revealing the potential to define at least 10 Sustainable Offshore Wind Areas covering 2,647 km^2, establishing a target of 10.7 GW total installed capacity, representing 11% of the preliminary target in the Ambitious scenario set by the World Bank for the horizon up to 2050.

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Acronyms

ANEEL	National Electric Energy Agency
ANP	National Petroleum Agency
CE	Ceará
CEU	Coastal Environmental Units
CEPEL	Electrical energy research center
CLV	Cable-laying vessel
CTV	Crew transfer vessel
CZ	Coastal Zone
EEZ	Exclusive economic zone
EIA	Environmental Impact Assessment
EIS	Environmental Impact statement
EPE	Energy Research Office
FeOWA	Feasible Offshore Wind Area
FID	Final Investment Decision
GHG	Greenhouse gases
GWA	Global Wind Atlas
GWEC	Global Wind Energy Council
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
ICMBio	Chico Mendes Institute for Conservation of Biodiversity
IEA	International Energy Agency
kW	kilo Watt
kWh	Kilo-watt hour
LCOE	Levelized Cost of Electricity
MMA	Brazilian Ministry of Environment
MME	Brazilian Ministry of Mines and Energy
MSP	Marine spatial planning
MW	Mega Watt
NcOWA	Non-conflicting Offshore Wind Area
ONS	National Electric System Operator
O&G	Oil and gas
OWA	Offshore Wind Area
OWE	Offshore Wind Energy
OWF	Offshore Wind Farms

PV	Photovoltaic
RJ	Rio de Janeiro
RN	Rio Grande do Norte
ROV	Remotely operated vehicles
SCADA	Supervisory control and data acquisition system
SEA	Strategic Environmental Assessment
SuOWA	Sustainable Offshore Wind Area
Spp.	Species
SUU	Sustainable use units
TLP	Tension-leg platform
ToR	Term of Reference
WTIV	Wind turbine installation vessel

Chapter 1 – Introduction

Renewable energy is one of the four decarbonization pillars in the International Energy Agency's (IEA) 2050 scenario (Net-zero GHG emissions) (IEA, 2023) and the most recognized form of decarbonization of the energy sector (PAPADIS & TSATSARONIS, 2020).

However, according to IRENA (2024), we need to triple renewable energy generation by 2030 if we want to keep global warming below the 1.5°C climate target. Conference of the Parties (COP28) to the UNFCCC, which took place in Dubai in 2023 and at which 130 countries jointly committed to achieving a total renewable energy capacity of at least 11 TW by 2030. To achieve the additional 7.3 TW of installed renewable energy capacity required, all forms of renewable energy and associated technologies must be utilized (IRENA, 2024).

In terms of offshore wind energy generation, this target could mean an installed capacity of 494 GW by 2030 (SKOV, 2023). However, in 2022, the cumulative installed offshore wind capacity amounted to around 64 GW, and with an expected average annual growth rate of 6.3 % until 2026, rising to 13.9 % by 2030, the total installed offshore wind capacity is expected to reach only 315 GW in 2030 (WILLIAMS, ZHAO, *et al.,* 2022). This leaves a gap between the commitments and current growth trends in the offshore wind industry, meaning that at least 54 GW of additional installed capacity is required annually to achieve the expansion target (IRENA, 2023c).

In the current context, offshore wind and other marine renewable energy technologies remain expensive and subject to high risk factors in the development and deployment phases; private investors demand transparency, market visibility and clear development targets set by governments to ensure future prospects and returns on investment (IRENA, 2023b).

BROWN *et al.,* (2018 in PAPADIS & TSATSARONIS, 2020) emphasise that the availability of resources and proven technologies is essential for the transition to RE-based electricity systems; a database of suitable renewable energy projects is necessary to consolidate a reliable project pipeline for further decades to scale up renewables by 2050. Although most technologies are already available, the challenge is scaling (IRENA, 2023c). Global offshore wind technology and its project pipeline are no exception. Section 1.1 explores the context of offshore wind energy within different market contexts at an international level.

1.1 The international context of offshore wind energy

Offshore wind energy does not follow any particular trend of development and expansion worldwide. For example, high-income economies such as the United States or Australia have not yet expanded or deployed large-scale offshore wind power generation on their territory. As offshore wind is an emerging technology in most global markets, the context can be described according to technology and market maturity, as suggested by BERGERSON *et al.,* (2019). Based on the development and diffusion pattern of offshore wind technology identified by DEDECCA *et al.,* (2016), a classification of offshore wind market development was made in this study to facilitate the understanding of the international offshore wind market context instead of following the classical country classification of the World Bank. This classification is divided into three categories, from the least developed to the most developed status of the offshore wind market, as follows:

a) Innovation market: from the development and installation of the first offshore wind turbine to the start of the first large-scale commercial farm.
b) Market adaptation: from the start of the first large commercial wind farm to the start of the first very large commercial wind farms.
c) Market stabilization: from the start of the first very large commercial wind farms.

In the following, the international context of the historical development of offshore wind technology is presented, from the most developed to the least developed status.

1.1.1 Status of market stabilization

In market stabilization status, the European market has over 30 GW (47%) of global installed capacity. The first 11 offshore wind turbines with an output of 450 kW were developed and installed in 1991 in Vindeby, Denmark; this first offshore wind farm comprised around 5 MW of the total installed capacity. In 2023, Denmark has an installed capacity of 2.3 GW. The UK market contributes 46% (13.8 GW) to the European market (GWEC, 2023). In 2000, the United Kingdom installed the Blyth offshore wind farm with a capacity of 4 MW, two kilometers off the coast of Northumberland (BVG ASSOCIATES, 2021). The largest offshore wind farm currently in operation is Hornsea 2 with a total installed capacity of 1.32 GW, located 89 km off the coast of Yorkshire and operated by Danish developer Orsted (ORSTED, 2022). Germany (8.1 GW) and the Netherlands (2.8 GW) also stand out within this group (MUSIAL *et al.,* 2023).

China is the most important global player in the offshore wind market until 2023. China has installed the Binhai North H1, its first offshore wind farm with 100 MW of installed capacity, 7 km off the coast of Jiangsu (THE WIND POWER, 2024). China currently leads the global market with a cumulative installed capacity of more than 30 GW; the country has the largest share of turbine nacelle production with 58% of total production (16 GW per year) (GWEC, 2023); and Goldwin[1]'s GWH252-16MW model is the largest operating wind turbine in the world, installed off the coast of Zhangzhou County (Fujian region), with 16 MW rated capacity and a rotor diameter of 252 meters (4COFFSHORE, TGS, 2022, BULJAN, 2023).

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[1] Goldwind is a Chinese global clean energy company.

1.1.2 Status of the market adjustment

The market adaptation status groups countries that have started to install large commercial offshore wind farms. In this context, Taiwan is one of the most important markets with an installed capacity of 831.6 MW. Taiwan completed its first OWF, the Formosa 1 (Phase 1) offshore wind farm with 8 MW, in 2017; this wind farm is located between 2 and 6 km from the coast of Miaoli County in the Northeast region. Today, Taiwan has five operational OWFs and an attractive pipeline of seven projects under construction and 10 projects with completed EIA studies (NORTON ROSE FULBRIGHT, 2023). Japan also belongs to this group with 140 MW of installed capacity in its first commercial offshore wind farm Akita Noshiro Offshore Wind Farm by 2023 and a target of 0.82 GW by 2030 (GWEC, 2023; HEGER, 2016).

Within the European region, France and Italy also achieve market adaptation status with their first commercial offshore wind farms, according to the Global Wind Energy Council – GWEC (2023). France has started generating electricity from two commercial offshore wind farms, Saint-Nazaire with 480 MW and Saint Brieuc with 496 MW of installed capacity, ahead of the UK region (Western region). After a total of eight tendering rounds, France expects 18 GW to be commissioned by 2030 (MUSIAL *et al.*, 2023; NORTON ROSE FULBRIGHT, 2024).

1.1.3 Status of the innovation market

Most countries in the offshore wind market are represented in the group of innovation markets. Their main characteristic is that they have only pilot projects or have not yet installed a single offshore wind turbine – most of the projects are early planning proposals. The most important market here is the North American market. The United States has installed 42 MW spread across two test offshore wind farms located off the northern east coast. Its first pilot, the Block Island offshore wind farm – the "*Starting Five*" – was installed off Rhode Island in 2018 with 30 MW of installed capacity (ORSTED, 2017). In May 2023, the first two commercial-scale offshore wind farms, Vineyard Wind 1 (800 MW) 24 km off the coast of Martha's Vineyard and South Fork Wind (90 to 180 GW) 30 km off Rhode Island, began installing their first turbines (BOEM, 2021a, b, MUSIAL et al., 2023).

In addition, Portugal and Spain are other important examples in Europe that are in the innovation market. Currently, Portugal only has 25 MW connected to the Windfloat Atlantic (WFA), the first semi-submersible floating wind farm 20 km off the coast of Viana do Castelo. In December 2023, the country also completed the public consultation to approve the Strategic Environmental Assessment and Strategic Plan for Offshore Renewable Energy, which aims to develop 3.5 GW in the first tender round in areas off Viana do Castelo, Leixões and Figueira da Foz (GWEC, 2023; REPÚBLICA PORTUGUESA, 2023; WIND FLOAT ATLANTIC, 2024). Spain remains with an installed capacity of 10 MW, including the DemoSATH project, which has been in operation since September 2023 and consists of a floating 2 MW turbine 3 km off Bilbao (GWEC, 2023, RWE, 2023).

Australia is another interesting market in this group. Located in the south-eastern Pacific region, Australia has a technical offshore wind potential of 1,572 GW for fixed-bottom and 3,391 GW for floating technology according to GWEC (GWEC & OREAC, 2021); currently the government has defined six areas of interest and officially declared two: Bass Strait off Gippsland (Victoria) and Pacific Ocean off Hunter (NSW) (DCCEEW, 2024; NORTON ROSE FULBRIGHT, 2024a).

Brazil and Colombia stand out from this Innovation Market Group because they are leaders in Latin America and the Caribbean and serve as examples for emerging and developing countries. The Brazilian oil company Petrobras S.A. has announced investments in two offshore wind pilot projects off the states of Rio Grande do Norte and Rio de Janeiro. Colombia, with a technical offshore wind potential of 50 GW, started the first land leasing process in November 2023 and has interesting offshore wind initiatives in the early planning phase with a cumulative potential capacity of 4.2 GW (ANH, 2023; GWEC, 2023; RCG & ERM, 2022).

The market for floating offshore wind energy can be categorized as an innovation market. This market is still in its infancy with 187.7 MW of total installed capacity in pilot plants worldwide, led by the UK with 42% (78 MW) and Norway with 35% (66.1 MW) (GWEC, 2023; HEGER, 2016).

1.1.4 Outlook, challenges, and opportunities

Regarding the prospects for offshore wind energy in the international context, most countries have set their expansion targets by 2030, such as Germany and the USA with 30 GW, the Netherlands with 22.2 GW, Portugal 10 GW, Spain 3 GW (with a focus on FOWE) and Colombia from 200 MW to 1 GW. Meanwhile, other countries have set longer timeframes to achieve their targets, such as France with 18 GW by 2035, Norway with 30 GW by 2040 and the USA with 110 GW by 2050 (ERM, 2023; LEE, ZHAO, 2023; MUSIAL *et al.*, 2022; NETHERLANDS ENTERPRISE AGENCY, 2015; RCG & ERM, 2022; WINDSPEED TEAM, 2010; WORLD BANK, 2022).

However, there are a few cases such as Australia, which has not set national targets, but the state of Victoria has set at least 2 GW by 2032 (NORTON ROSE FULBRIGHT, 2024a); and Brazil, with a technical offshore wind potential of 694 GW (EPE, 2022) and more than 230 GW of projects in the early planning phase (LAUXEN, 2024), is another country that has not set targets for offshore wind development for any timeframe until 2023. However, without clear targets for offshore wind development set by governments, investors will not take risks and invest in the offshore wind industry.

At this point, several challenges and opportunities in setting expansion targets and accelerating offshore wind energy can be addressed in order to meet climate protection commitments to the required extent and timeframe.

In the international context, the main challenges and bottlenecks are associated with achieving adequate volumes that facilitate cost reductions and financing issues (IRENA, 2023b, NORTON ROSE FULBRIGHT, 2023); legal risks and uncertainties, (*e.g.*, in South Korea, there are at least 29 laws and permits that must be approved for the construction of an offshore wind farm) (GWEC, 2023); infrastructure (ports, grid connection and transmission), logistics, supply chain gaps and vessel shortages can lead to an increase in project costs and risk management due to a lack of strategic investment and planning (U.S. DOE, 2018). For example, many offshore wind energy projects in the U.S. are struggling to maintain profitability due to rising capital costs and interest rates. As a result, some projects have asked to renegotiate offtake agreements with contractors or states (MUSIAL, *et al.*, 2023).

On the other hand, to accelerate the development of offshore wind, especially within the innovation market group, it is necessary to focus on enablers. The GWEC (2023) identifies four enablers for the development of the offshore wind industry: a) seabed leasing, b) permitting and environmental licensing, c) regulation and market design, and d) supply chain development.

In the current context, where most markets and projects are in innovation market status, and particularly in the case of Brazil, seabed leasing is crucial for exploring the feasibility and economic viability of offshore wind projects.

A successful leasing model must foster collaboration between strategic stakeholders and prioritize the long-term sustainability of the offshore wind industry. The leasing model should achieve five milestones before the first leasing competition is held: setting national climate targets, conducting MSP, establishing a leasing authority, defining the leasing and revenue support structure, and creating the relevant legislation (GWEC, 2023). The first step is to define a robust and efficient process to accelerate the leasing of seabed areas to developers. It is important that the targets and quantities of seabed areas are aligned with global long-term decarbonization goals (including the use of offshore wind) (GWEC, 2023).

In addition, IRENA highlights that the main bottleneck in accelerating offshore wind is the long permitting process[2] (2.25 years on average), including environmental and other permits (seven per project on average); this could be a concern for the Brazilian government due to the number of licensing processes of conceptual projects submitted to the environmental agency (IBAMA), which currently reaches 96 opened processes (LAUXEN, 2024).

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[2] The permitting process can follow three approaches: centralized (one-stage) where the government takes responsibility for site feasibility, EIA, stakeholder engagement, and consenting; decentralized (two-stage) where the developer leads the process; and hybrid, a combination of the previous two approaches.

To speed up permitting protocols, IRENA's Collaborative Framework for Ocean Energy and Offshore Renewables (CFOR) with the GWEC (IRENA, 2023c) has worked with GWEC on three key solutions: defining centralized authorities that work with developers, implementing various public consultation channels during planning and construction, and introducing mandatory maximum lead times for permitting.

In terms of market design, the GWEC (2023) recommends the non-competitive leasing model for pilot projects or emerging markets through negotiations between strategic stakeholders. Nonetheless, auctioning is the most popular competitive mechanism for the allocation of new offshore wind capacity (*e.g.,* in the UK, Germany, the Netherlands and the US).

IRENA & CEM (2015a) define best practices for the design of renewable energy auctions when the objective is to scale up a specific emerging renewable energy technology (*e.g.*, offshore wind) and increase participation in the energy mix. First, the definition of auction demand must focus on technology deployment rather than cost efficiency, and a technology-specific auction or exclusive demand band must be defined for the desired technology. Second, qualification requirements must focus on technological, project-specific and location constraints. Third, non-monetary criteria such as socio-economic benefits, location, developer experience, etc. must also be considered when selecting the winner. Fourth, the seller's liability must limit the risk of delays and underbidding to remove uncertainty for developers. The auction designer must allocate and quantify risk in a transparent manner by enforcing strict compliance rules and penalties. These practices may increase contract prices and complexity due to the insufficient maturity of the market and technology, but auction design can evolve in parallel with market development and move towards more cost-effective systems.

Some examples of lease allocation in the international offshore wind context are:

- The UK: In July 2022, the 4th round CfD auction allocated 7 GW of new offshore wind projects. In addition, The Crown Estate has set a special auction for floating wind turbines in five areas in the Celtic Sea with a capacity of 4 GW. In August 2022, the Crown Estate announced the offshore wind leasing process Innovation and Targeted Oil and Gas (INTOG) and awarded three more floating wind projects under the ScotWind seabed leasing (GWEC, 2023, p. 94).
- Germany: In 2023, the first dynamic bidding process was conducted for each of the four non-centrally pre-screened sites identified for the auction, reaching a total volume of 7 GW; three offshore wind areas in the North Sea (2 GW each) and one in the Baltic Sea (1 GW); the auction attracted investments of around €12.6 billion (BUNDESNETZAGENTUR, 2023, p. 3).
- The USA: In 2022, the BOEM conducted three of seven leasing auctions, the 'Offshore Wind Leasing Path Forward 2021–2025'. In these auctions, 13 leases were sold, including six leases in the New York Bight, two leases off Carolina Long Bay, and five leases off the

coast of California. The auctions generated a total of 5.44 billion dollars, with the New York Bight accounting for more than 73.5% (4 billion dollars) (U.S. DOI in MUSIAL *et al.,* 2023, p. X).

- Portugal: The first competitive leasing process was planned for the end of 2023, but the official opening of the offshore wind market awaits the approval of the Allocation Plan for the Exploration of Offshore Renewable Energies (PAER in Portuguese), which was publicly consulted between November 2 and December 13, 2023 (COMISSÃO CONSULTIVA PAER, 2023; REPÚBLICA PORTUGUESA, 2023b). The leasing model should follow a competitive model with a minimum three-month prequalification phase, regardless of its degree of centralization and the associated electricity remuneration model; centralized (with bilateral CfD incentive for 20 years) or decentralized (without CfD) systems can be applied, but without geographical overlay. The competitive process must maximize the location of marine activities, socio-economic benefits and investment in the local supply chain (non-monetary criteria) (REPÚBLICA PORTUGUESA, 2023, p. 19).
- Colombia: In November 2023, the National Hydrocarbons Agency (ANH, 2023, MME, 2022) announced the first round of the tender process to obtain the temporal exploitation licence and the future granting of seabed rights for the construction of offshore wind farms. The procedure comprises six stages in which the developer can submit an individual or consortium bid for the areas nominated by the ANH or DIMAR, whereby each developer can obtain up to two permits for different areas.

In this context, Brazil has extensive experience, particularly with the implementation of auctions for conventional renewable energies and hybrid systems (IRENA, CEM, 2015). However, according to COSTA (2020), changes in auction methodologies for emerging low-carbon technologies are needed to facilitate the procurement of new installed capacity from offshore wind.

Finally, the success of supply chain development in the short term also requires actions focused on creating holistic working groups, identifying sites for facility construction (*e.g.,* ports, ships, factories) following a predictable project pipeline (supply chain demand) (SHIELDS *et al.,* 2023), with supply chain efficiency identified as a key opportunity to reduce the cost of offshore wind (U.S.DOE, 2018).

1.1.5 The current Brazilian legal framework

The regulatory framework has evolved considerably since 2016. At that time, the first initiative for an offshore wind farm, the Asa Branca wind farm, was announced, to be installed 5 km off the municipality of Amontada in the state of Ceará, Northeast region (ASA BRANCA USINA EÓLICA, 2016). In addition, BI Energia Ltda. has initiated the environmental licensing process with the submission of the Technical Characterization Form (FCA in Portuguese) of an offshore wind farm with a capacity of 310 MW off the municipality of Caucaia, in the state of Ceará, to the Brazilian Institute of Environment and Renewable Natural Resources – IBAMA (BI ENERGIA LTDA., 2016).

The first initiative to regulate the offshore wind energy sector was Law Project (PL) No. 11.247/2018 (formerly PL 484/2017 of the Senate) (COLLOR, 2018). It mainly deals with the promotion of offshore wind energy within the Brazilian EEZ. This PL defines the concept of offshore wind areas and names “prismas" (spaces with 3D boundaries), establishes the responsibilities of federal authorities and guidelines in case of conflicts with the offshore O&G industry. Further guidelines relate to the conditions for the granting of rights and the necessary permits for the auctions for renewable energies.

In 2020, IBAMA (2020) published the Terms of Reference (ToR) for the environmental licensing of offshore wind projects. This document provides a detailed overview of the content of the environmental impact study that developers must submit to IBAMA. It explains that due to the lack of maritime spatial planning in Brazil, project developers should carefully consider the distance to the coast where the project is to be installed and operated in order to avoid impacts and conflicts with marine uses.

In early 2021, former Senator Jean Paul Prates (PRATES, 2021) (current President of Petrobras S.A.) presented PL 576/2021, the second approach to regulating offshore renewable energy, which was submitted to the Senate for approval. PL 576-2021 also establishes the planning process for the designation of offshore wind areas (*Prismas* in Portuguese) based on environmental zoning studies and other environmental planning tools. It emphasizes that the zoning and tools must support the EIA process to analyze and evaluate the impact of the specific projects.

In the meantime, several other instruments regulate the development of offshore wind energy. At the beginning of 2022, Decree 10.946/2022 (PR, 2022) establishes leasing regimes for offshore renewable energy in a planned (centralized) or independent form (decentralized), following recommendations such as those made by GONZALES et al. (2020).

Other instruments such as the *Portaria Normativa* N° 52/2022 (MME, GM, 2022) and the *Portaria Interministerial* 3/2022 (MME/GM, 2022) and the *Portaria* SPU/ME N° 5.629/2022 (SPU, 2022) have complemented the regulatory framework and provide several guidelines for the development of the offshore energy sector. However, the regulatory framework still lacks procedural and methodological definitions to guide strategic planning and deployment. Therefore, Decree 10.946-2022 remains the highest level of the regulatory framework.

In addition, the first pilot study on marine spatial planning (BNDES, 2023) is ongoing since 2023, and the BNDES (2023a) announced investments of R$12 million in the second call for tenders for an MSP study focused on the Southeast region. MSP studies are essential for the development of offshore wind energy in the country, but both studies may take more than three years to reach final conclusions.

However, in the first quarter of 2024, the Senate is still in the process of consolidating the regulatory framework into the Offshore Renewable Energy Law – Project Law No. 5.932/2023 (PL in Portuguese), which will be consolidated by the Chamber of Deputies (CAMARA DOS DEPUTADOS, 2023; EPBR, 2024). This PL aims to bring together the contributions of previous project laws and current instruments. In this context, it is emphasized that PL 5.932/2023 establishes as a first basic principle the sustainable development of offshore renewable energy potential, with the aim of reducing greenhouse gas emissions in energy generation and the production of green hydrogen. It proposes a leasing model for the allocation of areas (planned and permanent bids), licensing guidelines – including maritime spatial planning and environmental impact assessments –, restriction criteria and compatibility of multiple uses of marine areas, as well as competitive strategies in the case of overlapping projects, among other considerations.

1.2 Motivation and research objectives

1.2.1 Motivation

The reason for this research is the lack of solid strategic planning studies at the federal or sectoral level for the development of the offshore wind industry in developing countries, even in a few emerging economies such as Brazil. Even considering that instruments at the local level, such as environmental licenses for offshore wind technology, are still in their early stages. However, the most important reason is the lack of vertical integration between the strategic and operational phases of an offshore wind project, from development to commissioning (PHYLIP-JONES & FISCHER, 2015). Today, there are no effective links between strategic and operational tools that guarantee and improve the spatial and temporal sustainability of the offshore wind industry in emerging markets.

Offshore wind energy is one of the emerging renewable energy technologies and a promising contributor to reducing greenhouse gas emissions. According to BARBOSA (2018), Europe has adopted renewable energy, including offshore wind, as a strategy to tackle climate change, reduce CO2 emissions and reduce dependence on fossil fuels.

BARBOSA (2018) identifies three common aspects in the analyzed countries that have developed offshore wind energy. These aspects are the definition of national targets for the share of offshore wind energy, the permitting process aimed at minimizing environmental and social impacts, and the procedure for designating offshore wind areas. BARBOSA (2018) also highlights that since the second round of auctions, the UK has defined and prioritized suitable areas using SEA studies, even as European coastal countries have introduced marine spatial planning and zoning.

The lack of strategic planning studies for offshore wind development, such as a Strategic Environmental Assessment or a cross-sectoral study such as Marine Spatial Planning, is therefore critical for a new energy generation technology that has high potential for reducing greenhouse gas emissions at a national level. This also represents a gap in the expertise and experience of professionals in dealing with this new energy generation technology (EPE, 2020a).

Currently, there are no Strategic Environmental Assessments (SEA) in Brazil to support offshore wind development, and Marine Spatial Planning (MSP) studies are in the pilot stages, which will take at least three years to complete. This state of affairs could lead to economic and social conflicts and, in particular, to impacts on the coastal and marine environment (HERNANDEZ C. *et al.,* 2021). The Energy Research Office (EPE) has identified several challenges that need to be addressed for the sustainable development of OWE in Brazil (EPE, 2020a). Until 2023, the Brazilian government has not officially defined offshore wind areas, installation targets and goals for energy production from offshore wind resources.

Therefore, the hypothesis of the current research is that a methodological framework, supported by a computational tool based on geographic information systems (GIS), can improve the strategic planning process of offshore wind energy in Brazil. GIS platforms and techniques have the necessary resources to integrate robust data-driven tools that address standardized and repeatable procedures to accelerate site assessment and evaluation of current project proposals.

A decision support system can support the implementation of SEA or MSP instruments by linking the strategic stages with local procedures such as the identification of offshore wind areas for renewable energy auctions and the EIA process. Thus, this improvement can provide Brazilian decision and policy makers with more accurate insights into available offshore wind resources, suitable areas, supply chain needs or competitiveness in renewable energy auctions.

The SEA and MSP studies are the starting point for building knowledge and making the decision-making process more accessible for developers, the community and policy makers. These tools guide policies, plans, programs, and measures to develop new technologies considering environmental, social and economic aspects – within the framework of the sustainable development approach. This means that these instruments can promote OWE development under sustainable conditions.

VASCONCELOS (2019) suggests that both instruments, SEA and MSP, are the best options for the strategic planning of offshore wind energy development in Brazil. On the other hand, the EPE and the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) (EPE, 2020a) have concluded that a strategic environmental impact assessment is ideal to support the development of this renewable resource in Brazil. Despite this, it is not clear how both instruments interact between each other and how they are integrated into the strategic planning process.

The SEA is one of the most widely used tools to assess the environmental impact of policies and programs at the regional level (IUCN, 2010). The Brazilian Ministry of Environment (MMA/SQA, 2002) has defined several SEA applications, two of which focus on physical land use planning and sectoral planning; however, there is currently no physical planning of marine space and only one SEA study has been conducted for the offshore O&G sector, which has not been implemented. The SEA approach should focus on assessing the environmental impacts of policies, plans, and programs (EALES *et al.*, 2003). Therefore, the SEA of OWE should inform the strategic decisions on OWE development and answer the question: *How can offshore wind energy be developed sustainably in Brazil?*

However, SANCHEZ (2017) concludes that the SEA must be legally defined within the legal framework in order to avoid misinterpretation and implementation errors. He adds that this instrument is a process that focuses on strategic decisions within the planning process. SEA should target public policies, plans or programs and not only a prior assessment of projects that require an environmental permit. SEA is a tool that must simplify the environmental impact assessment process through the vertical relationship from policy to plan, then to program and finally to projects.

SEA for OWE should inform decision making to guide the sustainable development of policies, plans and programs prone to promote this technology in the country. Transparency and governability are the real obstacles to the adoption of SEA in Brazil in the different sectors (SÁNCHEZ, 2017). However, it is necessary to find solutions – such as making it mandatory for certain decisions, *e.g.*, environmental assessment of areas for offshore activities such as offshore wind or O&G – to avoid it becoming a bureaucratic obstacle for developers and decision-makers.

The SEA studies facilitate the EIA process (IUCN, 2010). Both must have a vertical relationship with other instruments such as MSP and Environmental Zoning. The vertical relationship is the interaction between policies, plans, programs and projects (EALES, SMITH, *et al.*, 2003) (see Chapter 3). However, it is not clear in the literature how the interaction can take place or which instrument has a higher hierarchy between MSP and SEA.

At this point, the EIA is the study that identifies and assesses the impacts of the project and determines the mitigation and monitoring measures. The first and most important step in the mitigation hierarchy is the adoption of avoidance measures (BENNUN *et al.*, 2021) (see mitigation hierarchy in Chapter 3). Project developers must prioritize avoidance measures such as site selection, as these anticipate and prevent potential impacts (BENNUN *et al.*, 2021; IUCN, 2010) and promote sustainable development from a social and environmental perspective.

However, these instruments complement each other and can support strategic decisions with different approaches in the development of offshore wind energy. For example, MSP provides a cross-sectoral vision that allocates marine areas for offshore wind farms. The SEA, on the other hand, provides a specific sectoral environmental impact assessment at a strategic level. Nevertheless, these instruments share a sustainable development approach based on a range of possible strategic planning scenarios.

LÜDEKE (2017) mentions site or spatial planning as one of the avoidance measures. The decision-making instruments, namely SEA, MSP, Environmental Zoning, and EIA, have the spatial component in common as one of the measures to avoid environmental impacts at a strategic or operational level.

Nevertheless, the vertical relationship between SEA, MSP and EIA has shown failures in countries such as the UK and Germany. These failures could be avoided in Brazil. Several studies have identified problems related to this relationship. According to LÜDEKE (2017), good practices in MSP and the exclusion of unsuitable sites are considered the most important avoidance measure; SEA is crucial for avoiding impacts during the preparation and before the adoption of MSP.

LÜDEKE (2017, p. 23) identified problems related to the impact assessment of offshore wind energy in a ten-year study in Germany. He pointed out that the problem of MSP and SEA is based on a lack of knowledge within the legal framework. The study also states that the EIA process needs to be updated with newer knowledge, considering contemporary approaches:

> "*Unless standardized methods and thresholds are established in Europe and internationally, it will remain impossible for agencies to effectively (cumulatively) assess and compare impacts.*"

PHYLIP-JONES & FISCHER (2013, 2015) also found that the strategic planning and environmental impact assessment of OWFs in the UK and Germany lacked a link between SEA and EIA. The study suggested improvements to the effectiveness of SEA. First, the scientific rigor of impact prediction and standard procedures needs to be increased. Secondly, SEA needs to incorporate the results of EIAs carried out in the same geographical region. Overall, the effectiveness of the SEA should be assessed through review packages.

In conclusion, this research highlights the need to fill the knowledge gap in terms of structured methodological frameworks and tools to support decision-making in the localization and prioritization of areas for the sustainable development of OWE in Brazil at regional and local levels, linking the strategic process with the implementation stages, *i.e.*, it is necessary to enhance vertical integration between policy making, the formulation of plans and programs (road mapping) and the execution of projects.

Improved computational tools can help avoid the potential problems of weak vertical integration between the development and deployment stages of offshore wind energy. Nevertheless, MSP and SEA instruments also need to strengthen the vertical relationship (see

Chapter 3) to support local processes such as renewable energy auctions and EIAs for effective decision-making on the development of this industry at regional and local levels. This interaction can be strengthened when it comes to the need for a standardized methodological framework for potential assessment and the possibility of data sharing that integrates the results of previous and future studies in the same geographical locations. This advantage allows for regular updating of development scenarios and project pipeline assessment in the short, mid, and long term.

A structured methodological framework, combined with a data-driven GIS-based decision support system, therefore has the potential to enhance the strategic planning process (e.g., MSP or SEA or customized assessments), supporting strategic stakeholders, whether public or private, to drive the sustainable development of offshore wind energy in Brazil.

This idea was successfully applied in the early stage of offshore wind energy development in the North Sea (SCHILLINGS *et al.*, 2012), in three coastal regions in China (HONG, 2011), in the four oceanic regions in the United States (BEITER *et al.*, 2016) or in the Portuguese's marine space (CASTRO-SANTOS, GARCIA, *et al.*, 2019).

By 2023, several research studies have been published using spatial analysis to assess offshore wind potential within the Brazilian EEZ. VINHOZA & SCHAFFEL (2021), AZEVEDO *et al.*, (2020) used the Analytical Hierarchy Process approach to assess offshore wind potential at different scales and identify suitable and feasible areas. Both studies integrated information using discrete data, which can lead to cumulative generalizations (loss of information) before final classification. The neglect of important criteria such as military constraints or the consideration of areas as absolute constraints that may not be direct constraints may lead to over or under estimation of the offshore wind potential. In addition, MÜLLER (2019) carried out the technological analysis and cost estimation of the areas prioritized by SILVA (2019). TAVAREZ *et al.*, (2020) and DOS REIS *et al.*, (2021) have also carried out technical and economic assessments of offshore wind potential. However, most of these studies based their calculations only in a unique wind turbine technology. Current trends in Brazil show that developers are interested in investing in larger wind farms with larger turbines with an average rated power of 15 MW (4COFFSHORE & TGS, 2022; LAUXEN, 2023). In this context, larger wind farms and turbines can have a major environmental and social impacts (BOEHLERT & GILL, 2010).

1.2.2 Research Objectives

The aim of this research is to propose a robust data-driven and GIS-based methodological framework for improving the strategic planning process of offshore wind energy development addressing to increase the sustainability of the offshore wind projects. The GIS-based decision support system is developed to support decision makers – public and private – in improving the technical, environmental, social, and economic performance of offshore wind projects through vertical integration from the strategic to the operational stages.

Integrating concepts of territorial limits, ecosystem-based analysis and sea-use competitive assessment from the Marine Spatial Planning (MSP) methodology; Assessment of strategic environmental impacts from the Strategic Environmental Assessment (SEA) addressing to link impacts with the Environmental Impact Assessment (EIA) process can improve the sustainable planning process of offshore wind energy. Therefore, the integration of these instruments through a data-driven standardized and semi-automated GIS-based multi-criteria procedure represents the vertical relationship that should be strengthened to avoid future sustainability conflicts in any initiative (EALES, SMITH, *et al.,* 2003). Furthermore, vertical integration is essential for structuring precise and successful national and regional strategies for offshore wind energy development (GILMAN *et al.,* 2018).

Offshore wind energy encompasses the technology to generate electricity from offshore wind resources. It includes the fixed bottom and floating foundations as the main technological difference. Due to the level of development of floating technology around the world, current research is focused on fixed bottom foundation technology. Also, the uncertainty about the available data in the deep-sea regions within the Brazilian EEZ has influenced the definition of the scope, especially in terms of environmental, social and economic data to assess the impact of this industry. Although the current research focuses on fixed-bottom technology, the approach can also be applied to floating technology.

Furthermore, the methodology of the current research aims to bridge gaps between MSP, SEA and EIA and create a common point for information exchange to strengthen the vertical relationship between these instruments. It provides tools to support the implementation of these instruments at different levels. In addition, the contribution to previous studies in the current research approach is based on the available spatial data integrated in a DSS. The proposed approach is based on various spatial multi-criteria techniques, including fuzzy multi-criteria analysis, implemented through the GIS platform to reduce subjectivity and time consumption during the strategic planning process.

1.3 Structure of the thesis

Chapter 1 presents an introduction to the offshore wind in the international and national context. Additionally, the relevance of the research, including its aims and general structure are stated.

Chapter 2 presents the state-of-the-art of offshore wind energy technology and its development dimensions.

Chapter 3 addresses the state-of-the-art of strategic planning and sustainability as applied to the offshore wind industry.

Chapter 4 presents the methodological framework developed to support the strategic planning and development of offshore wind energy within the sustainable development approach. This chapter also presents the validation of the methodological framework in the case study of the state of Ceará in northeastern Brazil.

Chapter 5 highlights the originality of the current research, indicating the policy implications of the sustainable development of offshore wind energy in the Brazilian marine and coastal zone and outlines the implementation of the methodological framework to draw strategies for private developers.

Chapter 6 summarizes this research, draws the main conclusions, points out the limitations of the proposed approach and indicates further studies that should be conducted in this area.

References and appendices can be found at the end of the document. Appendix A collects all the detailed maps that supported the spatial planning process.

Appendix B details the activities from the development, commissioning and decommissioning of an offshore wind farm that guided the environmental and sustainability analyses.

Appendix C presents the industrial property register of the GIS-SPOWER-BR Toolbox.

Appendix D documents the GI-SPOWER-BE Toolbox and the mains GIS-based tools focused on modeling offshore wind constraints, use-competition and technological modeling.

Appendix E shows the VIZ-SPOWER-BR Geonalytics dashboard and examples of dynamic filtering of spatial data.

Appendix F explains the equations that support the GIS-SPOWER-BR Toolbox.

Appendix G provides details on the parameterization of the proposed strategic scenarios.

Appendix H summarizes the sources and references used to parameterize the strategic scenarios.

Appendix I shows the activity-activity matrix used to analyze competition for ocean use.

Appendix J contains publications and collaborations related to the development of this thesis.

Chapter 2 – Offshore wind energy

This chapter presents and describes the theoretical foundations of offshore wind technology and the technological factors related to strategic and sustainable planning. The review focuses on examining key factors affecting the sustainability of offshore wind farms. The literature review included scientific studies, technical reports, white and grey literature with the aim of identifying the current status of this renewable technology up to 2023. This document contains the current state of the art in the field of offshore wind energy, focusing on the most relevant current literature. In addition, previous international experience with offshore wind energy was considered in the literature review and related to the specifics of the Brazilian context (see Chapter 1).

2.1 Offshore wind energy

According to MANWELL *et al.*, (2009), offshore wind energy is “the electricity generated by wind turbines installed offshore and implicitly in the sea (or lakes)”. Energy generation from this non-conventional renewable resource has several advantages and disadvantages compared to onshore wind energy.

Offshore wind energy has been described as more advantageous than onshore wind energy (MATHEW, 2007; MANWELL *et al.*, 2009). The greatest strength is the large area available in the offshore environment. According to Mathew (MATHEW, 2007), another advantage is that offshore wind turbines have higher speeds than onshore wind turbines, which means the possibility of a higher energy yield.

Despite the many advantages, there are also disadvantages. The main disadvantages are the higher capital investment and the higher total project costs compared to the costs of onshore wind projects (MANWELL *et al.*, 2009).

The costs for foundations, turbines, cables and installation costs are much higher than onshore (WIZELIUS, 2015). The more difficult conditions and installation procedures are further disadvantages compared to onshore wind energy. These disadvantages represent the weaknesses of offshore wind energy (OWE) compared to onshore wind energy.

In addition, the industry could be threatened by a lack of experience and regulatory uncertainty in growing markets. WIZELIUS (2015) explains that spatial wind power plans that do not express an explicit intention about the suitability of different areas for the projects entail uncertainties in permitting and a high risk of monetary and time costs.

Although the environmental impacts in terms of land use, noise and visual disturbance have been classified as environmentally acceptable for offshore developments (MATHEW, 2007). KÖLLER *et al.*, (2006) have shown that other environmental problems can also occur, such as noise emissions (especially in underwater habitats), vibrations or barrier effects.

Table 2-1 has consolidated the above-mentioned characteristics into a SWOT matrix of offshore wind energy, identifying the strengths, opportunities, weaknesses and threats of this technology based on the relevant literature.

Table 2-1. SWOT matrix of the offshore wind energy compared to onshore wind.

Strengths	Weaknesses
- Larger available area for major projects. - Greater distance to cities and other load centers. - Generally higher wind speeds. - lower intrinsic turbulence intensity. - lower wind shear.	- Higher capital investment. - Higher project costs. - More difficult working conditions. - More difficult installation and O&M procedures. - Lower availability. - Need for higher quantities of raw materials and materials such as steel or cement. - Need for special design/technology innovations (*e.g.*, ships and barges, special corrosion protection measures).

Opportunities	Threats
- Higher energy yield. - Reduced environmental impact. - Additional benefit for the environment. - Credits (*e.g.*, renewable energy certificates). Lack of expertise and experience.	- Regulatory uncertainties. - Unknown environmental, social and economic impacts in certain regions (*e.g.*, Latin America). - Higher costs than calculated during the operating and decommissioning phases. - Lower energy yield than estimated. - Lower competitiveness (in terms of sorting). -

Source: based on literature review (KAISER & SNYDER, 2012; LESSER, 2020; MANWEL *et al.*, 2009; MATHEW, 2007; WIZELIUS, 2015).

Defining the strengths, opportunities, weaknesses, and threats (Table 2-1) of offshore wind energy compared to onshore wind energy has helped to guide the literature review by addressing relevant knowledge gaps while considering environmental planning processes. In addition, MANWELL *et al.*, (2009) listed the most important factors of offshore wind energy as follows:

1) Prediction of wind resources
2) Characteristics and design of offshore wind turbines (technology)
3) external design conditions
4) characteristics of potential locations (site selection)
5) design and layout of wind farms
6) installation, operation and maintenance, decommissioning strategies and methods
7) Environmental issues (available data, impact assessment and monitoring)
8) energy economics (local costs, energy processes and incentives).

These factors are important in the OWE environmental planning process. They should be considered from the SEA process to the EIA process (PHYLIP-JONES, FISCHER, 2015). However, the sustainability analysis should not be limited to the analysis of environmental issues. If technical, environmental and economic factors are not analyzed, the projects may not be technically feasible, environmentally sustainable and economically viable (WILSON, ELLIOTT, *et al.,* 2010).

Turbine characteristics, deployment strategies and analyzes of the processes make it possible to identify potential impacts on the environment and society. The potential of wind resources provides information on the locations with the best wind resources for the installation of an OWF. The characteristics of the potential sites provide information on the environment that could be impacted and the receptors that could be at risk from the various activities required to construct an offshore wind farm (also referred to as stressors). By analyzing the relationship and cause-effect chain between stressors and environmental receptors, it is possible to identify potential impacts. While the design of the wind farm (layout and spacing between turbines) will determine the size of the area impacted by an OWF, the location of the turbines and electrical systems will give a more accurate indication of the direct impacts that may occur. The economics of wind energy are important to analyze the economic potential and potential impact on the local and regional economy as well as the financial viability of an OWF. All these dimensions should be considered in the sustainability analysis of an offshore wind farm or in the strategic planning of a pipeline of projects.

In addition, the literature review made it possible to identify technological concepts and their role in the context of strategic planning. In the following sections, terms such as “offshore wind farm”, “offshore wind turbine”, “foundations”, “supply chain and logistics”, “electrical system”, “grid connection and transmission” and other important concepts related to offshore wind energy technology are explained in more detail. These concepts are important to provide a complete and robust framework for OWE technology and to avoid misunderstandings of complex terms, processes and relationships. From the previous concepts, two factors become particularly strategic: supply chain and logistics, and grid connection and power transmission, both of which are presented in separate sections.

2.2 An offshore wind farm

This section explains the concept of an offshore wind farm (OWF) in more detail. The aim is to understand the relationship between the strategic planning process, project planning and the development phases of an OWF in terms of a sustainability framework during the life cycle of the project. Baker & Bisset (2003) defined an offshore wind farm as “a series of different components comprising different construction phases, activities and different operational phases, including substations, grid connections, storage yards and docking sites”. This definition was used in the SEA study conducted for the 2nd round of the OWE auction in the UK in 2011. In contrast, this study defines an offshore wind farm as the physical infrastructure and indirect local environment required to generate electricity from the offshore wind resource.

The development phases take into account the activities and processes required to install, operate and decommission an offshore wind farm, i.e. the activities necessary to increase the value of the energy resource. Both the technology and the processes represent the stressors that can have environmental and social impacts (VAISSIÈRE, LEVREL, *et al.*, 2014). Technology and process analysis are therefore key factors in the environmental planning process.

According to Boehlert & Gill (2010) and Gill (2005), a definition of the phases of the offshore wind farm is necessary to identify the specific activities that constitute the stressors that could affect the environmental, social or economic receptors. Following the analysis of the offshore wind farm supply chain, an analysis of the specific activities and phases was required.

In the literature, the phases and activities of offshore wind farms are defined differently. The study “A guide to an offshore wind farm” is the most recent study detailing the specific activities involved in the planning and development of an offshore wind farm. This study was conducted by BVG Associates (2019) for The Crown Estate (UK) and Offshore Wind Energy Catapult. It defines four stages of development: Planning, installation and commissioning, operation and maintenance and the decommissioning phase.

There are other definitions of the OWF stages in the literature. The Clean Energy Group (2017), for example, defines four phases of an offshore wind project, namely: surveying, installation of foundations, installation of turbines and substations, and operation and maintenance. WIZELIUS (2007, 2015), on the other hand, describes six main phases: Planning, obtaining permits, agreements and contracts, financing, installation and operation. Kaiser & Snyder (2012), on the other hand, define the process in four phases: Lease Acquisition, Evaluation and Design, Construction (including Procurement and Delivery, Fabrication and Delivery, and Installation), and Commissioning. In the last study, the phases were defined in the context of an economic approach. Subsection 3.10.2 explains the approaches used in the economic evaluation of OWE.

As for the references consulted, the present study is based on the BVG Associates study on the identification of stressors in the impact analysis (see section 3.7). Table 2-2 summarizes the phases and general activities.

Table 2-2. Offshore wind farm: stages and main activities.

Stage	General activity
	Development and consenting services Environmental assessment Resource and metocean assessment Geological and hydrological studies

Stage	General activity
Planning[3] and development (Feasibility study)	Engineering and consulting
Installation and commissioning	Construction port Offshore logistics Foundation installation Turbine installation Offshore substation Offshore cable installation Onshore substation installation Onshore cable installation
Operation and Maintenance	Operation (electricity generation) Maintenance and services (parked state)
Decommissioning	Turbine decommissioning Foundation decommissioning Cable decommissioning Substation decommissioning Decommissioning port Reuse, recycling, or disposal Environmental surveys

Source: the Author based on BVG Associates (2019a).

Other authors such as Manwell *et al.*, (2009) have used the term feasibility study for the activities embedded in the planning phase. Another peculiarity is that the BVG Associates study noted that the environmental investigations precede the wind resource and marine investigations. This is a recommendation for good planning practice in the offshore wind industry based on European experience (BVG ASSOCIATES, 2019a). The following sections provide further details on the phases and activities.

2.3 Development phase

The development phase consists of planning activities, obtaining permits, agreements and contracts, and financing studies. Sometimes this phase is also referred to as the feasibility study, but both terms refer to the same activities. The planning phase is crucial as it involves estimating the available wind resources (MANWELL *et al.*, 2009). As Mathew (2007) stated, "a clear understanding of offshore conditions is essential for planning." In Brazil, this phase is crucial due to the lack of SEA, MSP or primary data in the offshore environment. Therefore, as described

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[3] Literature differs about the term used for referring to the first stage of an offshore wind farm (BVG ASSOCIATES, 2019a, MANWELL, JAMES F.; MCGOWAN, J. G.; ROGERS, 2009, MATHEW, 2007, WIZELIUS, 2015). This research uses the Planning and Development stage for describing the first stage of an offshore wind farm, indifferently. Installation and commissioning, O&M, and decommissioning are used as development stages. All these stages and embedded activities and sub-activities comprise the main activities described within in the supply chain analysis (see Section 2.4).

above, the feasibility study must include surveys of the environment, wind resources, metoceanic conditions and social parameters. The development phases are described as follows:

- **Development and licensing services**: These activities include work to obtain approval and manage the development. These activities include the scoping report, which aims to determine the extent of impacts on receptors in order to define the specific process and methods of environmental impact assessment. In Brazil, this activity is represented by the environmental impact assessment required to obtain the "Pre-installation License" (see Chapter 3). This license represents an early opinion of the planning authorities that helps in the design and direction of the project. Developers should consider sufficient design flexibility to obtain planning permission and avoid the risk of being more flexible than necessary. Another consideration is not to specify a technological solution that could be restrictive or unsafe for the impact assessment.
- **Environmental surveys:** The activities aim to determine the impact on the environment and establish the baseline for assessment through impact modelling to calculate the change in environmental parameters. It is a series of environmental surveys that include "bird, fish, marine mammal and habitat surveys as well as navigation studies, socio-economic surveys, commercial fisheries, archaeology, noise analysis, landscape and visual assessments and aviation impact assessments" (BVG ASSOCIATES, 2019a). In terms of the UK experience, companies and developers recognize the importance of detailed surveys. It can reduce permitting delays and additional environmental monitoring requirements. As a result, development costs can be reduced.
- **Resource and metocean assessment:** these assessments aim to provide metoceanic data as input for the technical planning of a wind farm, the potential energy production and the prediction of operating conditions at the proposed wind farm site (BVG ASSOCIATES, 2019a). They are crucial for planning activities. Developers should collect wind speed data for the planned hub height of the wind turbines. In Brazil, wind speed data should be collected at a minimum height of 100 meters. Data at 150 meters is recommended, as Brazilian developers are interested in larger turbines with an average rated capacity of about 15 MW (IBAMA, 2021). The data must represent the climatology of the proposed site and the time series should exceed a period of 15 years. Data on wind direction, temperature, pressure and humidity are also required. The extreme wind and wave climate is the most important interface between the wind resource and metocean disciplines. Floating lidar as a measurement tool – measuring up to 300 meters above sea level – is now widely used and has gained industry acceptance due to the significant installation and cost benefits.
- **Geological and hydrological investigations:** These investigations will examine the seabed in the vicinity of the wind farm and the export cable. They aim to assess the

geological conditions and technical characteristics. These include in particular: geophysical surveys of the seabed, bathymetry and geotechnical surveys of the seabed properties. They usually require data collection over larger areas, but with similar approaches to O&G, so there is a potential synergy between the two industries. Data collection begins at least five years before the planned operation of the wind farm. Under auction schemes, the UK has emphasized these surveys as project developers need more certainty on design and costs before the development process.

- **Engineering and consulting**: These activities cover the front-end engineering and design studies (FEED) after the EIA and permitting processes. FEED studies are a multidisciplinary process that provides the framework for and supports engineering and procurement decisions on project implementation. FEED studies include analyses of the specific technologies that will be used to minimize Levelized Cost of Electricity – LCOE. These analyses must take into account the characteristics of the turbines, the type of foundations, the layout of the wind farm, the design of the electrical system, the substation and the type of grid connection. The planning of onshore and offshore activities such as port and ship strategies, contract methods and risk management takes place here. The results of the FEED are the basis for the construction management teams that build and commission the wind farm. In auction systems, FEED studies have become important tools to reduce uncertainty about costs in the planning phase.

Permits and environmental studies are crucial for strategic planning and a sustainable approach. They provide the necessary data for identifying and modeling the impact on the environment and social components. This process enables the formulation of appropriate methods for conducting the EIA and the prioritization of key impacts and consequences (BVG ASSOCIATES, 2019a). The outcome of this process supports the planning authorities' opinion on the viability of the project and the granting or non-granting of the environmental permit. Chapter 3 focuses on explaining the permitting process and the strategic analyzes embedded in the sustainability approach.

On the other hand, as previously mentioned, the wind resource is one of the most important factors analyzed during the planning process of an OWF (MANWELL *et al.*, 2009). For this reason, it is necessary to understand the basic theory of offshore wind energy resources.

2.3.1 Offshore wind energy potential

As defined above, the basis of wind energy is the wind resource. However, the wind resource represents the maximum amount of energy contained in the wind (MANWELL *et al.*, 2009). The wind energy potential is gradually divided into different categories of wind energy potential until the net energy effectively converted into electricity at the point of generation – i.e. generated by each turbine - is reached.

The World Energy Council (1993 apud MANWELL *et al.*, 2009) has defined five categories of potential: Meteorological potential, site potential, technical potential, economic potential, and implementation potential. However, this classification does not describe the social or environmental factors and constraints that must be analyzed for the different potential levels; incorporating these additional factors into the wind energy potential analysis directly influences the results of each potential and varies from onshore to offshore environments.

On the other hand, MUSIAL *et al.,* (2016) and BEITER *et al.*, (2016) details the resource classification to estimate the offshore wind energy potential in the United States in five categories:

- *Total offshore wind resource potential*: recoverable and unrecoverable (mainly further than 200 nm).
- *Gross resources potential*: It considers the recoverable resources, policy limits, turbine power density, wind hub height, energy content of capacity, gross and net capacity factor.
- *Technical resource potential:* This includes technological exceptions as well as exceptions for marine use and the environment.
- *Economic potential:* Calculates the energy costs, the electricity price and the capacity value.
- *Deployment:* Determines the installed capacity and the electricity generated.

In Brazil, several studies have estimated the OWE potential in the entire EEZ. However, most of them estimates the technical OWE potential only considering the federal protected areas as environmental constraint criteria (DE ASSIS TAVARES *et al.*, 2020; DE AZEVEDO *et al.*, 2020; EPE; 2020a, DOS REIS *et al.*, 2021). If the technical OWE potential is estimated only considering technological parameters, future social conflicts and environmental issues may arise. The following subsections summarize the background concepts that support the estimation of technical and economic potentials.

2.3.1.1 Wind resource

The wind resource is the product of pressure differences in the world caused by temperature fluctuations. The round shape of the sun and the earth as well as the earth's rotation lead to irregular solar radiation during the day and night. Air masses move around the world from high to low pressure areas to balance the global pressure. This movement is known as wind resource and flows predominantly in a horizontal axis. The oceans and lakes also balance out the temperature fluctuations to a lesser extent. Other forces such as the inertia of the air, the rotation of the Earth and friction with surfaces that cause turbulence influence atmospheric winds (MANWELL *et al.*, 2009, WIZELIUS, 2015).

Manwell *et al.*, (2009) asserts that wind resource characteristics are critical to project planning and development and that they are site-specific and affect the following issues:

- Site selection
- Turbine design
- Performance evaluation (including micro-siting)
- Operation

The estimation of wind resources is the core of the site selection process. The accuracy gradually increases as the process progresses. The areas with high wind resources should be identified first. The most accurate information possible is needed for site selection and the final economic evaluation of the project. This information should represent the spatial variability of the site and the variation of longer time series of wind data (MANWELL *et al.*, 2009).

The wind resource corresponds to the "gross wind resource" previously defined by Beiter *et al.*, (2016). MANWELL *et al.*, (2009) listed at least six methods for estimating the wind resource, including: 1) ecological methods, 2) wind atlas data, 3) computer modeling, 4) mesoscale modeling, 5) statistical methods, and 6) long-term, site-specific data collection. All of these methods are particularly useful at different stages of early planning and development.

In the early planning phase, three methods are of interest: wind atlas data, mesoscale modeling and statistical methods. The first method is useful because most publicly available data on wind resources are wind atlas data based on remote sensing data. They are usually used for site selection. The spatial resolution of the data is usually between 5 km and 200 meters. Mesoscale modeling is a similar method, but can be improved by using local data from the developer (MANWELL *et al.*, 2009).

Statistical methods are a more accurate estimate of wind resources developed for industrial purposes. These methods, also known as Measure-Correlate-Predict (MCO) models, attempt to estimate the long-term characteristics of wind resources. They are generally used to assess energy generation at suitable locations. Prior to the installation of wind turbines at a specific site, wind speed measurements are taken over a period of time (EL-SHARKAWI, 2017) to estimate wind power and wind potential for planning purposes. Long-term reference datasets include information from various channels, such as airport data, weather balloon observations, historical upper-level atmospheric data (reanalysis data) and data from weather towers (MANWELL *et al.*, 2009).

What is particularly interesting for current research is that the determination of location is closely linked to environmental planning. The wind follows different spatial and temporal patterns. These patterns can be divided into global winds, regional winds and local winds. The last two are of particular interest for offshore wind energy. Regional winds are characterized by phenomena that occur in specific regions, such as hurricanes and monsoons (secondary circulation). Local winds are persistent circulations of air masses that occur on a small scale and on a seasonal or daily basis, such as land and sea breezes, thunderstorms or tornadoes (tertiary circulation) (MANWELL *et al.*, 2009).

GIS-based decision support systems and geoprocessing are useful tools to support the planning process. These approaches usually include a resource assessment using the average annual wind speed as a representation of the wind resource. Examples of this approach include studies by HONG *et al*., (2011), MUSIAL *et al*., (2016, 2019) and SCHILLINGS *et al*., (2012). Figure 2-1 shows the relationship between the temporal and spatial scale of wind resources. Large scales (between 1 km and 10 km) and daily to annual time scales are considered for site selection; GIS-based DSS were used for site selection.

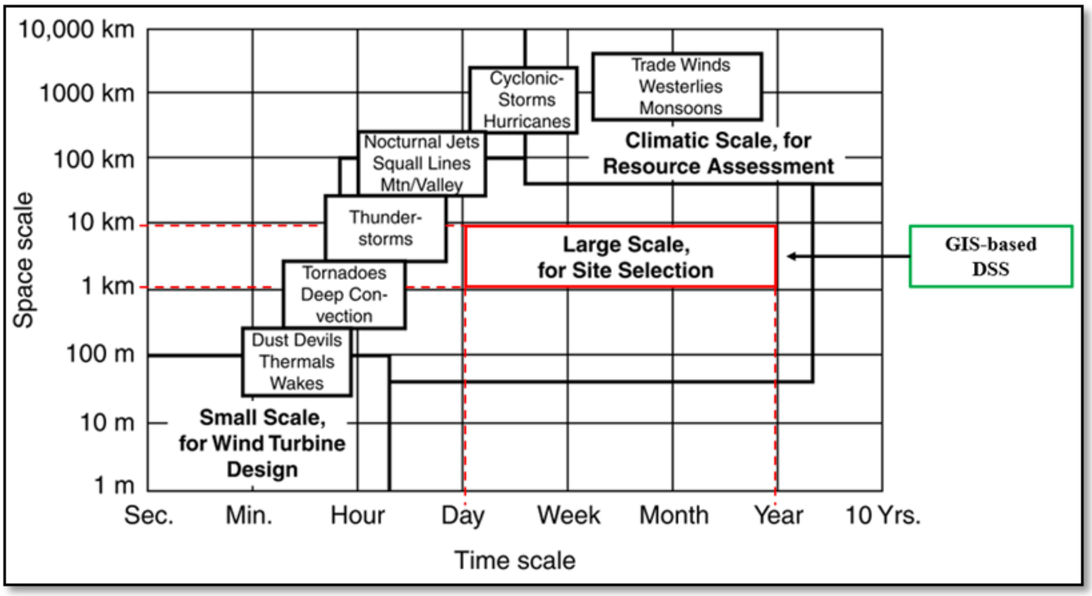


Figure 2-1. GIS-based DSS application on time and space scale of wind resources. Source: Spera (1994 apud MANWELL *et al.*, 2009).

MANWELL *et al.*, (2009) found that the seasonal behavior of wind speed is not defined by one year's data. Therefore, it is important that developers invest in the collection of meteorological time series that are as long as possible (at least 1 year of data). In addition, he pointed out that the characterization of wind speed throughout the year is important to define high-yield and low-yield seasons as well as the possible errors within each month.

On the other hand, the earth’s surfaces also influence the airflow pattern. Wind direction can change due to surface variations and wind speed decreases near the surface and increases with height. This phenomenon is known as “wind shear”. With today's turbine technology, wind energy is generated within the “friction layer” of the atmosphere. Wind energy is generated by turbine rotors installed on towers on land or in the sea. The wind resources for energy generation are interesting up to a height of 200 meters. Within this height limit, the terrain conditions influence the wind at the site and within a radius of around 20 km. On open and smooth surfaces such as in offshore environments, the wind is not strongly slowed down by the low friction. Wind speeds tend to increase with height, but do not vary drastically in these environments (near vertical) compared to onshore regions. Figure 2-2 shows the behavior of the sea breeze and typical wind profiles (relationship between wind speed and height) (WIZELIUS, 2015). This is one of the advantages of offshore wind power.

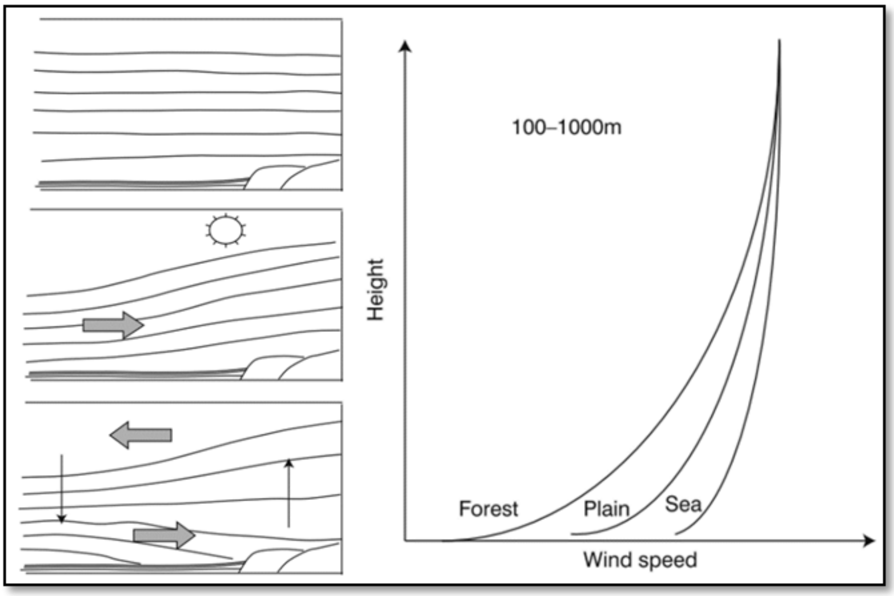


Figure 2-2. Sea breeze behavior (left); typical wind profile (right).
Note: the wind profile in open and smooth surfaces does not change much with the height, mainly on the sea surface.
Source: Modified from WIZELIUS (2015).

Turbulence is the irregular movement of air – *e.g.*, movement in different directions around the prevailing wind direction – in the form of waves and vortices. The opposite state is the “laminar state”, when the air flows parallel to the ground. Turbulence can be identified as small fluctuations in wind speed during the wind measurement. The turbulent state of the air flow can be generated by: Temperature variations that generate vertical movements of the air; surface irregularities such as mountains or deep valleys (complex terrain) and obstacles such as buildings or tall structures (MANWELL *et al.*, 2009; WIZELIUS, 2015). Figure 2-2 also shows possible air movements due to temperature fluctuations during the day and night and due to surface roughness.

Figure 2-3 (below) shows an example of turbulence caused by an obstacle. The rule of thumb established in the literature is that from a distance of 20H in wind direction, the obstacle allows the full recovery of wind characteristics (wind speed, flow state and power).

Wind turbines are also an obstacle. They cause a turbulent phenomenon known as the "wake effect", which affects the turbines in the direction of the wind. Subsection 2.3.1.2 explains this effect and how it affects the wind resource available to generate electricity.

Overall, the wind resource in the nearshore environment or offshore wind resource has specific characteristics that make it interesting for power generation. Smooth surfaces such as on open water (roughness class = 0) generate a low friction of the air flow and thus a laminar state of the air flow (low turbulence). Consequently, the wind profile in the sea is more uniform with increasing height than on land. On the other hand, as wind speed decreases and turbulence increases as the airflow approaches the coast, offshore wind resources generally have higher speeds and less turbulence than nearshore wind resources (WIZELIUS, 2015). These are several advantages of offshore wind energy over onshore wind energy.

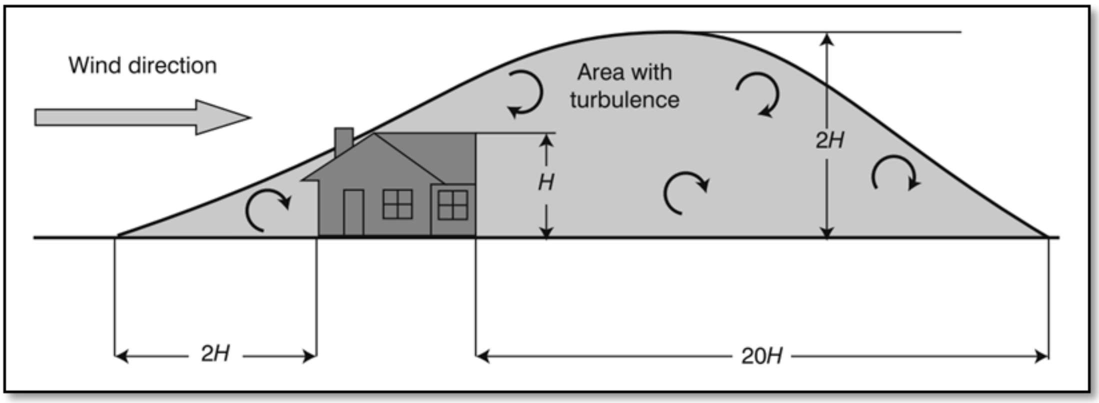


Figure 2-3. Wind turbulence caused by obstacles.
Note: If H is taken as the height of the obstacle, the turbulence is perceived at a distance of 2H upwind and 20H downwind. In the vertical axis, the turbulence is perceived up to a height of 2H above the ground after the obstacle.
Source: WIZELIUS (2015).

The current research area does not cover the wind resource estimation, but aims to use wind resource estimation data for further analysis. Nevertheless, basic concepts are important to understand the structure of the spatial model and the use of the spatial data of offshore wind resources.

2.3.1.2 Wind power

The kinetic energy per unit time or power in the wind (P_{wind}) is calculated on the mass flow of air and the continuity equation of fluid mechanics, represented by Eq. 2-1.

$$\boldsymbol{P_{wind}} \textbf{ or } \boldsymbol{Porwe\ density} = \frac{1}{2}\boldsymbol{\rho A U^3} \ \textbf{ in } [\boldsymbol{W/m^2}] \qquad \textbf{Eq. 2-1}$$

Where ρ is the air density (varying from 1.115 to 1.225 kg/m^3 under standard conditions DE ASSIS TAVARES *et al.*, 2020), U is the wind speed (assumed to be uniform), also called undisturbed updraft, and *A* is the circular area formed by the blades – depending on the rotor diameter – also called the swept area. Figure 2-3 illustrates this basic concept.

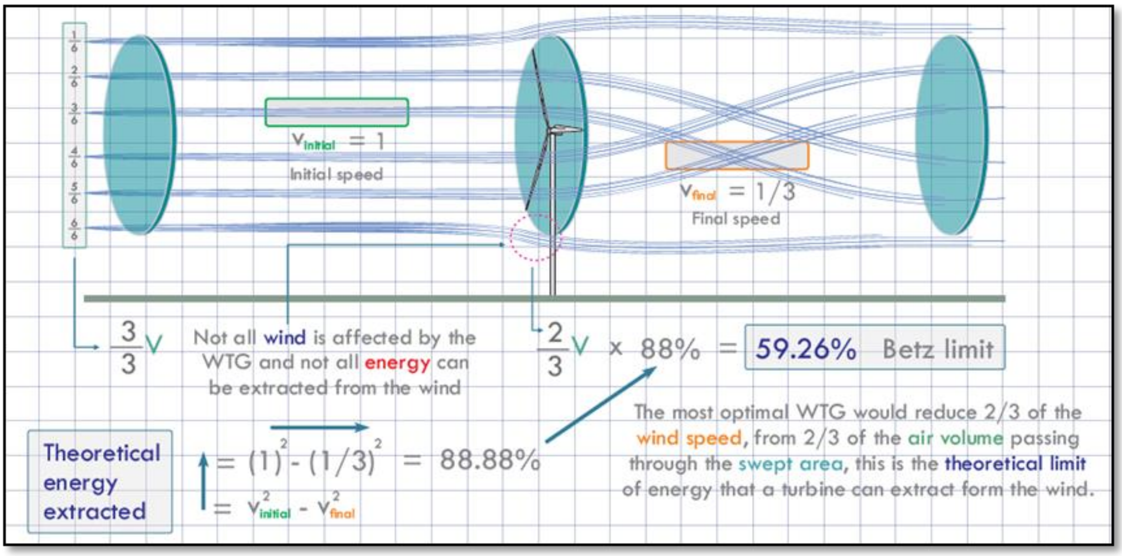


Figure 2-3. Wind power and turbine efficiency.
Source: Extracted from SIMPLE RENEWABLES (2020).

Other metric used to characterize the wind resource is the energy generated by a wind turbine. The power transferred to the wind turbine generator is measured in W/m^2 and can be expressed as follows:

$$\boldsymbol{P_{tur} = C_p P_{wind} = \frac{1}{2}\rho A U^3 \mathrm{C}_p} \qquad \textbf{Eq. 2-2}$$

Where C$_p$ in % is the power coefficient that represent the portion of power extracted by the turbine technology from the wind energy (sometimes it is also called efficiency of the drive train and symbolized by the Greek letter η). This concept refers to the wind turbine efficiency. In 1962, Albert Betz, a German physicist, used momentum theory to demonstrate the maximum efficiency that an ideal wind rotor can achieve. This value was estimated at 59.3% (16/27) and it refers to the portion of the kinetic energy of the wind that an ideal wind rotor can generate.

This means that a wind turbine driven by buoyancy force can theoretically extract a maximum of around 59.3% of the energy contained in the wind and convert it into electricity; this power coefficient is also referred to as the Betz limit (C$_{pmax}$) (MATHEW, 2007; WIZELIUS, 2015; ANAYA-LARA *et al.*, 2018). Current wind turbine technology achieves an efficiency (C$_p$) of between 25% and 50% (ANAYA-LARA *et al.*, 2018; SIMPLE RENEWABLES, 2020).

Figure 2-4 illustrates the difference between the recoverable gross wind resource and the maximum technical wind resource due to the physics limitations of current wind turbine technology.

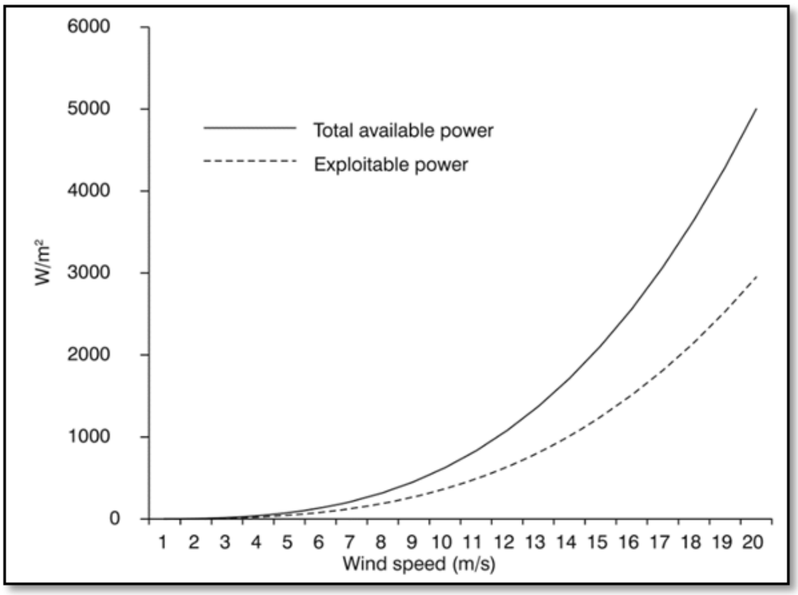


Figure 2-4. Total available power vs. exploitable power of the wind resource. Source: WIZELIUS (2015).

Sometimes the power density of the turbine is confused with the capacity density of a wind farm or a specific area. The Capacity density of an area or a wind farm is calculated by dividing the total installable capacity by the total area of interest (MULAS HERNANDO *et al.*, 2023).

The capacity factor is considered one of the most important indices as it is used to evaluate the field performance of a wind turbine (MATHEW, 2007). It measures how much energy can be generated from the wind in a given period, typically one year. The CF is defined as the ratio between the energy actually generated by the turbine and the energy that the same turbine could technologically generate in a given period at its rated power (MANWELL *et al.*, 2009; MATHEW, 2007; WIZELIUS, 2015; ANAYA-LARA *et al.*, 2018). The capacity factor depends on the location and technology of the wind turbine and is considered a measure of the wind resource (WIZELIUS, 2015). General capacity factor calculation is represented by Eq. 2-3:

$$\mathbf{CF} = \frac{\boldsymbol{Annual\ Energy\ Production}}{\boldsymbol{Rated\ Power} \times \mathbf{8{,}760}}\ [\%] \qquad \textbf{Eq. 2-3}$$

As mentioned above, social and environmental constraints must also be taken into account when estimating the technical potential. Nevertheless, further technical, environmental, social and economic analyses can be carried out to improve site selection and minimize environmental problems. In this context, site selection is the most effective measure within the mitigation hierarchy to avoid impacts on the environment and biodiversity (BENNUN *et al.*, 2021).

The characteristics of the entire space influence the conversion of the wind's kinetic energy into electrical energy by a wind turbine. However, since losses occur with every energy transfer – the energy conversion – the flow conditions and the conversion efficiency are important (BENNUN *et al.,* 2021). The generated electricity is then transmitted to the grid connection point, where transmission losses also occur. The energy can be delivered to a decentralized consumer such as the chemical industry, an O&G offshore platform or an isolated community (MANWELL *et al.,* 2009). Current research focuses on grid-connected systems. However, the theory and most of the concepts can also be applied to distributed systems.

2.3.1.3 Wake effect

Wind turbines can also be an obstacle for other wind turbines. However, the behavior of the wind flowing through a wind turbine is different. Turbines extract some of the kinetic energy from the wind and convert it into electricity. The wind that has just passed the turbine has a lower kinetic energy and higher turbulence than before it reached the turbine. This effect is referred to as the "wake effect" or "wind suction" (GONZÁLEZ-LONGATT *et al.,* 2011; WIZELIUS, 2015). A lower wind speed generates less energy and the turbulent wind increases the dynamic mechanical load on the structure. MANWELL *et al.*, (2009) stated that "[…] *when turbines are close together, wake effects reduce overall energy production.*" Therefore, it is important to consider the wake effect when planning wind farms in order to maximize energy production and turbine lifetime (GONZÁLEZ-LONGATT *et al.,* 2011).

JENSEN (1986 apud WIZELIUS, 2015) developed the Single Wake Model, which relates the wake effect to the distance of neighboring wind turbines (considering a rate of 7.5 meters every 100 meters downwind of the rotor). The wind speed increases with distance until the wind has completely recovered its kinetic energy – *i.e.*, until the wake effect disappears. He used equation 2-4 to show the relationship between the wind speed *v* and the distance to the rotor *x*:

$$\boldsymbol{v = \mathrm{U}\left[1 - \frac{2}{3}\left(\frac{R}{R + \alpha x}\right)^{2}\right]} \qquad \textbf{Eq. 2-4}$$

Where *v* is the wind speed *x* meters downwind of the rotor; *U* is the undisturbed wind speed upwind of the rotor; *R* is the radius of the rotor; and α is the "decay constant". The scalar α represents how wake vortices expand with distance and can be estimated more precisely using the equation Eq. 2-5 (GONZÁLEZ-LONGATT *et al.,* 2011):

$$\boldsymbol{\alpha = \frac{1}{2\,ln\left(\frac{z}{z_0}\right)}} \qquad \textbf{Eq. 2-5}$$

Where z is the hub height and Z_0 is the constant of the “surface roughness”. For offshore environments, roughness class 0 (no impairment by an upwind obstacle), the wake constant α is usually equal to 0.04 meters, otherwise 0.08 meters is a suitable value (GONZÁLEZ-LONGATT *et al.*, 2011; WIZELIUS, 2015).

This model (see Eq. 2-5) assumes a wake vortex that increases its diameter linearly, from A_0 at the turbine to $A(x)$ at a distance of x in the wind direction (see Figure 2-5). This assumption makes it possible to determine the proportionality between the radius *R* and the distance *x* behind the turbine (GONZÁLEZ-LONGATT *et al.*, 2011). Figure 2-5 illustrates the simple wake model.

WIZELIUS (2015) emphasized that Jensen’s model is the first to describe the wake effect. Although more complex models were developed later (see AMIRI, SHADMAN, *et al.*, 2024), the simple wake model illustrates how the wake effect can influence the spacing between the turbines and the design of the OWF. This simple model can be used in the development phase for site selection during strategic planning stages. More complex wake models are used for turbine design and micro-siting, usually with respect to small-scale wind resources and time series between seconds and days (MANWELL *et al.*, 2009, WIZELIUS, 2015).

On the other hand, the wake vortex effect not only affects the efficiency of power generation and the dynamic load on the structure. The wake vortex effect can increase the barrier effect that a wind farm exerts on birds and cause critical impacts such as behavioral and habitat disturbance (HERNANDEZ C. *et al.*, 2021).

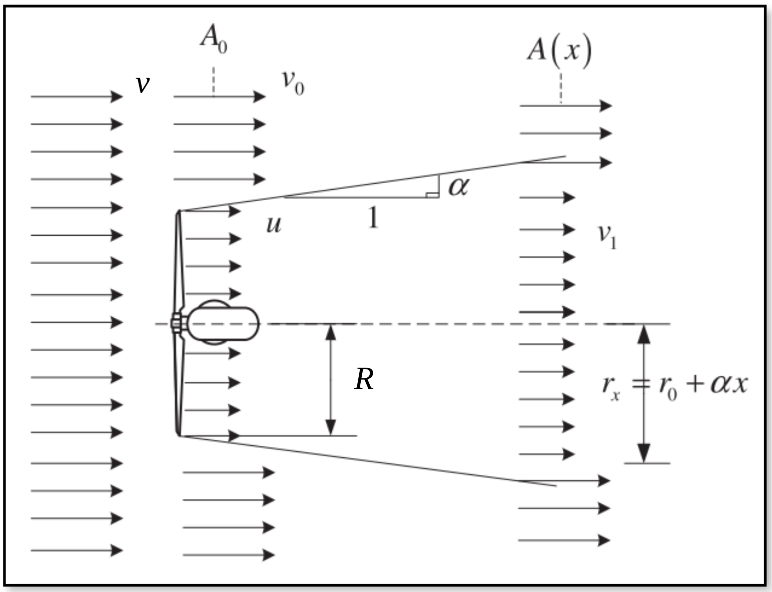


Figure 2-5. J. O. Jensen single wake model assuming linear expansion of the wake cone. Source: Adapted from GONZÁLEZ-LONGATT *et al.*, (2011).

A common practice in strategic stages is to neglect the wake effect in energy calculations (BEITER *et al.*, 2016; SCHILLINGS *et al.*, 2012). In the development phase, the energy losses caused by the wake effect are then included in the turbine separation, which influences the conceptual design of an OWF (see subsection 2.3.1.4). These studies dealing with the design of offshore wind turbines have considered a distance between the turbines of 5RD to 8RD, where RD stands for the rotor diameter. Section 2.3.3 explains the theory behind the calculation of the turbine spacing and the layout of the wind farm. Chapter 3.8 analyzes turbine spacing as one of the input parameters used in applied OWE spatial planning studies. The parameters vary depending on the approach of the study.

2.3.1.4 Offshore wind farm layout

The aim of a wind farm is to bundle wind turbines in order to simplify the technology and increase economic viability. EL-SHARKAWI (2017) defined the distance between turbines as the minimum distance between the blade tips of neighboring turbines. However, the inter-turbine spacing must ensure that the wind recovers downstream (speed and low turbulence conditions for power generation) before reaching the downwind turbines. This minimizes losses due to the wake effect (EL-SHARKAWI, 2017; MANWELL *et al.*, 2009). The spacing of the wind turbines is a strategic parameter as it has a direct impact on the layout of the wind farm and the total area (see Figure 2-9 and Figure 2-10).

The design of an OWF also affects the ecological and economic factors of the wind project. From an ecological perspective, OWFs represent an artificial barrier that influences bird behavior and the distribution of marine mammal habitats (DAI *et al.*, 2015; MASDEN *et al.*, 2015; WILSON *et al.*, 2010). The placement and spacing of wind turbines can therefore increase or decrease the barrier effect on wildlife. In economic terms, energy production can increase when the distance between turbines increases, but costs and energy losses also increase, creating complex problems and many trade-offs (ELKINTON *et al.*, 2008, p. 13). As an example, Figures 2-6 show linear layouts, while Figure 2-7 shows the square layout of a commissioned offshore wind farm.

Figure 2-6. Linear layout of an OWF from horizontal view.
Source: HUNTER (https://unsplash.com/photos/-Are4snbNOE).

Figure 2-6. Linear arrangement of an OWF, the distance between the turbines is clearer than in the horizontal view.
Source: POWER TECHNOLOGY (2021).

Figure 2-7. Square layout of an OWF.
Source: FRASER (2020).

Various conceptual models for the design of wind farms can be found in the literature. Square and diagonal layouts are the most popular arrangements for designing the spacing between turbines (see Figure 2-8). The square layout is more suitable for sites with variable wind directions; the distance between the turbines is calculated by the Eq. 2-6 (EL-SHARKAWI, 2017):

$$\boldsymbol{S} = \frac{\boldsymbol{D}}{\boldsymbol{2r}} \qquad \textbf{Eq. 2-6}$$

Where S is the separation factor, *D* is the distance between two neighboring towers and *r* is the length of the blade (taking into account *R* ~ *r*, but *R* > *r*).

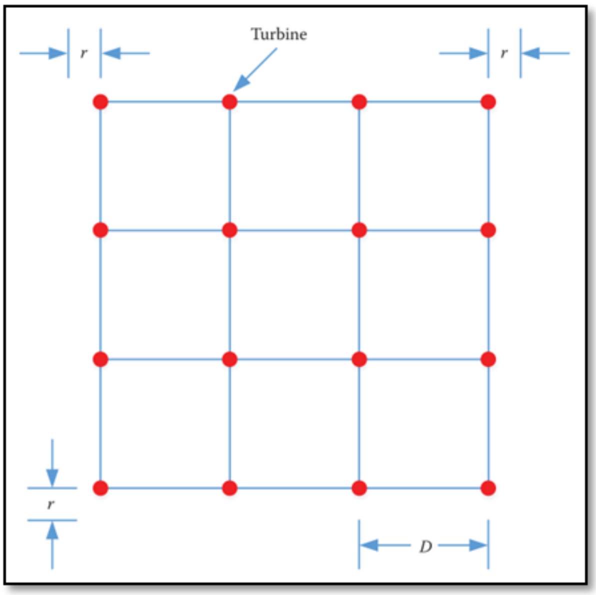


Figure 2-8. Square layout or square arrangement of a turbine array; recommended for variable wind directions.
Source: EL-SHARKAWI (2017).

The diagonal arrangement is preferred for locations with constant wind directions, such as coastal locations (see Figure 2-9). Two distances are used in this configuration: *D1* represents the distance – parallel to the wind direction – between the turbines and *D2* represents the distance between the turbines facing away from the wind – perpendicular to the wind direction (EL-SHARKAWI, 2017).

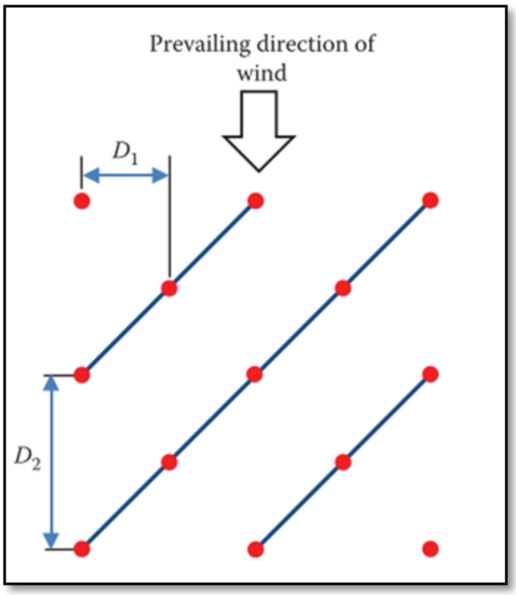


Figure 2-9. Diagonal layout or diagonal arrangement of turbines array, recommended for constant wind directions.
Source: (EL-SHARKAWI, 2017).

D_1 and D_2 commonly range as follows (EL-SHARKAWI, 2017):

$$6r \leq D_1 \leq 10r$$
$$10r \leq D_2 \leq 20r$$ **Eq. 2-7**

These ranges may reflect the analysis of turbulence generated by obstacles (see Figure 2-3), which shows that the wind requires a distance equal to 20 times the height of the obstacle downwind to fully recover its properties.

WIZELIUS (2015) has shown how the different distances between the turbines ensure the separation between parallel and perpendicular turbines in a diagonal arrangement. Figure 2-12 shows how the total area of influence increases as the turbines become larger.

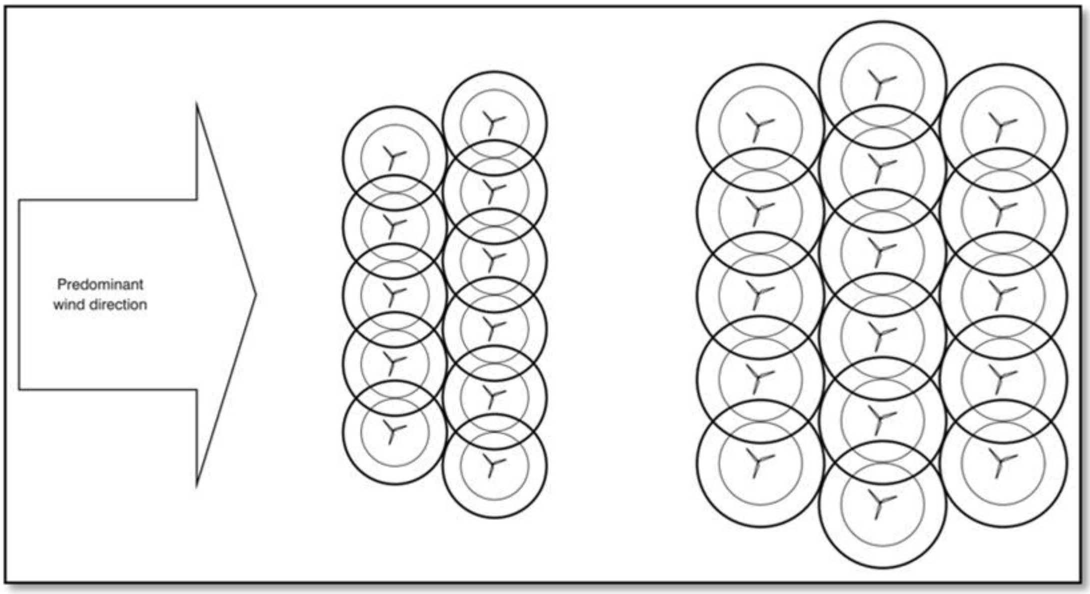


Figure 2-12. Total area of the offshore wind farm depending on the distance between the turbines. Source: WIZELIUS (2015).

According to WIZELIUS (2015), a rule of thumb for the configuration of the distances between the turbines for offshore environments can be *D1 = 6RD* and *D2 = 8RD*. Figure 2-10 illustrates this possible configuration.

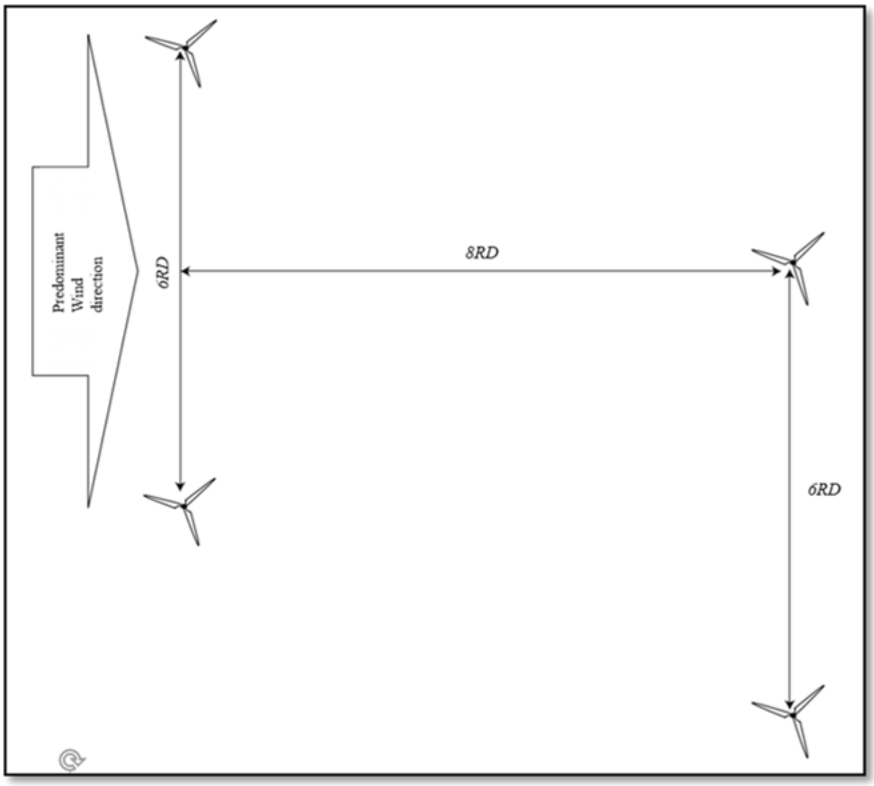


Figure 2-10. Distances between turbines in diagonal layout.
Source: adapted from WIZELIUS (2015).

As mentioned above, the total area becomes a strategic factor for two reasons: first, in onshore environments, the total area required by the wind farm must be equal to or less than the area available for the construction and operation of the wind farm – this affects the scale and cost of land acquisition (EL-SHARKAWI, 2017). Secondly, wind farms in offshore environments are becoming larger and larger. They then require larger available areas to avoid conflicts with other industries such as the offshore O&G industry or to prevent environmental impacts (HERNANDEZ *et al.*, 2021). The total area required to install a wind farm depends on the number of turbines, the length of the rotor blades and the spacing factor (EL-SHARKAWI, 2017). If a square arrangement is chosen (Figure 2-8), the total area can be calculated using Eq. 2-8:

$$\boldsymbol{A_{Sq} = [(T-1)D+2r]^2} \qquad \textbf{Eq. 2-8}$$

Where A_{Sq} is the total area of the wind farm in a square arrangement, T is the number of turbines in a row, D is the distance between adjacent turbines within a square arrangement and r is the length of the rotor blades.

Eq. 2-8 shows that the analysis of the total area depends on three variables: the number of turbines T, the distance between the turbines D and the length of the rotor blade r. However, the rotor diameter (RD) = $2r$ is the most important parameter; it can be considered as an independent variable, since only the technological development of wind turbines or power generators can change this variable. The distance between the turbines depends on the rotor diameter, as shown in Eq. 2-8 indicates. The number of turbines depends on the total installed capacity required for the conceptual project or to ensure the economic viability of the project. The calculation of the total area therefore depends directly on the technical characteristics of the selected wind turbine.

Offshore wind turbine technology has made it possible to increase the size of the turbines in order to increase the swept area and thus generate more energy. As the blades and turbines become larger, OWFs span larger areas (see Figure 2-12) to optimize energy production. As a result, larger wind farms in offshore environments bring with them additional environmental and social issues that can also have significant and cumulative impacts (BASTOS *et al.,* 2016; BRABANT *et al.,* 2015; MASDEN *et al.,* 2010).

Most relevant studies on offshore wind turbine planning have used the quadratic array as the standard conceptual model to simplify the complexity of the calculations (BEITER *et al.,* 2016; HONG, 2011; SCHILLINGS *et al.,* 2012). Regarding the environmental analysis, the total area defines most of the environmental components that may be affected by the project. Defining the total area of influence for each component (geophysical, ecological, social and economic) is mandatory in the EIA process. This includes the area that may be directly and indirectly affected by the project (IBAMA, 2020).

As OWFs occupy larger areas than onshore wind farms, the technological analysis has become more important and a key factor in the early planning phase to avoid environmental and social impacts, especially in site selection (BENNUN, J.;, *et al.,* 2021). Technological analysis is important as the differences between the technologies of turbines, support structures and the electrical system can impact the project and the environment in different ways. Compared to other industries such as onshore wind and O&G, the differences can be significant. For example, the total number of turbines within the site of an offshore wind farm and the size of the turbines are typically much larger than for onshore wind farms (BARRETO, 2019); there are different support structures for the foundation of fixed-bottom offshore wind turbines and they require many more structures to generate the same amount of power compared to offshore O&G platforms. Therefore, these differences need to be analyzed in the early planning phase.

2.3.2 Offshore wind farm components

An offshore wind farm project consists of a meteorological system, a support system, wind turbines and an electrical system (KAISER & SNYDER, 2012). Among them, the turbine technology, the foundations and the electrical system are the most important from an environmental planning point of view. Figure 2-11 depicts the components of a typical offshore wind farm project depending on the project phase (only considering fixed-base technologies).

As Figure 2-11 shows, the components of the meteorological system are mainly required during the development activities (also called survey activities). In addition, the geophysical survey vessel and the biological resources survey vessel are required. The support system, the wind turbines and the electrical system are installed during the installation phase. However, these components will continue to interact with the environment during the operation and maintenance phase.

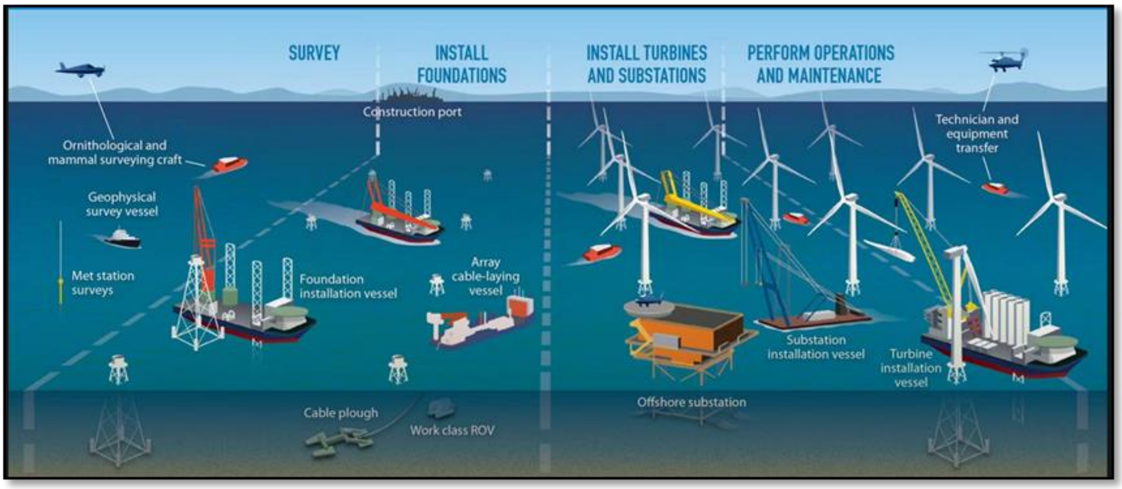


Figure 2-11. Offshore wind farm project components.
Source: CLEAN ENERGY GROUP (2017).

Meteorological systems include the measuring instruments (which can be mounted on a mast or buoy), the foundation of the mast or the anchor of the buoy, the platform with the boat load and other equipment (KAISER & SNYDER, 2013). Other meteorological measurement systems such as LiDAR and SODAR were used to characterize the meteorology of the project area (BVG ASSOCIATES, 2019a). In this subsection, these components are not discussed in more detail, as the differences between the technologies have not shown any significant impact on the dynamics of the offshore environment. Instead, the main components of an offshore wind farm are described in the following subsections.

2.3.2.1 Offshore wind turbines

An offshore wind turbine is the machine that enables the kinetic energy of the wind to be converted into electricity. The main differences between offshore wind turbines and their onshore version are two: size and surface treatment. Offshore wind turbines are larger than onshore wind turbines and have a special anti-corrosion coating on the structures (BARRETO, 2019).

The components of a wind turbine are: Tower, rotor hub, rotor blades, nacelle, gearbox, main shaft, generator and primary systems. Most authors agree that the tower, rotor hub, rotor blades and nacelle are the most important components of a turbine (BARRETO, 2019; KAISER & SNYDER, 2013; KALDELLIS & APOSTOLOU, 2011). Figure 2-12 shows the largest wind turbines in the world in 2022, all of them offshore turbines. The turbine used as an example is an onshore wind turbine; this turbine is 120 meters high and twice the size of a Boeing 747, which is 76.4 meters long, or four times the height of Christ the Redeemer statue, the iconic statue at the top of Corcovado Mountain in Rio de Janeiro, Brazil.

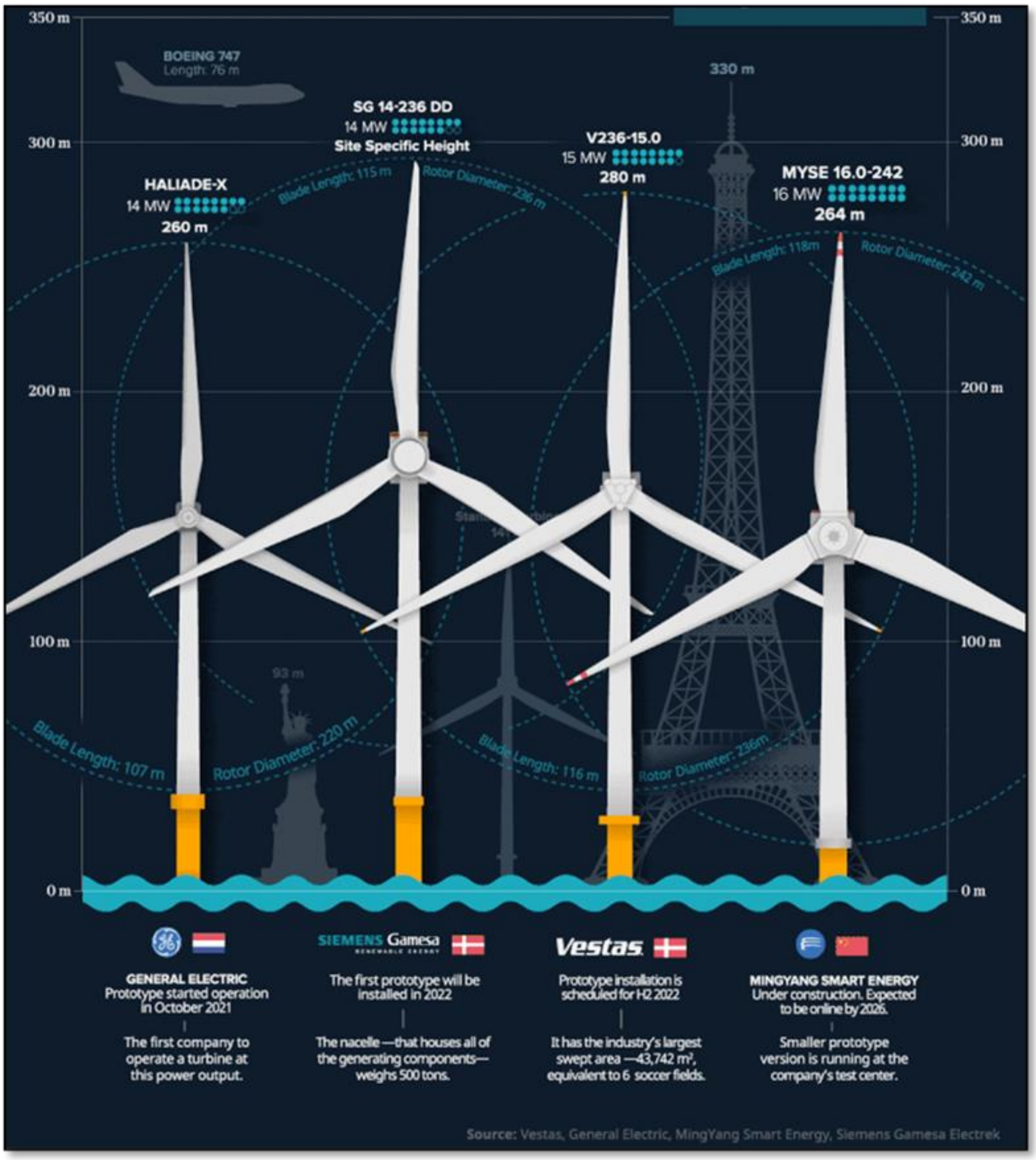


Figure 2-12. Schematic description of the components and functions of the wind turbine in the operating phase.
Source: extracted from ELEMENTS (2022).

In 2020, the Global Wind Energy Council – GWEC (2020) claimed: "*A single offshore wind turbine now has more capacity than the output of the world's first two offshore wind farms combined.*". In early 2021, General Electric launched the Heliade-X with 14 MW rated capacity, 220 meters rotor diameter and a total height of 248 meters (GE, 2021) (more than 6 times the Christ the Redeemer statue). Table 2-3 summarizes the characteristics of wind turbines by 2021. It is important to emphasize that two types of turbines were considered: commercial and reference turbines. The reference turbines are developed by research institutions such as NREL (in the USA) and DTU (in Denmark). The aim of the reference turbines is to serve as an open benchmark and enable collaboration between external researchers and industry. In addition, reference turbines help to develop new advanced technologies and study their impact in order to anticipate market trends, technical or environmental issues (GAERTNER, RINKER, *et al.*, 2020).

Table 2-3. Technical characteristics of offshore wind turbines by 2021.

Manufacturer or Designer	Model	Rated power [MW]	Blade length [m]	Rotor diameter [m]	Total height [m]
WEG	WEG AGW-110	2	~55	110	Ss
Samsung	S7.0	7	85	-	Ss
MHI	MHI SeaAngel	7	~83.5	167	Ss
MHI Vestas	V1364	10	80	164	Ss
Adwen	AD-180	8	88.4	180	Ss
Siemens Gamesa	SWT-8.0-154	8	~77	154	Ss
Enercon	E-126	7.50	~63.5	127	Ss
Ming Yang	SCD (2 blades)*	6	~70	140	Ss
Senvion	Sevion 6.2M152	6.15	~76	152	Ss
GE	Haliade 6MW	6	~75.4	150.80	Ss
Sinovel	SL600	6	~77.5	155	Ss
Hyunday	Dongfang	5.50	68	-	Ss
Adwen	AD5-135	5	~67.5	135	Ss
Alston	Haliade 150	6	73	-	Ss
Senvion	Senvion 6.2M126	6	~63	126	Ss
Siemens Gamesa	SWT-7.0-154	7	~77	154	Ss
Siemens Gamesa	SG 8.0-167 DD	8	~83.5	167	Ss
MHI Vestas	V164-8.0 MW	8	~82	164	Ss
MHI Vestas	V164-10.0 MW	10	~82	164	Ss
GE	Heliade-X	12	107	220	248
GE	Heliade-X	13	107	220	248
GE	Heliade-X	14	107	220	248
MHI Vestas	V236-15.0 MW	15	115.5	236	Ss
NREL	5-MW (R)	5	~64.5	129	154
MaREI & DNV-GL	8-MW (R)	8	~82	164	192
DTU	10-MW (R)	10	~89	178	208
NREL	WTG-15.0-246 (R)	15	~120	240	270

Notes: for comparison: WEG AGW-110 is the most installed onshore wind turbine in Brazil; (R): reference turbines; (~) values calculated based on rotor diameter; Ss: site-specific.
Source: The author based on JONKMAN *et al.* (2009); DESMOND *et al.*, (2016); BAK *et al.*, (2013); WEG (2017); GAERTNER *et al.*, (2020); SHADMAN *et al.*, (2020); DE ASSIS TAVARES *et al.*, (2020); WIND TURBINE MODELS (2021).

2.3.2.2 *Structural support system*

The support system consists of a foundation, transition piece and scour protection. The foundation has the task of supporting the turbine, while the transition piece connects the wind turbine to the foundation and helps to absorb inclination tolerances. The scour protection is designed to ensure mechanical integrity due to the conditions in the sea and on the seabed.

(KAISER & SNYDER, 2012). Foundations are the most important component of the support system (BHATTACHARYA, 2019).

The selection of suitable foundations depends on several factors. Weather conditions, seabed characteristics, equipment and vessels, legal framework and environmental issues generally influence this decision. Currently, foundations are divided into two types depending on water depth: fixed (or grounded systems) and floating foundations. Fixed foundations are divided into different technologies: shallow foundations (“gravity” foundations" and “suction basket foundations”) and deep foundations (“monopile”, “tripod” and “jackets”). Floating foundations are divided into “anchored TLP (tension leg platform)”, “ballasted spar buoy” and “buoyancy stabilized semi-submersible” (BHATTACHARYA, 2019; KAISER & SNYDER, 2012). Figure 2-13 shows the foundation technologies as a function of water depth.

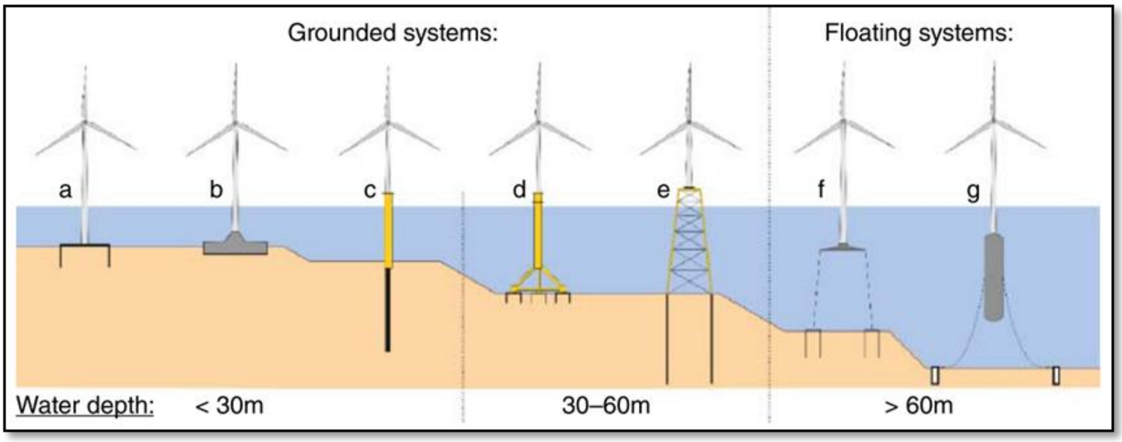


Figure 2-13. Schematic representation of foundation technologies, classified according to water depth.
Note: Fix-bottom foundations: Suction caisson, b) Gravity-based, c) Monopile, d) Tripod and e) Jacket; Floating foundations: f) Mooring and Spar-buoy.
Source: BHATTACHARYA (2019).

Monopiles are the most common foundations and consist of a single large diameter tubular steel pile. The pile is made of tubular steel and typically has a diameter of 3 - 7 meters. Monopiles are usually driven 25-40 meters deep into the seabed. In most cases, monopile foundations are installed in water depths of up to 25-30 meters (BHATTACHARYA, 2019). Figure 2-14 shows real foundations transported by barge.

Less common substructures are jacket, tripod and gravity foundations. A jacket foundation is a welded steel frame made of tubular elements. This type of structure can be founded in the seabed using flexible piles, gravity foundations and suction boxes, also known as multipods. Tripod foundations are three cylindrical tubes driven into the seabed and welded to a central steel shaft that supports the wind turbine. Figure 2-15 shows real jacket and tripod foundations.

Gravity foundations stabilize the substructure by their own weight. They are designed to prevent tipping or lifting; sometimes additional ballast is required (BHATTACHARYA, 2019; KAISER & SNYDER, 2012).

Figure 2-14. Monopile foundations and transition piece.
Source: ARG-Flickr (2012).

Figure 2-15. Jacket foundation (left); Triple foundation supporting an OWT (right).
Source: Mike Marren (left) and Erich Westendarp (right).

The foundation types represent the main technological difference and the technical limitation. Most studies dealing with spatial planning of OWE have divided their analyses based on this difference, i.e. fixed or floating foundations. The current research focuses on the analysis of fixed foundations, as this is the first step in the development of offshore wind energy. Currently, in Brazil, most of the foundations proposed in the early planning phase of OWF projects are monopiles (GWEC, 2021).

2.3.2.3 *Electrical system*

The electrical system enables the energy generated by offshore wind turbines to be collected, transmitted and delivered to the grid at the connection points or to decentralized consumers. Typically, the electrical system includes: "inter-array cables" (33-66 kV) connecting the wind turbines to the "offshore substation"; then the "offshore substation" collects the electricity and increases the voltage to transmit the electricity to the onshore substation via a high-voltage export cable (132-220 kV) (GWEC, 2021). The choice of transmission technology is a strategic factor to ensure the viability of OWF projects and it should be determined during the development phase, preferably in the early planning phase. Distance and total electrical power are decisive factors for the selection of the connection technology of the OWFs (EPE, 2020a). Figure 2-16 illustrates the electrical system configuration required to connect an OWF to the grid.

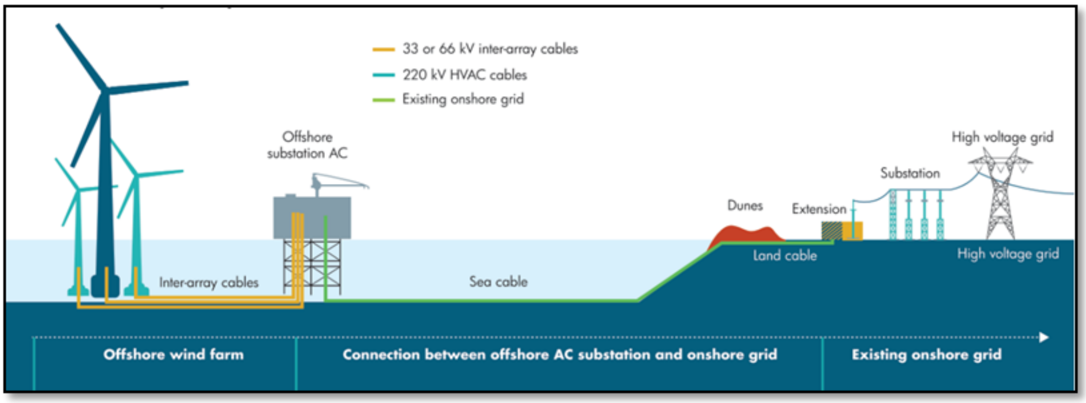
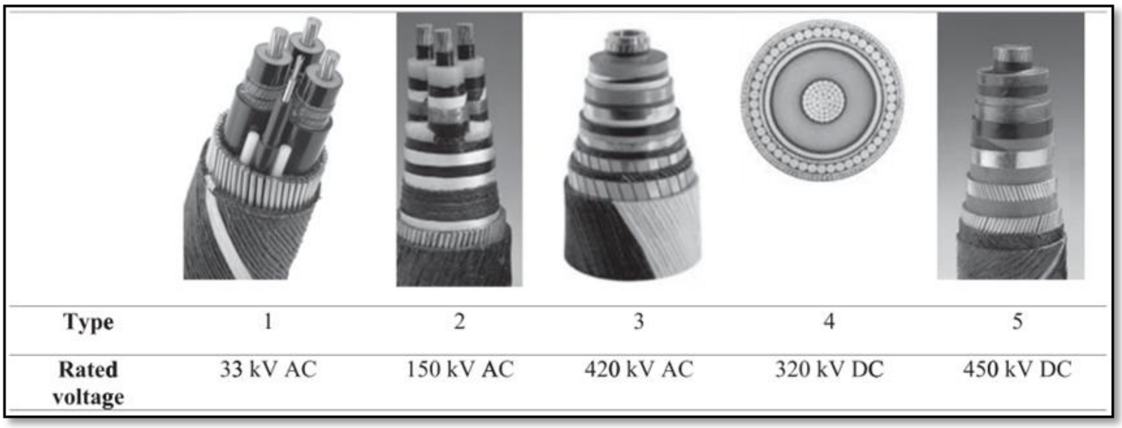


Figure 2-16. Grid connection system.
Source: GWEC (2021).

The electrical system can be configured differently depending on the layout of the plant, the total amount of electricity generated, the distance between the turbines and the substation. Typically, inter-array cables between the fields are designed for voltages between 33 and 66 kV and the transmission of alternating current (see Figure 2-17). They collect and accumulate the power generated by several turbines until they reach the voltage required for the cable connection. Export cables usually have three-core cables with an outer protection of galvanized steel wire (see Figure 2-17). (KAISER & SNYDER, 2012).

Furthermore, the distance between the offshore substation and the onshore substation determines the type of transmission that is used. The transmission between offshore substation and onshore substation depends on the distance. Alternating current transmission is used for distances between 10 and 100 km. Direct current transmission cables are used for distances of more than 500 km (EPE, 2020a, TAORMINA *et al.*, 2018).



Type	1	2	3	4	5
Rated voltage	33 kV AC	150 kV AC	420 kV AC	320 kV DC	450 kV DC

Figure 2-17. Generic submarine power cables.
Note: 1) max. length: 20-30 km, typical rating: 30 MW; 2) max. length: 70-150 km, typical rating: 180 MW; 3) max. length: <50 km, typical rating: 700 MW/three cables; 4) max. length: >500 km; typical rating: 1000 MW/pair cable; and 5) max. length: 20-30 km, typical rating: 30 MW. Three-core cables: 1, and 2; sigle-core cables: 3, 4, and 5.
Source: (TAORMINA *et al.*, 2018).

The function of the offshore substation is to increase the voltage of the collector system generated by the wind turbines to high voltage; the increase is intended to minimize transmission losses. The substation is designed with the total capacity of the OWF in mind and is not always necessary (KAISER & SNYDER, 2012). However, considering the large OWFs that are at an early planning stage in Brazil, most of the proposed OWFs may require an offshore substation. Most foundations used to support OWTs can also support offshore substations in waters up to 60 meters deep; an additional technological alternative is the self-righting foundation (EPE, 2020a). Figure 2-18 shows an offshore substation in operation.

Figure 2-18. Offshore substation.
Source: Askjell Nicolas Randoy.

In Europe, the transmission system operator (TSO) is responsible for connecting the OWF to the grid connection point and the costs are borne by the developers. In contrast, China has made developers responsible for financing the construction of transmission facilities (GWEC, 2021).

The environmental analysis should consider the entire electrical system, focusing on the configuration between the fields and the route of the export cables to identify and avoid sensitive habitats that could be affected by the installation and operation of the cables (BENNUN, J.;, *et al.,* 2021). In addition, the technological analysis should consider the alternatives of the collection systems and balance the trade-offs between the losses due to the wake effect – when turbines are close to each other - and the higher infrastructure costs – when the distance between turbines increases (BEITER *et al.,* 2016). The properties of the soil should be investigated along the cable routes for planning purposes. The studies support activities for scour protection, cable protection and water turbidity modification (BHATTACHARYA, 2019).

On the other hand, a significant increase in electricity capacity through larger turbines and wind farms requires an improvement in transmission methods and an expansion of the electricity grid infrastructure that supports the feeding of high voltages into the grid during consumption peaks (BEITER *et al.,* 2016).

2.4 Supply chain and logistics in Offshore wind

Offshore wind projects requires certain components and a range of materials, raw materials, finished parts, specialized equipment and machinery, skilled workers and highly trained technicians, transportation, storage, private and public facilities, and other resources to install and operate an OWF. Thus, supply chain and logistics analysis is critical due to the nature of the offshore wind industry. All these resources form a complex supply chain that must function as a unified system based on excellent logistical synchronization. Therefore, it is important to define the concepts of supply chain and logistics in the context of the OWE industry.

MENTZER *et al.,* (2001) define a supply chain as the interaction of three or more people or organizations directly linked in the upstream and downstream flow of a product, services, finance or information, from the source to the customer. Another definition is: A generic supply chain is a set of activities and actions performed to maximize the added value of a product or process and provide the organization with a competitive advantage in the respective industry context (PORTER 1985; FEARNE *et al.,* 2012; DEMONEL & MARX, 2015 apud MEDEIROS, 2019). Figure 2-19 illustrates the general relationships between activities and organizations based on Porter’s definition.

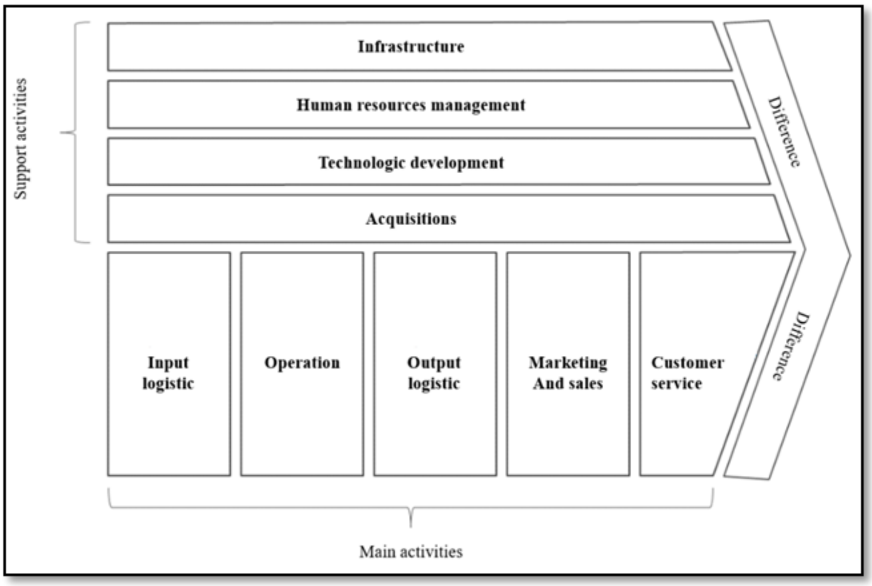


Figure 2-19. Schematic generic supply chain.
Source: Porter (1985 apud MEDEIROS, 2019).

In this context, a supply chain is divided into “main activities” and “supporting activities”. The main activities relate to the production of the good or service. Supporting activities refer to the additional processes and characteristics required for the production of the good or service (MEDEIROS, 2019).

Considering the context of the offshore wind industry and an OWF, academic references have summarized the activities into three main phases: Installation, Operation and Maintenance stages (MANWELL *et al.*, 2009; MATHEW, 2007; WIZELIUS, 2015). However, the analysis of the supply chain and logistics required for the construction of an offshore wind farm is much more complex than shown in Figure 2-19 in terms of the number of resources, supply chain integration and the life cycle and components of the wind farm (DEDECCA *et al.*, 2016).

On the other hand, from a supply chain management perspective, WILDEN *et al.*, (2022) have transformed the classic supply chain model into a Double Bell model, which presents more complex relationships, activities and organizations in a more understandable way. The Double Bell model makes it possible to identify the suppliers and customers as well as the specific relationships with the local company.

WILDEN *et al.*, (2022) stated that with the advancement of information technologies based on computational systems and software such as the Internet of Things or Block Chian, the need for information will increase to reach the new operational levels. Therefore, communication between stakeholders will become a decisive factor for competitiveness. A successful supply chain can only be created if the parties involved communicate effectively with each other. Information about demand must come from customers and information about supply must come from suppliers (WILDEN *et al.*, 2022).

On the other hand, international experience and specialized consulting firms have conducted technical studies using the term supply chain to capture most of the activities involved in an OWF project. In the US, Navigant Consulting (2013) identified the offshore wind market and its supply chain challenges and opportunities. The key challenges were:

- The size of offshore wind turbines, scale of projects, design and site-specific characteristics make it difficult to accurately predict market demand.
- Need for new manufacturing and storage facilities due to larger components and sizes (*e.g.,* foundations, towers, blades and nacelles).
- The US will compete with the leading offshore wind markets in Europe and Asia.
- Significant investment will be required to retrofit or build new offshore wind turbines and offshore wind farms.
- Offshore wind turbine manufacturing capacity in the U.S. will depend on foreign suppliers' perception of stability.
- The impact on employment could reach about 14,000 full-time jobs by 2030 (high growth scenario of 54 GW cumulative capacity).
- The modernization of the supporting infrastructure, starting from a single port, would mean an increase in employment and GDP.
- Market dynamics and speculation increase uncertainty about the nature and scale of the components and make it difficult to predict demand for the scenarios considered.

NAVIGANT CONSULTANCY (2013) also highlighted natural risks such as hurricane risks, surface and sheet icing, and areas of higher water levels as important regional considerations. Specific considerations were made for each of the five coastal regions of the United States (North Atlantic, South Atlantic, Great Lakes, Gulf Coast, and Pacific Coast). These technical studies are relevant because they show the state of the supply chain when the market and technology were not yet mature in the United States. In this context, it is very likely that Brazil can avoid problems related to hurricanes and icing due to its unique site conditions. Nevertheless, the regional and market-specific characteristics must be analyzed and the experiences of other markets taken into account.

In terms of the physical components of an OWF, the study also identified the key components that need to be supplied in an offshore wind supply chain as follows:

- Wind power potential
- Offshore wind turbine generators
- Gearboxes and generators
- Turbine electronics: power converters and transformers
- Bearings
- Pitch and yaw systems

- Castings and forgings
- Blades
- Important materials for blades: resin and reinforcing fibers
- Towers
- Offshore foundations and substructures
- Offshore subsea cables
- Offshore substations
- Installation and construction vessels

Specific environmental analyzes should be considered for these components, agricultural potential, offshore wind foundations and substructures, offshore subsea cables, installation and construction vessels. In section 3.7, these components are analyzed as part of the sustainability approach for OWE. In addition, offshore wind supply chain requirements should be estimated based on regional development scenarios and technological profiles such as in the US (NAVIGANT CONSULTING, 2013) or in Europe (CAMERON *et al.*, 2011). Analyzing the deployment scenarios and installation targets for OWE in Brazil seems to be essential for strengthening the OWE supply chain.

By 2019, BVG Associates (2014, 2019b) conducted a consultancy analyzing the offshore wind industry in the UK and Norway. The studies divided OWF adoption into six main activities or stages within the supply chain, which are listed below and highlighted in color in Figure 2-20:

1. Development (in red)
2. Turbine supply (in orange)
3. Balance of plant[4] supply (in green)
4. Installation and commissioning (in blue)
5. Operation, maintenance & service (OMS) (in purple)
6. Supporting services (in violet)

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[4] Balance of plan components comprises all wind power plant components different from turbines and foundations.

Figure 2-20. Representation of the offshore wind supply chain in Norway.
Source: BVG Associates (2019b).

On the other hand, BVG Associates (2014) highlighted the potential synergies between offshore wind and other industries in the UK. They identified high synergies with the O&G industry – mainly due to expertise in the offshore environment, ports and maritime logistics – and with the onshore wind industry. Industries such as aerospace, automotive and nuclear have been identified with low synergies and could serve as parallel support sectors (BVG ASSOCIATES, 2014; CARVALHO, 2019; EPE, 2020a, MEDEIROS, 2019).

When analyzing the offshore wind turbine supply chain, the main materials for offshore wind turbines become relevant as they can represent potential bottlenecks in the supply chain for manufacturing the main component of an offshore wind farm. SPYROUDI (2021) has identified Siemens as the main player in offshore wind turbine manufacturing, holding about 60% of the market (approx. 3,700 offshore wind turbines). Among the raw materials used to manufacture turbines, steel accounts for the largest share (71-79% of total turbine mass), followed by fiberglass (11-16%), iron or cast iron (5-17%), copper (1%) and aluminum (0-2%). However, carbon fiber and newer alternative materials are being explored as they could make the final product lighter.

In current research, the developer company or offshore wind project is seen as the main actor within the overall supply chain (or as the Local Firm within Double Bell model of supply chain management). Previous studies and concepts of the supply chain are compiled and condensed into a simplified Double Bell model to illustrate the complexity and importance of the information flows of an OWF supply chain considering an ideal perspective. shows the Double Bell model adapted to an offshore wind farm supply chain (development, installation and operation).

It is important to emphasize that the flow of information along the supply chain is crucial for sound strategic planning and development of an offshore wind project, even in emerging markets such as Brazil. Information from customers must also include indirect customers such as local communities that may not use the energy directly. The inclusion or involvement of these communities as third-tier or indirect customers is not fully discussed in the supply chain analysis. This could be a future obstacle in the roll-out of projects as there could be conflicts with local communities due to information gaps and lack of participation at the lowest level in the early planning stages of projects. Innovative strategies of data collection with higher participation could be used (web-based crowdsourcing or public participation platforms) (RESCH *et al.*, 2014).

Shields *et al.*, (2023) have structured an excellent example of how a supply chain roadmap for offshore wind energy can be conducted. They analyzed the fundamental elements involved in developing a strong national offshore wind supply chain in the US, as:

- Ports and vessels infrastructure
- Manufacturing of critical components
- Tier 2 and 3 suppliers
- Training and manufacturing workforce
- Equity and justice in supply chain development

They found that it could take the US between six and nine years to develop a complete domestic supply chain. Production facilities for offshore wind turbines could cost between 200and 400 million dollars and take 3to 5 years to complete. The development of ports and marine infrastructure could limit offshore wind deployment to 14 GW by 2030, given the US target of 30 GW of offshore wind by 2023. Finally, it was noted that job market in the supporting supply chain could provide up to five jobs for every job in large-scale manufacturing facilities.

2.4.1 Offshore wind logistics

There are several elements related to offshore wind logistics, such as ports, vessel infrastructure, manufacturers and components. These elements are critical to evaluating the required logistics of an OWF and vary from country to country and region to region, i.e. port infrastructure is not equally developed in all offshore wind resource hotspots. Port infrastructure and vessel availability have been identified as strong bottlenecks globally, while logistics and marine transportation are clear barriers for the offshore wind industry (CHEN, 2020).

2.4.1.1 Ports

Ports are one of the most important infrastructures influencing the development and deployment of offshore wind turbines. They serve as facilities for receiving, assembling and offloading components during installation and as an operational base for repairs and operations during the O&M phase (BEITER *et al.*, 2016). Figure 2-21 shows the Aberdeen port and suggested installation port and O&M port layouts.

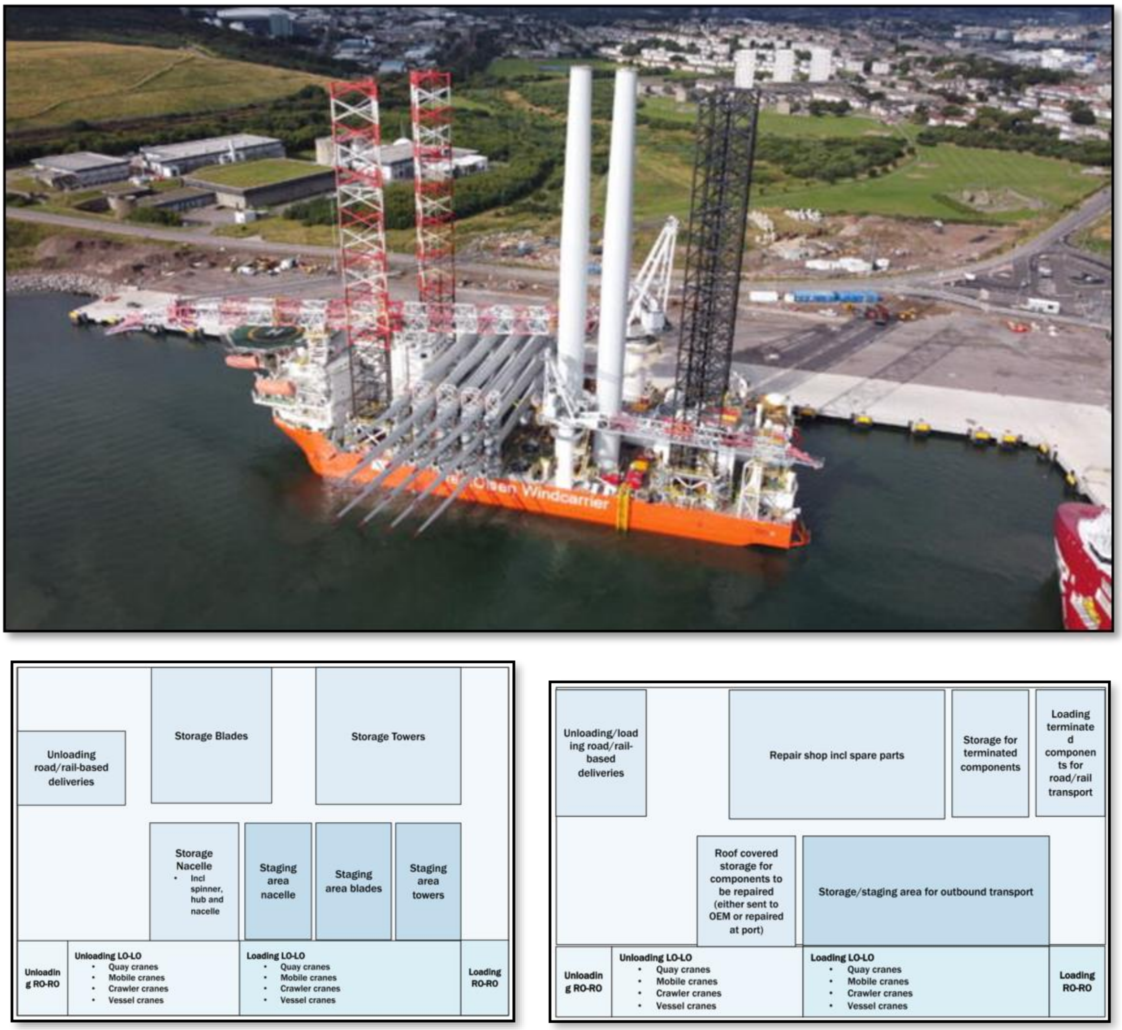

Figure 2-21. Port and installation vessel.
Note: Aberdeen port (Top); Suggested port layout: installation (bottom lef), O&M (bottom right).
Source: PORT OF ABERDEEN (2023) and AKBARI (2015).

As main pivot point, ports must have minimum characteristics for operation (SHIELDS *et al.*, 2022). Table 2-3 summarizes the basic physical characteristics that ports must ensure depending on the different components they can handle.

Table 2-3. Fabrication port requirements for fixed-bottom offshore wind components.

Component	Laydown Area (m^2)	Quayside Length (m)	Channel/Berth Draft (m)	Bearing capacity (t/m^2)	Air Draft (m)
Blade	323,748.5	120	6	15	25
Nacelle	161,874.3	500	10	15	25
Tower	182,108.5	150	10	7.5	25
Monopile foundation	404,685.6	500	8	12	25
Jacket foundation	323,748.5	150	8	15	60
Gravity-based foundation	40,468.6	500	10	15	250

Component	Laydown Area (m^2)	Quayside Length (m)	Channel/Berth Draft (m)	Bearing capacity (t/m^2)	Air Draft (m)
Cable	182,108.5	150	6	15	50
Transition piece	202,342.8	500	10	15	40
Steel plate	1,214,056.9	500	10	15	25
Flange	202,342.8	150	6	15	25
Foundry	202,342.8	150	6	15	25

Source: SHIELDS *et al.*, (2023).

In addition, ports that support offshore wind energy activities must provide most services related to (PORT OF ABERDEEN, 2023):

- Survey and inspection vessels and transportation of components
- Know-how and facilities for the production of components
- Transportation and installation vessels, crane barges, service operations vessels, and anchor handling equipment for installation and commissioning
- Installation vessels for the installation of substructure components (cable laying and rocks)
- Service vessels, crew transfer vessels, walk-to-walk vessels, cable-laying vessels, operation and maintenance vessels and remotely operated vehicles (ROVs)
- Construction vessels, crane vessels and auxiliary vessels for repowering and decommissioning.

2.4.2 The status of the supply chain in the Brazilian context

In the Brazilian context, there are few studies that directly address offshore wind energy and its supply chain, as the country does not yet have a consolidated offshore wind industry (MEDEIROS, 2019). Building a well-established supply chain requires significant investment and time to acquire the expertise to build new production facilities, improve the supporting infrastructure and produce basic components domestically or import foreign technology.

Nevertheless, Brazil has advantages over the rest of Latin America due to mature industries such as onshore wind and offshore O&G production. The national onshore wind industry is a suitable starting point to diagnose the status of a future offshore wind turbine supply chain in Brazil.

In 2018, ABDI (2018) updated the study on the wind energy industry supply chain. The results showed more details on the components and stakeholders related to the status of the onshore wind industry supply chain. Figure 2-22 summarizes the goods, services and players that are already established for the onshore wind industry.

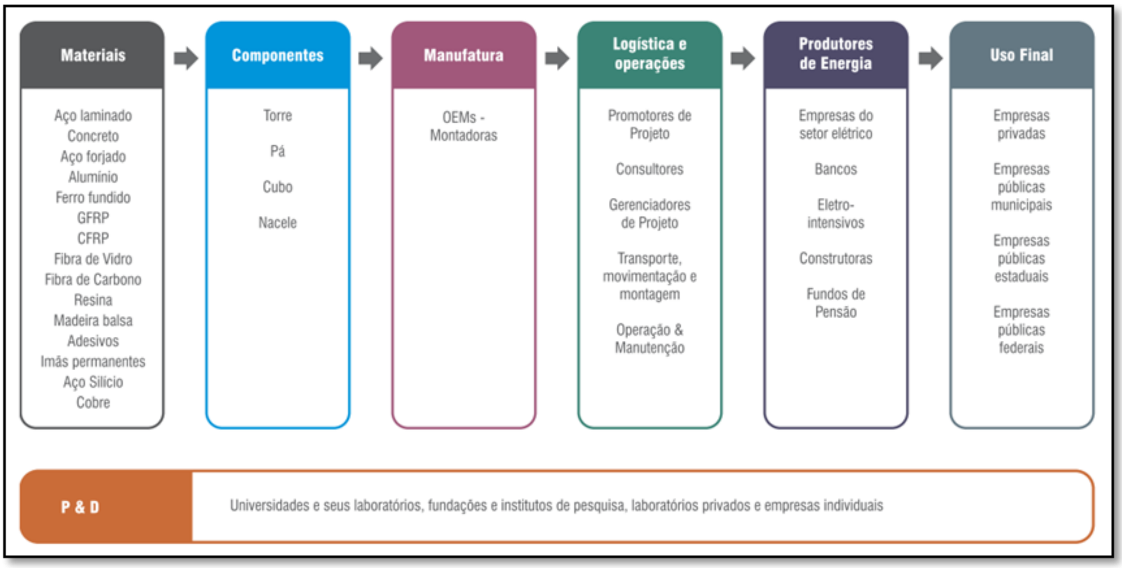

Figure 2-22. Onshore wind supply chain of goods and services.
Source: ABDI (2018).

However, the Energy Research Office – EPE (2020a) has recommended that the supply chain for the onshore wind industry needs to be updated to meet the requirements of the offshore wind industry, especially the technological and spatial requirements. This update could be possible through the identification and evaluation of manufacturers and suppliers in each segment of the Brazilian market that have recognized experience and expertise to provide products or services to the offshore wind industry. Figure 2-23 proposes an initial approach for mapping an offshore wind farm supply chain using the Double bell model (WILDEN *et al.*, 2022).

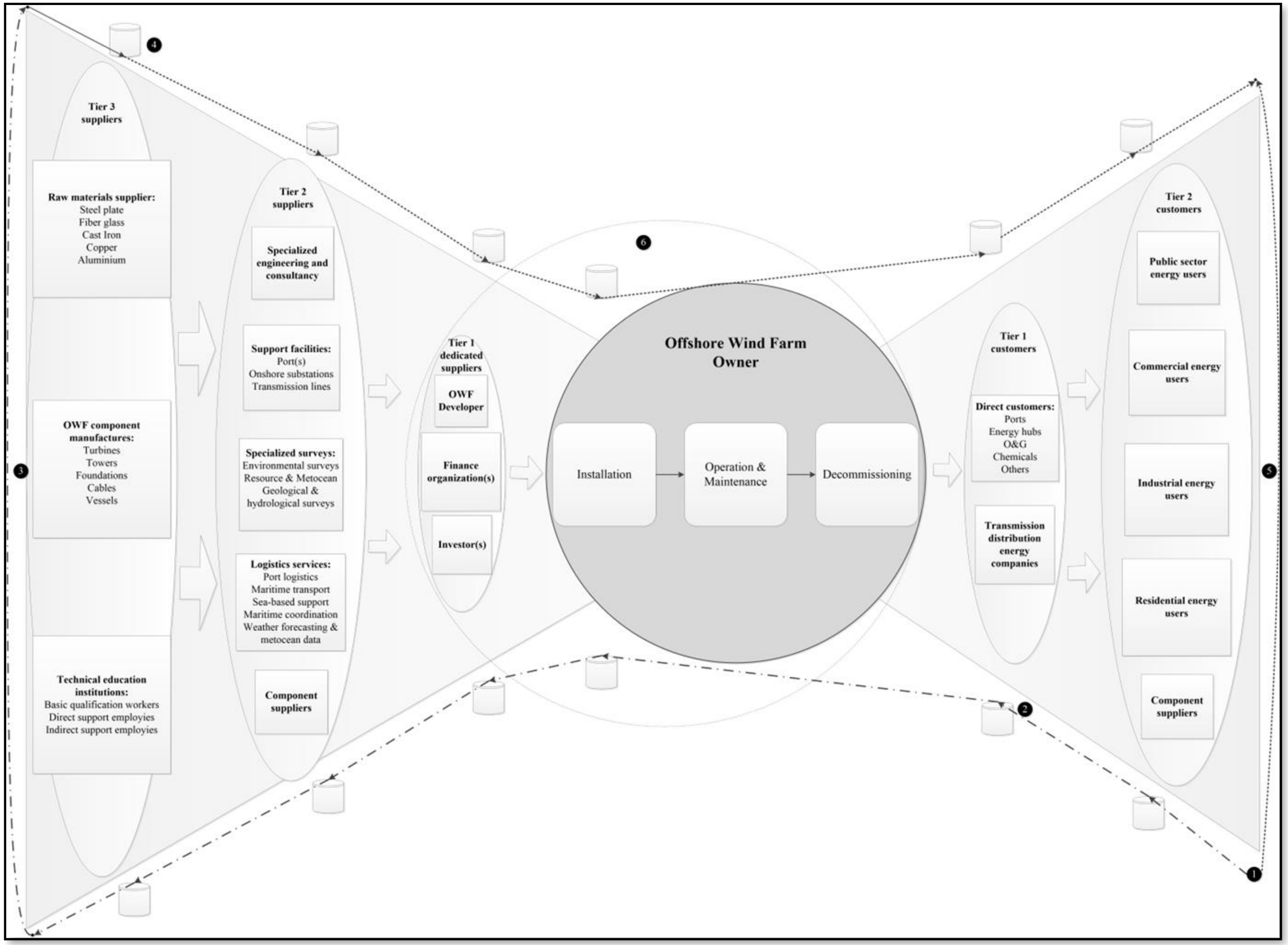

Figure 2-23. Double bell model of an offshore wind farm.
Note: 1) Demand information is provided by the customer, 2) Coding, transmission, decoding of information from customer to supplier, 3) supply feedback, 4) Coding, transmission, decoding of information from supplier to customer, 5) demand feedback, and 6) orchestration of the supply chain. Linear arrows: Information flow; wide arrows: Transportation. Squares: value creation process; round squares: project phases.
Source: The author based on ARAUJO *et al.*, (2023); BVG ASSOCIATES (2019a); DEDECCA *et al.*, (2016); SPYROUDI (2021); WILDEN *et al.*, (2022).

In 2019, MEDEIROS (2019) analyzed the criteria required for a rapid and dynamic development of the offshore wind supply chain in Brazil, relying on a five-dimensional framework: national and environmental policies, chain coordination, professionals, technology and innovation, and infrastructure to achieve techno-economic viability. Figure 2-24 depicts these five dimensions, emphasizing the presentation of strong environmental policies as a necessary foundation for this goal.

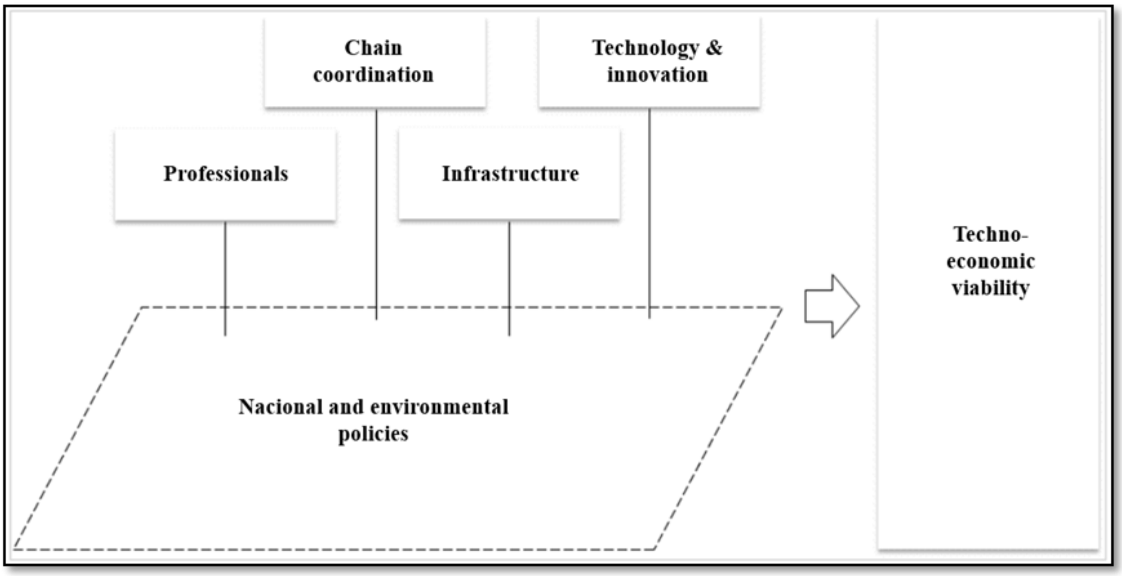

Figure 2-24. Proposed framework for offshore wind development in Brazil.
Source: Translated from MEDEIROS (2019).

The study also emphasized that all preliminary studies, including environmental impact assessments, should be carried out before developers set prices in order to reduce uncertainty and volatility. One of the key guidelines suggested by this study is that strategic planning initiatives should consider the role of ports in the investment and lifecycle of the project. The role of ports is strategic and should include the establishment of an industrial technology hotspot, as projects may require ports for storage, installation and operation. Technological adaptation to manufacture nacelles for higher power turbines is the main challenge identified in the Brazilian supply chain adaptation study.

In this study, the guidelines were formulated based on a theoretical ideal supply chain for offshore wind energy in Brazil, after analyzing the case of Denmark (MEDEIROS, 2019). Based on MEDEIROS (2019), Table 2-4 summarizes a schematic ideal supply chain configuration that considers the main activities and components for the Brazilian market.

Table 2-4. Ideal theoretical supply chain of the offshore wind in Brazil.

Supply-chain	Component	Criteria	Services	Products
Input logistics	Techno-economic viability	National incentive policy, current technology (from	Assessment of wind resources (including	Detailed databases (metoceanic,

Supply-chain	Component	Criteria	Services	Products
		manufacturing to R&D policy)	measurement consultancies)	geophysical, biological, socio-economic, logistics, labour).
	Environmental viability	Environmental agencies, environmental regulatory framework, society, communities	Service companies such as archeologic consultancies.	Baseline information products
	Manufacture industry	R&D of new technologies, qualified professionals, trained workforce, available raw materials	Educational specialized services in OWE	Turbines (Nacelle, blades, rotors), Towers, foundations, cables, vessels and barges, transmission structures and substations.
	Support services industry	Maritime and inland support logistics	Installation services	Components, equipment, vessels, and barges.
Operation	O&M	Qualified & specialized professionals and trained workforce	O&M services	Ports systems & logistics
Output logistics	N/D	Decommissioning activities	Decommissioning services	Equipment, vessels, and barges.

Note: N/D: not defined.
Source: The Author based on MEDEIROS (2019).

According to TOLMASQUIM *et al.*, (2022), Brazil faces a number of challenges in the coming years that need to be overcome in order to build a strong and competitive supply chain in the OWE industry. The main challenges concern the planning and expansion of transmission infrastructure, the improvement of port infrastructure and logistics, the availability of raw materials (*e.g.*, steel and copper), the adaptation of the manufacturing industry and the strengthening of the regulatory and financial framework. They emphasised that the planning process, regulatory framework and costs are the main bottlenecks in the development of offshore wind energy in Brazil. Nevertheless, the experience and expertise of the country's offshore O&G, onshore wind and construction industries offer a strategic advantage compared to other emerging markets.

In terms of employment and labor, Araujo *et al.*, (2023) have identified three occupational profiles commonly associated with the wind energy industry as direct jobs; these profiles are grouped into three groups: technological development and manufacturing of wind turbines; b) construction and installation; and c) operation and maintenance of OWFs. Indirect jobs are identified as other jobs along the supply chain that are not directly related to the previous groups.

In addition, the study (ARAUJO *et al.*, 2023) bases the methodology for estimating employment in the wind industry on SIMAS (2012). The methodology estimates the direct employment index and the indirect employment multipliers; the multiplier is based on the updated input-output matrix; both were calculated from the number of jobs estimated for each MW of installed capacity during the different phases of a wind project. In 2018, there were 14 specialized manufacturers in the wind energy sector (blades, towers and nacelles) in Brazil, with an average employment profile of 467 employees, 32.6% with primary education, 6% in technical-scientific occupations and a salary of R$8,470 (approximately US$1,617 by 2023). Projections estimated 37,140, 44,047 and 44,939 direct jobs by 2025, 2030 and 2035 respectively.

For the offshore wind industry, RUTOVITS (2015, apud ARAUJO *et al.*, 2023) proposes employment factors for manufacturing (15.6 employees/MW). Construction and installation (8 employees/MW), operation and maintenance (0.2 employees/MW), together 23.8 employees/MW.

The supply chain implies a broad vision of the industry that goes beyond the activities that directly add value to the product or service, in this case the generated electricity. The supply chain includes supporting activities and other resources such as production of raw materials, manufacture of main components (turbine, foundations and connection), supporting infrastructure, human resources, technology development, acquisitions and, for major projects, the involvement and acceptance of local communities. These elements should be analyzed during the strategic planning process and along the supply chain and logistics analysis of an OWF. All of these components influence strategic decisions about localization that directly impact the final cost of projects.

Overall, understanding the offshore supply chain is important to identify the elements and activities, time and embedded costs – especially the cost breakdown – required to assess the potential and development needs of an offshore wind farm. In a sustainability approach, its is necessary a wide understanding of the dynamics and relationships that may exist between the OWF and its supply chain (suppliers and customers) regarding all development dimensions (technological, environmental, social and economic).

The identification and details of the development process and activities for offshore wind projects are essential for the implementation of a successful supply chain in Brazil. Therefore, details of the installation, operation and maintenance, and decommissioning phases were researched and explained in the related study Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study from Brazil (HERNANDEZ C. *et al.*, 2021). However, details on the economic side of offshore wind energy are not examined in this study. The following section therefore explains the economic aspects of offshore wind development.

2.5 The economic viability of offshore wind energy

The economic factor plays a strategic role in the decision-making process for development of offshore wind projects. The wind projects must generate energy in a competitive system. The theory divides the competitiveness of wind energy into three variables: 1) energy production, 2) longevity and 3) cost-effectiveness (MATHEW, 2007). The last variable, cost-effectiveness, is analyzed by wind energy economics. Wind energy economics deals separately with two main components: 1) generation costs and 2) market value of wind energy (MANWELL *et al.*, 2009). Figure 2-25 presents both components and their key-drivers.

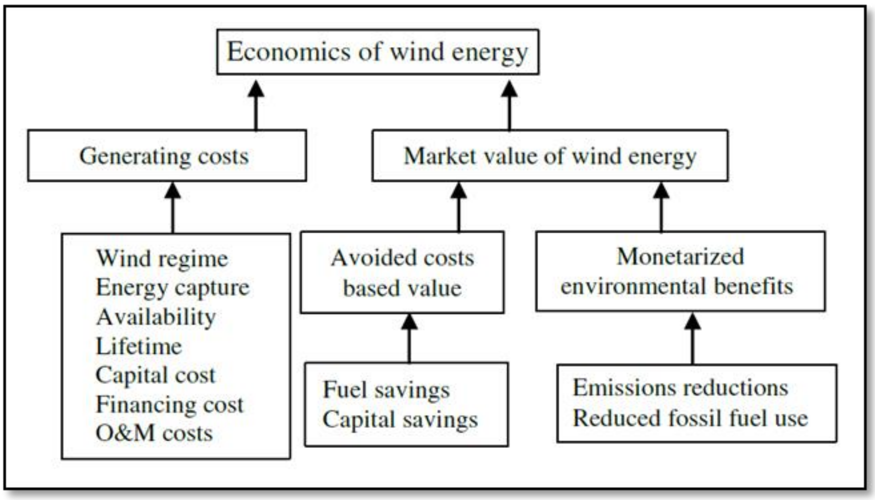

Figure 2-25. Components of wind system economics.
Source: MANWELL (2009).

Economic evaluation used to be the most important factor alongside system efficiency, energy production, climatic benefits or environmental impact. Developers of OWF projects look for attractive projects to invest their resources with the least risk. EDERER (2016) emphasizes that the evaluation of the development, installation and operating costs of OWFs are the most important issues in this industry.

The first approach to achieve cost efficiency is to optimize project costs, trying to reduce the cost per kWh to a minimum (MANWELL *et al.*, 2009; MATHEW, 2007). The factors that influence the total generation costs of wind energy are:

- wind regime
- energy capture efficiency of the wind turbines
- availability of the system
- lifetime of the system
- capital costs
- financing costs
- operation and maintenance costs.

However, this economic approach does not consider environmental aspects and possible external effects or externalities.

Firstly, three factors do not depend on the economic valuation. Wind, energy production and availability depend on natural resources and weather conditions, but technological capacity can be influenced by social and environmental constraints (see section 3.7). Capital, financing and operating costs depend on other factors, which are explained later in this subsection. It is important that the cost analysis should not be separated from the environmental and social concerns if the goal is to increase the sustainability of the project in the long-term.

BLANCO (2009), for example, claims that the costs of onshore wind energy are unknown to many. The situation is similar today with the costs of offshore wind energy. Economic analysis needs to give more importance to social and environmental factors in order to incorporate externalities in terms of time and resources into the decision-making process.

EDERER (2016) has produced a relevant study on the economics of offshore wind energy and the basic pre-investment decision process. This approach includes four main assessments: 1) definition of technical design, 2) assessment of expenditure, 3) assessment of remuneration and 4) assessment of profitability. Within this conceptual framework, the spatial and environmental factors are incorporated during the strategic stages – and not only in the operational stages as is usually the case. Figure 2-26 shows the basic process prior to the developer's final investment decision (FID).

POUDINEH *et al.,* (2017) emphasize on understanding the key drivers of offshore wind energy in order to promote project viability. The key difference with onshore renewables, such as solar and onshore wind, is the harsh environment in which the energy is generated. The offshore environment and its weather limit most activities (POUDINEH *et al.*, 2017a). Additional cost elements that need to be considered in the offshore environment are port logistics and vessel costs, travel costs for personnel, equipment and insurance due to the increased risk (SNYDER & KAISER, 2009).

Expenditure evaluation involves three key concepts related to the economic evaluation of an energy project: capital costs, financing costs and operation and maintenance costs. Energy projects typically receive subsidies to reduce these costs and support new industries in emerging or developing markets. Carbon taxes and emissions trading schemes (ETS) are additional cost-effective instruments used to promote low-carbon technologies such as offshore wind energy (POUDINEH *et al.*, 2017a). In the current research, these instruments are not considered as they are beyond the scope of the research, but subsidies, carbon taxes and ETS are strategic cost components that should be considered in further studies.

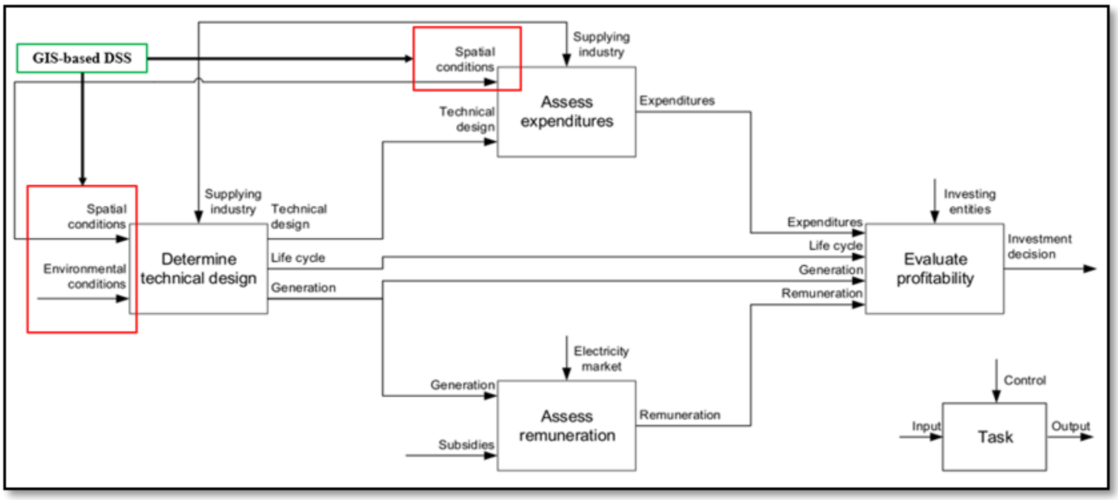

Figure 2-26. GIS-based decision support system embedded into the investment process decision for an offshore wind farm.
Source: modified from Ederer (2016).

Regarding the specific case of offshore wind energy, the literature has defined the main drivers required to estimate the costs of offshore wind energy (KAISER & SNYDER, 2012; EDERER, 2016; POUDINEH *et al.*, 2017a; BROWNING, 2019). These main drivers (cost components) can be summarized in groups:

- Capital expenditures (Capex).
- Operation and maintenance expenses (OPEX).
- Financing costs or fixed charge rate (FCR).

These concepts are integrated into the LCOE as a cost-benefit assessment, which together with local and regional electricity prices represent the economic potential of offshore wind energy (GILMAN *et al.*, 2018). However, LCOE is one of the simplified methods used in the economic analysis of wind energy projects and it has been used to indicate cost performance in specific contexts and locations (BEITER *et al.*, 2016; MANWELL *et al.*, 2009).

The modeling of capital costs and the calculation of the LCOE depends on several factors, including water depth, proximity to the coast, wind speed at the site, the presence of port and harbor infrastructure nearby, socio-economic factors, availability of skilled labor, the location of the national grid and the hinterland associated with the proposed project (BHATTACHARYA, 2019).

Other authors such as LESSER (2020) have expressed concern about the real costs of various offshore wind projects that have been implemented in Europe over the last decade. He also warned of the possibility that winning bidders may underestimate actual costs over time as newer, larger turbines show a sharp decline in energy production and reliability. This could lead to unexpected costs or lower revenues, which could cause developers to abandon the turbines before the power purchase agreement (PPA) expires.

2.5.1 Offshore wind economic potential

The economic potential of energy projects has emerged as a measure of the economic dimension in strategic stages. The most common approach is the cost-benefit analysis represented by the LCOE estimate, which focuses on the overall costs compared to the overall energy production (benefits).

There are various approaches to LCOE that take into account general or more detailed cost components, depending on the required accuracy and data availability. Among these approaches, the most frequently cited approach (BEITER *et al.,* 2016; HONG, 2011; MANWELL *et al.,* 2009, SCHILLINGS *et al.,* 2012) is defined by the Eq. 2-9 as follows:

$$\boldsymbol{LCOE = \frac{FCR(Capex) + Opex}{AEP}} \qquad \textbf{Eq. 2-9}$$

Where LCOE stands for the levelized cost of energy. Levelization is a process by which the costs or revenues to be paid during equal periods *N* (usually in years) in the future correspond to a present value, taking into account the discount rate for each payment over the lifetime of the project (MANWELL *et al.,* 2009). AEP represents the annual energy production – in most cases without discounting the energy production.

The fixed cost rate (FCR) represents the financial cost as a percentage of the investment cost – it takes into account the discount rate, the capital recovery factor (CRF) and other factors, depending on the specific valuation approach. MAWELL *el al.,* (2009) presents the CFR in Eq. 2-10 as follows:

$$CRF = \begin{cases} r/[1-(1+r)^{-N}], & \text{if } r \neq 0 \\ 1/N, & \text{if } r = 0 \end{cases} \qquad \textbf{Eq. 2-10}$$

Where r is the discount rate and N is the number of payments in years. Various studies have estimated the FCR on the basis of a discount rate of 7.5 % (HONG & MÖLLER, 2011) or 15 % (SCHILLINGS *et al.,* 2012). Beiter *et al.,* (2016) calculated the FCR for each location within the technical offshore area in the USA. Most approaches have defined FCR as a location-specific parameter.

Capex stands for capital expenditure and opex for costs incurred in O&M activities. MANWELL *et al.,* (2009) have described a simpler approach for the LCOE, the EPRI TAG method, which is represented by the Eq. 2-11:

$$\boldsymbol{LCOE = FCR\left(\frac{Capex}{CF \times 8760}\right) + \ Opex} \qquad \textbf{Eq. 2-11}$$

Where CF is the capacity factor, which multiplied by 8760 hours in a year is the AEP. It is important to note that this approach has limitations as it assumes a project life equal to the loan term and does not take into account variable returns on equity, variable debt payments or variable costs (MANWELL *et al.,* 2009). This approach can be applied in early planning stages to illustrate general cost of the projects.

Other studies have used more complex approaches to calculate the LCOE, including the discount for costs and energy production over time (BOSCH, *et al.,* 2019; CAVAZZI & DUTTON, 2016; DOS REIS *et al.,* 2021). BEITER *et al.,* have also categorized costs into fixed costs, variable costs and cost multipliers.

The accuracy of the LCOE calculation also depends on the level of detail of the cost breakdown and the elements that make up the individual cost components. IOANNOU *et al.* (2018) uses a very detailed cost breakdown (see Figure 2-27) to estimate the LCOE. This uses a more complex cost model that levels costs and energy production based on a weighted average cost of capital (WACC) discount rate. This approach is more suitable for further stages where higher accuracy is needed, and input data is available.

The model selection to assess the economic potential of offshore wind projects must consider the stage of development, the available data, and the assessment's objective, being aware of the risks and limitations of each model.

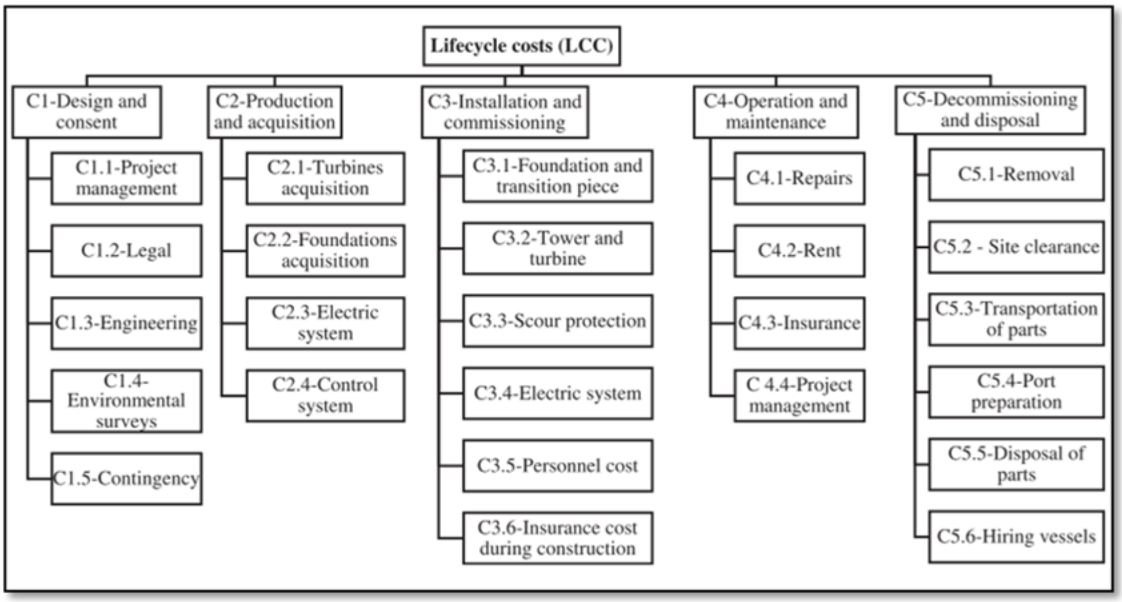

Figure 2-27. Detailed breakdown of life-cycle costs.
Source: IOANNOU *et al.,* (2018).

Chapter 3 – Strategic planning and sustainability

Chapter three presents the theoretical framework related to the strategic planning process and sustainability assessment for offshore wind energy (OWE). Sections 3.1 to 3.5 provide an overview of the state of the art in terms of methodological frameworks and concepts that incorporate the sustainability approach into the strategic planning process of various activities such as Marine Spatial Planning, Strategic Environmental Assessment, or site selection guidelines. Sections 3.6 and 3.7 deal with the concept of the Environmental Impact Assessment to present the state of the art in relation to the environmental impacts of offshore wind energy as a key insight for improving the sustainability of projects. Sections 3.8 and 3.9 present the state of the art related to Decision Support Systems and GIS-based techniques used in the offshore wind industry.

3.1 Strategic planning and sustainability

Strategic planning is defined as a "*periodic process that provides structured approaches to strategy formulation, implementation and control*" (AUSTER *et al.,* 2018, p. 1647). Chen (CHEN, 2020), who examined scenario planning for offshore wind supply chains, compared two recognized approaches: SCHWARTZ (2012) versus SCHOEMAKER (1995) (see Figure 3-1).

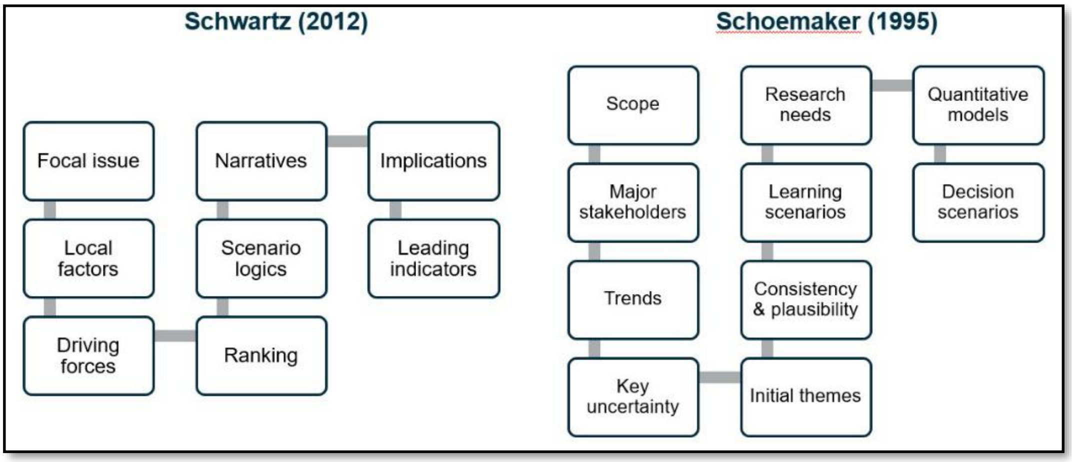

Figure 3-1. Steps of scenario planning. Comparison between Schwartz (2012) and Schoemaker (1995).
Source: CHEN (2020).

This study found that scenario planning is an essential process in the strategic planning process. Scenario planning is about designing and creating a vision of the future to describe different probable futures (CHEN, 2020).

On the other hand, the concept of sustainable planning is directly related to sustainable decision-making, as the planning process is an inherent process of successive decisions to define and achieve goals. HERSH (999) emphasizes that a general principle of sustainable decision-making integrates economic, political, social, ethical and other factors and requires a mix of quantitative and qualitative data.

In this context, according to the GARCIA (2007), the goal of the sustainability approach is to integrate sustainable development principles into the national policies, plans, and programs, and to avoid the loss of natural resources and biodiversity.

Here, the Ecosystem-based approach, which is defined as a strategy for the integrated management of land, water, and living resources that equitably promotes conservation and sustainable use (UNESCO, 2021) and incorporated into the Marine Spatial Planning methodologies, becomes essential for the strategic planning of offshore activities, including the energy generation from renewable resources.

Strategic environmental assessment and environmental impact assessment are instruments for analyzing and evaluating the sustainability of new technologies and potentially environmentally harmful activities. Recalling that SEA focuses on strategic and sectoral analyses of Policies, Plans and Programs (*e.g.*, long-term auction program for leasing O&G blocks)s at the regional level, while EIA focuses on project-specific assessments at the local level (BAKER & BISSET, 2003). The gap in sustainability planning lies in the integration of both approaches (PHYLIP-JONES & FISCHER, 2015).

In an offshore wind farm project, the environmental planning process is carried out by the project developer in the early project planning phase (within the development phase). The aim is to “assess the feasibility of potentially suitable project sites based on a set of criteria” (BENNUN, J., *et al.*, 2021) to ensure the sustainability of the project. Nevertheless, challenges to the sustainability of offshore wind energy development may arise if the government considers SEA only as a requirement that serves to fulfill legal requirements (WU & MA, 2019).

In this sense, several authors have contributed to the discussion on offshore wind farms (OWFs), their environmental impact and sustainability. VAISSIÈRE, LEVREL, *et al.*, (2014) emphasize the legal requirement to introduce a mitigation hierarchy that promotes prioritization of measures to avoid and reduce environmental impacts. This underlines the importance of proactive mitigation strategies in the development of offshore wind farms.

LADENBURG (2009) highlights the importance of the offshore wind issue and emphasize that its impact depends on the specific location of wind farms in relation to the coast. The location of wind farms is a crucial factor in determining their environmental impact. In addition, BAILEY *et al.*, (2014) point out the lessons learned from European experience in assessing the impacts of OWF on marine mammals and seabirds, particularly the importance of understanding the magnitude and significance of these impacts at the population level. Dai *et al.*, (2015b) recommend caution in siting offshore wind turbines near important habitats of native marine species due to uncertainty about their environmental impacts. Finally, Bray *et al.,* (2016) argue for a more comprehensive understanding of the impacts of OWF on seabirds, focusing on foraging success and its consequences for reproduction, survival and population trends. They emphasize the need for detailed research to assess the direct impacts on marine ecosystems. KALDELLIS & APOSTOLOU (2017) highlight the site-specific nature of the impacts of offshore wind farms and emphasize the need for individual studies and tailored approaches for each project to take into account the different environmental impacts at different sites.

For example, in the environmental impact assessment (EIA) of offshore projects within the 12 nautical mile zone of the German territorial sea, LÜDEKE (2017) found that not all negative impacts of offshore wind farms (OWFs) can be prevented or mitigated through spatial planning and technical mitigation strategies, but that compensatory measures will also be required.

The SEA assesses policies, plans and programs, while the EIA deals with the sustainability assessment of specific projects at the local level (IUCN, 2010). There are several differences between these two environmental planning instruments. Figure 3-2 shows that the main differences are in scale and scope. Both instruments interact with each other across the board during the planning and implementation process. These interactions are important because of the relationship that exists between the strategies, plans, programs and projects. This relationship ensures the implementation of strategies and measures for the sustainable development of new initiatives such as the development of a new technology or industry.

Figure 3-2 adds the Scale as another feature that differs between SEA and EIA. The scale or quality of spatial data in the SEA covers regional areas, whereas in the EIA the scale is local and the spatial data must be more precise. Nevertheless, the interaction between the two instruments is crucial for vertical integration, as the results of the SEA provide essential insights for the EIA studies and vice versa. Public authorities and private developers must strive to maintain the vertical relationship and close the gaps – as defined by EALES *et al.,* (2003) – between the two instruments.

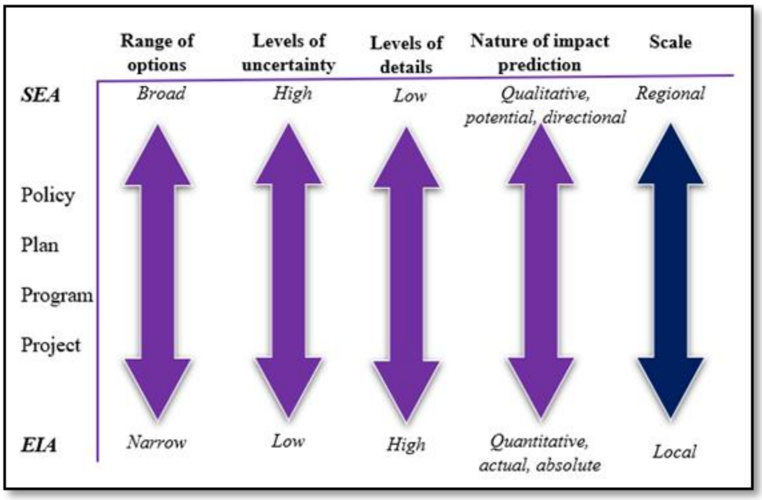

Figure 3-2. Vertical relationship between SEA and EIA, in relation to various interactions. Source: Supplemented on the basis of EALES, SMITH, *et al.*, (2003) and IUCN (2010).

Public and private efforts to overcome barriers that hinder vertical integration between the implementation of policies, plans, programs and projects need to be undertaken to improve the process, tools and data availability to support these instruments, as noted by LÜDEKE (2017).

3.2 Marine Spatial Planning

The Brazilian Energy Planning Agency It is important to deepen the analyzes using metocean data and to include restrictions on exploitable areas, such as environmental protection areas, trade routes, bird migration routes, oil exploration areas or other areas with conflicting uses (EPE, 2020a). In this context, Marine Spatial Planning approach becomes relevant.

Marine Spatial Planning (MSP) is an ecosystem-based approach to the integrated management of land, water and living resources in a way that emphasizes conservation and sustainable use and ensures equitable distribution of benefits (UNESCO-IOC & EUROPEAN COMMISSION, 2021). This strategy, highlighted by UNESCO-IOC and the European Commission in 2021, aims to harmonize human activities in the marine environment while protecting ecological integrity.

A key tool of MSP is zoning, which is used to delineate specific areas within the marine space and establish different rights and responsibilities for different uses based on an assessment of the suitability of each area (Day *et al.*, 2019). Such zoning practices are central to the effective allocation and management of marine resources to minimize conflict and maximize sustainable development. For offshore wind energy, the aim of this approach is to allocate marine areas for energy production (EHLER & DOUVERE, 2013).

In the context of MSP, conflicts can arise between different economic activities. Maritime traffic poses a challenge, especially in regions where production areas are located close to shipping routes. The close coexistence of offshore wind farms (OWFs) with traditional shipping activities can lead to potential conflicts. Where large energy generation areas intersect with shipping routes or shipping hubs, it is important to mitigate the risk to shipping and ideally keep it at or below existing levels. In cases where shipping is permitted within the boundaries of an OWF, the interaction between vessels passing through the wind farm area and those in adjacent shipping lanes must be considered, particularly if the OWF is on the starboard side of a shipping lane, must adhere to the Collision Regulations (COLREGs). These regulations stipulate that vessels in the shipping lane give way to vessels coming from the OWF to ensure safe and efficient vessel operations within the MSP (PIANC, 2018).

3.3 Strategic Environmental Assessment

Until 2023, the Brazilian authorities have not conducted any MSP or SEA studies to guide the deployment of offshore wind energy. In contrast, there is a broad experience in onshore and offshore O&G development (EPE, 2021; GARCIA, 2007; MARIANO *et al.*, 2018; TEIXEIRA, 2008) and hydroelectric power generation (MINISTERIO DE MINAS E ENERGIA, 2007).

The last example of Strategic Environmental Assessment in Brazil was the Environmental Assessment of Sedimentary Areas for Offshore O&G exploration in the marine sedimentary basin of Sergipe-Alagoas and Jacuípe (MAR, 2020). In this study, two scenarios were defined for the assessment: Reference and deployment scenario. The reference scenario was based on the production activities as defined in 2020. Deployment scenario assumes O&G production over the following 20 years, taking into account the discovery of new resources and the expansion of activities.

The strategic recommendations for O&G deployment in these areas were that suitable areas should be included in allocating offshore O&G blocks for exploration. Nonetheless, these recommendations remain with no practical application due to bureaucratic issues. This is a lesson learned from the planning process of the O&G industry that must be prevented in the strategic planning process of the offshore wind industry.

In the same year, according to Energy Research Office – EPE (2020), two draft laws were discussed until 2018 to create the legal framework for SEA as an environmental planning tool (PL N° 3.729/2004 and PLS n° 168/2018), but these initiatives have not been successful so far. On the other hand, EPE (2020) declared the need to adopt SEA as a structural solution for optimising the deployment of offshore wind projects with prior consideration of technical, economic, environmental and other relevant criteria in the national context.

An example of the potential problems that could arise when applying SEA to the offshore wind industry has already been registered in the O&G industry, particularly in the marine environment. Vilardo *et al.*, (2020) claimed that "the implementation of the AAAS in Brazil deserves further attention from scientists and professionals to understand how a long-awaited SEA instrument, developed by consensus, can encounter so many difficulties in its implementation."

According to the Brazilian Ministry of the Environment (MMA) (2002), Strategic Environmental Assessment can use different methodologies to analyze policy and strategic planning. The best known of these are:

- Scenario techniques and technical simulation models
- Analysis of ecological sustainability capacity
- Environmental indices
- Georeferenced information system – GIS
- Multi-criteria analysis and Delphi method
- Cost-benefit analysis

These methods can be integrated into a GIS-based methodological approach to support the strategic planning and sustainability of the offshore wind energy industry. Best practice in the SEA process must include the identification and comparison of equivalent options, the integration of physical, environmental, socio-economic, institutional, and political factors into the simple methodological approaches (MMA/SQA, 2002).

3.4 Hydroelectric inventory study

Other methods related to strategic renewable energy planning reflect local experience with hydroelectric generation. This hydrological inventory manual is a consolidated methodological reference in the country. The high quality of the inventory studies is crucial for the expansion plans and the national energy plans (MINISTERIO DE MINAS E ENERGIA, 2007) and is an excellent guide for strengthening the strategic planning of offshore wind energy.

The Hydrological Inventory Manual aims to provide a set of criteria, procedures and guidelines for estimating the hydroelectric potential of hydrologic basins, taking into account the different stages of project development. These potentials can be divided into technical, economic or socio-environmental and are embedded in scenarios of multiple use of water resources within the hydrologic basins (MINISTERIO DE MINAS E ENERGIA, 2007).

The last version, updated in 2007, added socio-environmental criteria adapted to the Integrated Environmental Assessment (i.e. the Strategic Environmental Assessment for hydroelectric projects in Brazil), as well as specific analyses for the selected alternative in the final studies. In addition, in this version, the methodology and criteria have been updated to take into account the positive socio-environmental impacts of the installation of hydroelectric projects (MINISTERIO DE MINAS E ENERGIA, 2007).

A hydroelectric project comprises five stages: a) estimation of hydroelectric potential, b) hydropower inventory, c) feasibility studies, d) basic project and e) implementation project. These stages are similar to the development process of offshore wind projects, especially in terms of stakeholder involvement and the environmental licensing process, as shown in Figure 3-3 depicts.

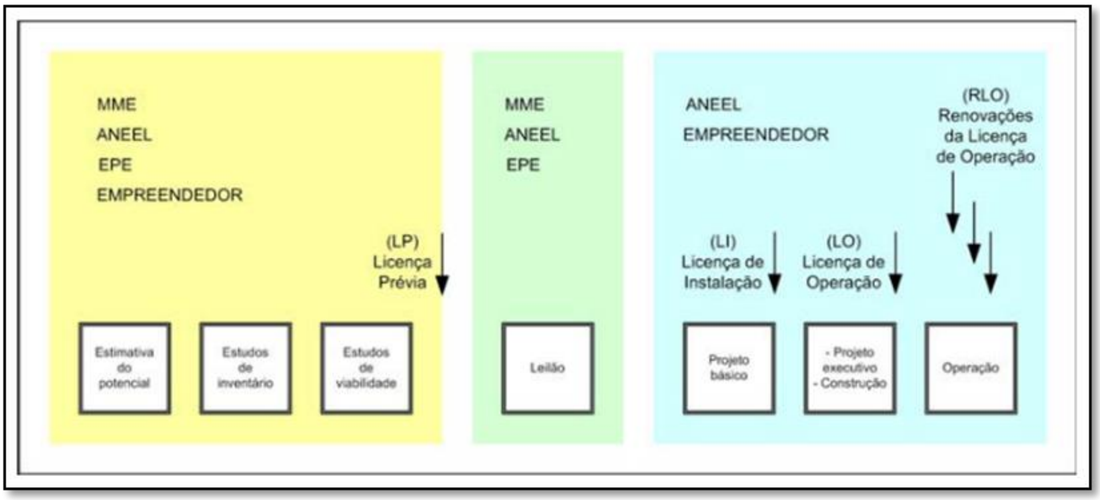

Figure 3-3. Deployment stages of hydroelectric projects.
Source: MME (2007).

This methodology defines specific procedures for selecting the “best option” within a sustainable approach using the analysis of the second-best option(s). It aims to maximize economic benefits while minimizing negative environmental impacts. This approach considers two objectives dealing with the sustainability of the alternatives, taking into account that the economic benefit usually leads to environmental degradation. For this reason, the analysis of the second-best option is carried out with a multi-objective approach: low negative environmental sensitivity (or high environmental suitability) and high economic profitability (cost-benefit) (MINISTERIO DE MINAS E ENERGIA, 2007).

It is important to note that this manual (methodological approach) is linked to the Tool System for Studies of Hydroelectric Inventory (SINV), which shows the importance of computerized systems that support the application of the methodology and the execution of all procedures.

3.5 Site selection and evaluation of criteria for nuclear power plants

Alternative approaches to strategic power generation planning focus on site evaluation. The Electric Power Research Institute (EPRI) (EPRI, 2022) published the structured methodology “Advanced Nuclear Technology: Site Selection and Evaluation Criteria for New Nuclear Energy Generation Facilities (Siting Guide)”.

The aim of the guide is to identify significant changes in the landscape for the construction of new nuclear power plants, to update references, data sources and experience and to check for completeness with regard to social, economic, and environmental aspects.

This methodology is relevant due to the complexity and number of criteria required for the site selection process and the sifting approach, which allows the most suitable sites to be identified in five stages in which the same criteria are analyzed in more detail than in the previous phase. Figure 3-4 illustrates the process.

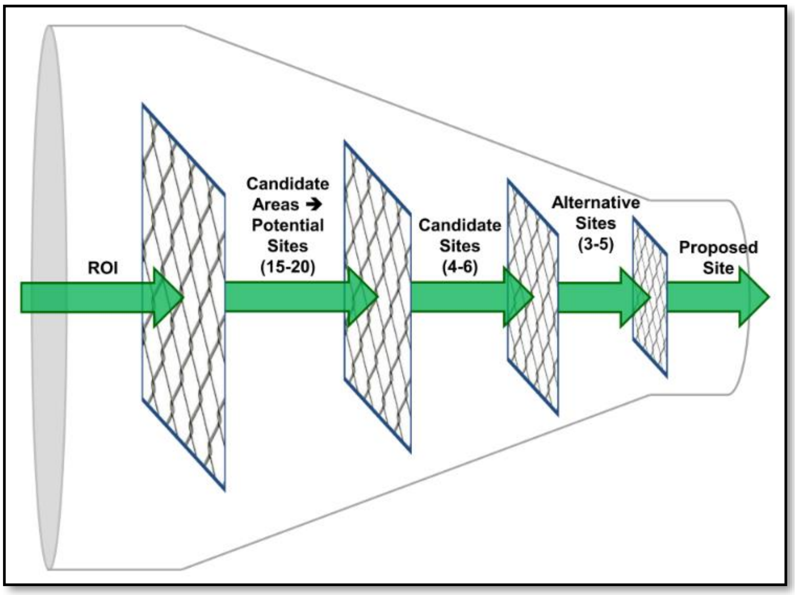

Figure 3-4. Conceptual Site Selection Process for siting a nuclear energy plant.
Source: EPRI (2022).

3.6 Environmental impact assessment

At the local level, the environmental impact assessment is one of the most important tools during the planning and operational phase, as it addresses the sustainability of any infrastructure or energy project (BVG ASSOCIATES, 2019a). This study assesses the potential impact on the geophysical, biological and human environment during the construction stages. The study must include an environmental management plan with mitigation measures necessary to ensure the sustainability of the specific project during its life cycle – sustainability in space and time. For offshore wind projects, a life cycle of 20 years is usually applied (BVG ASSOCIATES, 2019a; MANWELL *et al.*, 2009).

In Brazil, the environmental impact assessment is enshrined in law and is carried out in a legal process called environmental licensing. This legal instrument assesses the sustainability of any project that could have an impact on the environment. In short, the entire process consists of three types of licenses: Pre-Installation License, Construction License and Operating License. These three licenses represent the environmental permits required in Brazil for the development of any environmentally damaging activity. In the case of Offshore wind energy, this procedure is required due to its localization in the coastal environment.

At the end of 2020, the Brazilian Institute of Environment and Renewable Natural Resources – IBAMA (2020) published the Terms of Reference (TOR) as one of the first official guidelines for the environmental impact assessment process. The TOR focuses on the general guidance for obtaining the prior license. However, this instrument does not provide a structured and robust methodology to guide the licensing process for offshore wind farms in Brazil.

3.7 Environmental impacts of offshore wind energy

3.7.1 Environmental impact identification framework

The first challenge in environmental impact assessment is to identify the environmental impacts that could be caused by an OWF. BOEHLERT & GILL (2010) used a classification framework embedded in risk assessment analysis to identify and assess the environmental impacts and effects of marine renewable energy. Other studies used the same approach to analyze the environmental impacts of marine renewable energy technologies. TAORMINA *et al.,* (2018) applied this framework, focusing on cable-laying activities, and GARTHE *et al.,* (2014) used the framework as a 'frame of reference' for examining the environmental monitoring process of marine renewables, particularly offshore wind. Figure 3-5 shows the schematic framework of the approach used in the literature review to identify environmental impacts.

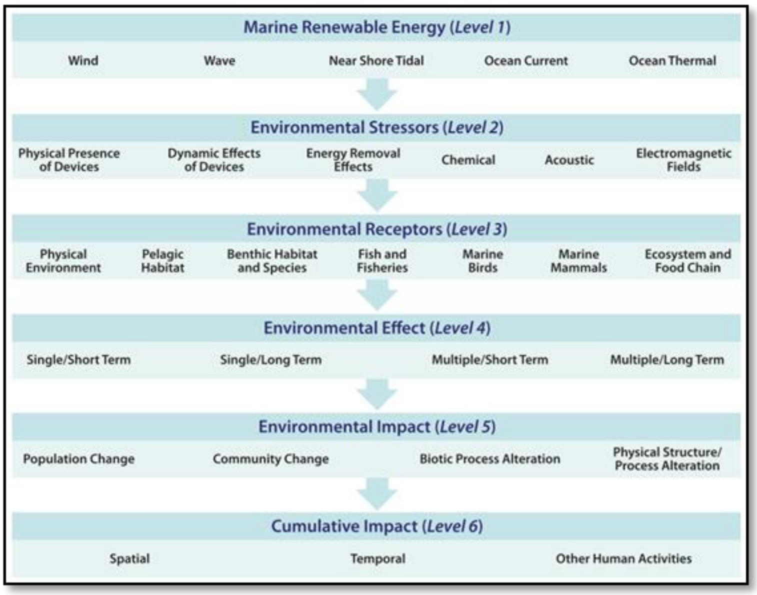

Figure 3-5. Framework for considering the environmental impacts of marine renewable energy, including different scales.
Source: BOEHLERT & GILL (2010).

Given this framework (see Figure 3-5 above) and the need to understand the impacts and the EIA process, the study "*Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil*" (HERNANDEZ C. *et al.*, 2021) was conducted as part of this doctoral thesis (see Appendix J). This study served as the basis for identifying the criteria and set default parameters within the sustainability approach. In addition, this study served as a basis for the collection of spatial data for the compilation of the GIS-based tools included in the GIS-SPOWER-BR Toolbox.

HERNANDEZ *et al.*, (2021) conclude that the spatial data publicly available in Brazil can form a baseline geodatabase to support the strategic planning and definition of offshore wind areas for the development of the country's thin energy resources. However, they also identified gaps in knowledge about native marine species and their spatial distribution that need to be addressed to support the identification, quantification and assessment of environmental impacts.

Further studies on environmental analysis of can be found in MAXWELL *et al.*, (2022), who analyze potential environmental impacts of floating offshore wind turbines, or in BAULAZ *et al.*, (2023), who defined an integrated conceptual model to characterize the impacts of offshore wind farms on ecosystem services.

3.8 Decision support systems for sustainable decision-making

Decision support systems are computerized tools that use techniques, methods and simulation models to support decision-making and participation processes (UNESCO-IOC & EUROPEAN COMMISSION, 2021). They combine decision support methods such as least-cost analysis (LCA), cost-benefit analysis (CBA) or multi-criteria decision analysis (MCA) through user-friendly interfaces for structuring problems and organizing information with little computational effort (HERSH, 1999).

The theory of MCA has been developed since 1960. It uses multiple criteria to support the choice of an action, i.e. this method seeks informed decision making, as an evolved selection of the optimal alternative by maximizing the utility function (HERSH, 1999). Figure 3-6 illustrated the decision-making process.

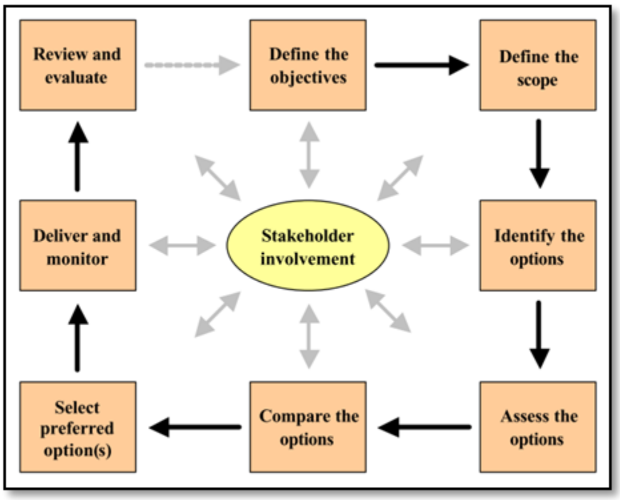

Figure 3-6. Steps in the decision-making and assessment process.
Source: EALES *et al.*, (2003).

Regarding the strategic decision of energy generation projects, the most commonly used approaches are life cycle analysis (LCA), cost-benefit analysis (CBA) and multi-criteria decision aid (MCDA) (STRANTZALI & ARAVOSSIS, 2016). The unifying factor in all approaches is the need to develop comprehensive system solutions, with a focus on achieving the "triple bottom line" goal, which strives for social, economic and environmental sustainability (HARRIS, 2002; POCH *et al.,* 2004; MATTIES *et al.,* 2007).

Regarding the application of multi-criteria assessments and GIS-based approaches, studies have been conducted on the assessment of shale gas (HERNANDEZ C., 2016) and the siting of onshore wind projects (SUNAK *et al.*, 2015),

In addition, numerous studies have integrated spatial analysis into multi-criteria analysis to compare and evaluate alternatives using local and expert knowledge in participatory processes (GONZÁLEZ *et al.*, 2015). Decision makers have used DSS as tools to assess natural resources or to set roadmaps and targets for renewable energy such as solar PV, wave, onshore and offshore wind (GONZÁLEZ *et al.*, 2015, SCHILLINGS *et al.,* 2012).

On the other hand, other approaches have conducted analyses using GIS-based methods and tools to gain insights into issues related to site assessment, natural resources assessment (HERNANDEZ C., 2016, SUNAK, *et al.*, 2015), cost estimation (BOSCH, 2018; BOSCHFELL, *et al.,* 2019, CAVAZZI & DUTTON, 2016; DOS REIS *et al.*, 2021), social values and environmental impacts (PUNT & GROENEVELD *et al.,* 2009) or ecosystem services (SHERROUSE *et al.,* 2011), the localization of industrial facilities to support offshore activities (NUNES *et al.,* 2014) or the optimization of transmission line corridors (CEPEL, 2013), among other applications.

These studies aimed to provide to the decision-makers other resources for dealing with issues related to the localization, and environmental, social and economic factors. This such as habitat disturbance, individuals mortality, physical damage, conflicts with fisheries and oil and gas industry, also the visual impacts and the social acceptance may be mitigated by improving the localization (see Section 3.7).

Public platforms like PAMGIA[5] WebGIS by IBAMA[6], ANEEL[7] WebGIS, ONS[8] WebGIS, and EPE[9] WebGIS are essential for enhancing the implementation of Decision Support Systems (DSS) focused on offshore wind. These platforms offer significant synergies, facilitating data integration and analysis to optimize decision-making in offshore wind projects. As for private initiatives, GEOVOLT (IMAGEM, 2024) is also a compatible system. GEOVOLT is a GIS-based

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[5] Geospatial Analysis and Monitoring Platform for Environmental Information – PAMGIA
[6] Brazilian Institute of Environment and Renewable Natural Resources – IBAMA
[7] National Agency of Electric Energy – ANEEL
[8] National Electric System Operator – ONS
[9] Energy Research Office – EPE

decision support system for the geographic management of renewable energy assets developed by Voltalia and IMAGEM in Brazil. The geoprocessing team uses GEOVOLT (GEO-DSS) for the strategic planning of wind and solar power generation. The time required for data collection and spatial analysis of land constraints has been reduced from one week to less than one day (IMAGEM, 2024).

3.9 GIS-based methods applied to Offshore wind energy

GIS-based methods model spatial relationships, geographic features or estimate indices by integrating the 2D and 3D dimensions, i.e. they include geographic coordinates as additional variables (x, y, z). These analyses can provide information for the localization and siting of large wind farms, including offshore wind farms, and wind turbines.

Previously, MANWELL *et al.,* (2009) divided the process of site selection for wind turbines or large wind systems into five steps:

- Identification of geographic areas that require further investigation
- Selection of candidate sites
- Preliminary evaluation of candidate sites
- Final evaluation of sites
- Selection of micro-sites

Micro-siting is the use of resource assessment tools to determine the exact location of one or more wind turbines on a parcel of land in order to maximize net revenue (MANWELL *et al.,* 2009). The process of micro-siting requires specialized methods (such as the P50 and P90 methods) and computational tools (such as OpenWind, WaSP, WindSIM or CDF models).

However, most of these programs are commercial and require specific input data to perform spatial and resource modeling. Then, DSS focusing on strategic decision making at regional level can support the process of site selection at micro level as a strategy to reduce vertical integration between policy and project stages.

MUSIAL *et al.,* (2016) have conducted relevant research in the specific field of strategic planning of offshore wind energy development using spatial approaches. In summary, their research aims to identify potential wind energy areas and allows for comparison at a global scale to assess the relative effectiveness of different areas. This helps in strategic decision making regarding the allocation of resources and investment in wind energy projects.

The data is critical for producing estimates of energy production in auctioned areas and other designated lease areas. This information is central to early energy planning and policy development.

In addition, the data is essential for developers engaged in site analysis. It provides developers with the necessary information to formulate initial economic and energy estimates, enabling informed decision making at the start of the project.

Regulatory authorities also benefit from the data. They use it to conduct alternative site analyses to ensure that energy projects comply with regulatory standards and environmental aspects.

Finally, the data is a valuable resource for local and regional decision-makers involved in long-term energy planning. It helps to make decisions that promote sustainable energy solutions and long-term regional energy strategies.

There are a variety of spatial energy planning approaches that can be used or adapted to support decision making about offshore wind development in different market contexts. The most representative studies include SCHILLINGS *et al.*, (2011) who developed a specific scenario-based, simulation- and optimization-based DSS tool for offshore wind energy planning in the North Sea. While BEITER *et al.*, (BEITER *et al.*, 2017, MUSIAL *et al.*, 2016) applied spatialized DSS analyses to estimate the offshore wind potential in the US EEZ for different scales and dimensions. Other updated studies include (GUSATU *et al.*, 2021; GUSATU *et al.*, 2020; SPYRIDONIDOU & VAGIONA, 2020; SPYRIDONIDOU *et al.*, 2020).

OU *et al.*, (2010) used a GIS-based approach to define offshore wind areas for electricity generation in the Chinese EEZ. Several other studies have used GIS-based approaches to assess offshore wind resources and technical potential in local areas such as Japan (GOVINDJI *et al.*, 2014; JAPAN WIND POWER ASSOCIATION, 2017), South Korea (KIM *et al.*, 2016), Taiwan (FANG, 2014), Greece (TERCAN *et al.*, 2020) or Brazil (DE AZEVEDO *et al.*, 2020, NOGUEIRA *et al.*, 2023). However, most of these studies have not integrated their methods into a structured methodological framework that integrates the concepts of sustainability, Marine Spatial Planning, or strategic impact assessment.

Other technical studies have incorporated marine spatial planning concepts to formulate the offshore wind roadmaps at the national level, for example in the case of Colombia (RCG, ERM, 2022) and the Philippines (WORLD BANK, 2022). Nevertheless, the methodological approaches differ considerably. Moreover, unlike China, the USA or Brazil, these countries do not have problems with the expansion of marine areas.

Finally, an interesting approach is applied to the Portuguese case, where CASTRO-SANTOS *et al.*, (2019) developed an automated GIS-based approach using ArcGIS Model Builder that integrates marine Spatial Planning concepts under scenario planning assumptions. This study considers four physical restriction criteria and three logistical restrictions to find suitable locations for marine renewable energy deployment. As another study, SIMÕES *et al.*, (2023) implemented a holistic planning methodology into an interactive tool that integrates the GIS-based planning tool (SANTOS *et al.*, 2019) and developed the techno-economic planning tool called MarinePlan. This approach considers constraints from various factors, including anthropogenic activities in the marine space as direct constraints. The techno-economic assessment is applied to the unconstrained areas.

3.9.1 Technical potential

Technical potential represents the subset of gross potential that is commercially exploitable within a reasonable timeframe. It includes the main technical constraints such as wind resource (less than 7 m/s), water depth (generally more than 1000 meters), with floating foundations considered the most viable alternative for water depths greater than 60 meters. (MUSIAL, Walter, HEIMILLER, *et al.*, 2016). Extreme climatic conditions are also considered a technical limitation. However, as mentioned above, some of these conditions may not apply in the Brazilian case.

The technical potential should be reviewed as it is essential in the environmental planning process. Suitable areas defined by technical potential are usually referred to as exploitable areas for OWE generation or “offshore wind areas” (the same concept as for offshore O&G blocks). The main concept used to estimate gross and technical potential is wind power (IEA, 2019). The following subsection summarizes the basic concepts required to calculate the technical potential.

MUSIAL *et al.*, (2016) calculated the technical potential of offshore wind resources in four steps:

- Definition of gross potential using technological exclusions.
- Calculation of the technical offshore capacity by multiplying the available area after technological exclusions by the assumed Capacity density. An updated value of 3 MW/km^2 was used, taking into account the technological development of array spacing in U.S. projects and offshore wind turbines in 2016 – typically the state of the art of wind turbines in 2015 had a rated power of 6 MW. However, this value relates specifically to that study’s approach. They calculated this potential using Eq. 3-1:

$$\begin{aligned}&\textbf{Gross Offshore Energy}\\&\quad= \textbf{Capacity density} \times \textbf{Gross Capacity Factor} \times \mathbf{8760}\ \frac{\boldsymbol{hours}}{\boldsymbol{year}}\end{aligned} \qquad \textbf{Eq. 3-1}$$

The gross capacity factor was calculated for each grid cell on the gross offshore resource area using OpenWind software, as it is interoperable with geodata and offers the possibility to model wake effects of deep arrays. If exceptions such as water depth (>1000 m.u.s.l.) and average wind speed (<7 m/s) are taken into account, the gross offshore wind resource (10,800 GW) is reduced by 78% (2,395 GW).

3.9.2 Social and ecological potential

Defined by NREL (2016) as the potential for renewable energy development considering environmental, social and land use conflicts.

In Brazil, XAVIER *et al.* (2020) apply participatory mapping to map traditional fisheries in Ceará. The limitations of these approaches lie in the extent of mapping large areas and the accuracy of the mapping. Therefore, they are difficult to include in integrated assessments in the first steps of strategic planning. However, the implementation of participatory mapping can be included in the action plan or in the development phases of offshore wind projects as an effective community management measure.

Another approach was estimated by VINHOZA & SCHAEFFER (2021a), where the social and environmental potential was represented by the exclusion of protected areas and priority areas for biodiversity conservation and a minimum distance from the coast of 8 km. However, this approach focuses on considering biological resources as a direct constraint and the minimum distance to shore was held constant based on the locations of European offshore wind farms.

3.9.3 Economic potential assessments

The economic potential can be expressed in terms of MWh or MW (BEITER *et al.*, 2017). However, the economic resource potential is the available supply of offshore wind energy at a given location where the levelized cost of energy of a project is equal to or lower than the expected levelized avoided cost of energy (MUSIAL *et al.*, 2016). This means that the levelized cost of energy does not represent the entire concept of economic potential; it must also take into account demand conditions and local market prices. The estimation of offshore wind potential needs to be updated regularly due to the availability of higher quality data and technological innovations (MUSIAL *et al.*, 2016).

However, most economic assessments of offshore wind energy potential (DOS REIS *et al.*, 2021; SIMÕES *et al.*, 2023; VINHOZA *et al.*, 2022) estimate the LCOE – the minimum break-even price – as a representation of the economic potential for offshore wind energy development. These studies implement GIS-based analysis to estimate LCOE of offshore wind energy applying different economic models (see Section2.5).

Most studies, regardless of the potential they assess, make static assessments that assume a constant offshore wind technology – represented by the selected turbine and its technical characteristics (rated power and rotor diameter). These static assessments only represent a specific probable development scenario which considers the selected turbine technology. However, the characteristics of the turbines influence strategic attributes of the wind farm such as the total area, the number of turbines and the total installed capacity. These attributes have a direct impact on the technical, supply chain, and logistical demands, these factors have a direct impact on the cost estimates as well.

Chapter 4 – Methodological Framework for Strategic Planning and Sustainability of the Offshore Wind Energy

This chapter presents the proposed methodological framework called Strategic Planning of Offshore Wind Energy, hereafter called SPOWER-BR, which aims to promote the sustainable development of an offshore wind project applied to the Brazilian emerging market.

According to MCMEEKIN *et al.*, (2020), a methodological framework is a structured guide for the implementation of a process or procedure. They stated that the development of a methodological framework is determined by existing methods and guidelines, refinement and validation, and the experience and expertise of the authors. Based on these factors, the development of the proposed methodological framework involved three phases: a) structuring the procedure for integrating, extracting and synthesizing data in an evolving and iterative process, b) identifying data to feed into the methodological framework, and c) testing it in a pilot case study and refining it based on the results. Furthermore, the research adds an additional phase involving standard mapping and visualization to deal with the large amount of resulting information.

Therefore, the methodological framework of SPOWER-BR has been structured to include four components related to the exposed procedures; three structural components: a) the structured procedure, b) the basic database and c) a computational toolkit and d) a complementary visualization tool. Figure 4-1 illustrates the general structure of the SPOWER-BR methodological framework. First, the SPOWER-BR process comprises structured stages and activities that guide the entire process. Second, the GIS-SPOWER-BR geodatabase, which contains spatial output data (spatial variables and features) for the execution of computational tools. Third, the GIS-SPOWER-BR Toolbox, a specialized toolbox developed for OWE strategic planning and registered under CPR No. BR512022001514-5 by the Brazilian National Institute of Industrial Property (INPI) (HERNANDEZ C. *et al.,* 2022). The fourth component is the VIZ-SPOWER-BR Dashboard, an analysis tool that summarizes the main results in a user-friendly and dynamic tool to analyze and compare the results of the modeled strategic scenarios.

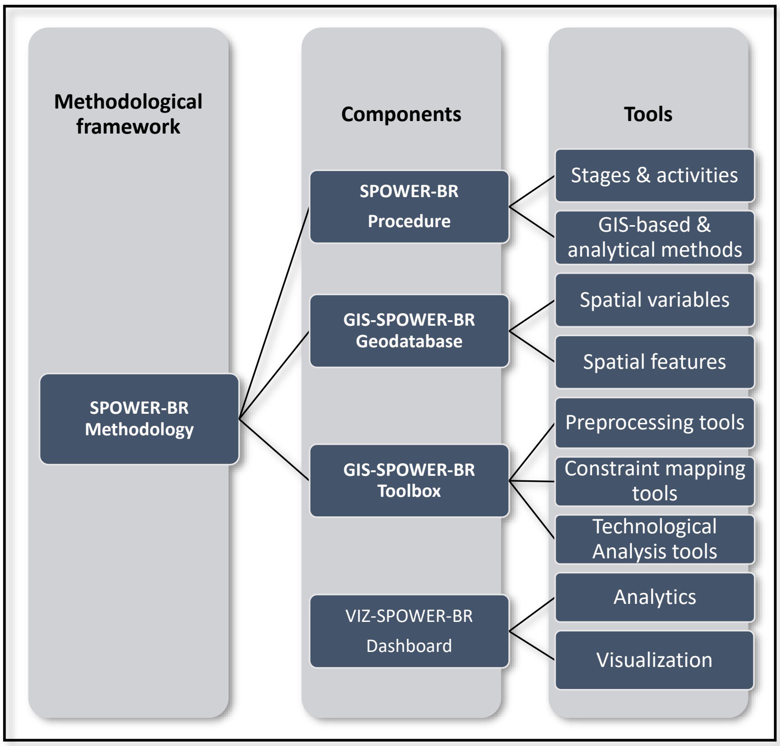


Figure 4-1. General structure of the methodological framework for strategic planning of Offshore renewable wind energy - SPOWER-BR.
Source: The author.

Appendix D documents the GIS-SPOWER-BR Toolbox, showing example of the user interface and examples of raw output data. Appendix E shows an example of the visualization of the VIZ-SPOWER-BR dashboard.

It is important to note that during the development of the current thesis, other studies were conducted to test different elements and analyses included in the methodological framework. The articles "*Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil*" (HERNANDEZ C. *et al.*, 2021) and "*Environmental assessment of proposed areas for offshore wind farms off southern Brazil based on ecological niche modeling and a species richness index for albatrosses and petrels*" (LEMOS *et al.*, 2023) provide the theoretical framework for the sustainability of offshore wind energy, taking into account technical, social and ecological aspects as well as technology and data availability in the Brazilian EEZ in order to formulate optimization indices.

The peer-reviewing of the articles "*Potential impacts of floating wind turbine technology for marine species and habitats*" (MAXWELL *et al.*, 2022) and "*An integrated conceptual model to characterize the effects of offshore wind farms on ecosystem services*" (BAULAZ *et al.*, 2023) complemented the knowledge to strengthen the sustainability approach integrated into the methodology.

Other studies such as "*Replacing fossil fuels by wind power in energy supply to offshore oil & gas exploration and production activities - Possibilities for Brazil*" (SCHAFFEL *et al.*, 2019) and "*Brazilian Policies and Regulations in the Offshore Energy Generation Chain:*

Implications for Short and Mid-term Investments" (MARIANO *et al.*, 2023) helped to understand the synergies between offshore wind power and the offshore oil and gas industry.

Development of the "*GIS-SPOWER-BR Toolbox: GIS-based methodology for Strategic Planning of Offshore Wind Renewable Energy for BRazil*" (HERNANDEZ C. *et al.*, 2022) consolidates the computational tools that support the performance of geoprocess analysis.

Finally, the studies "*Aplicação dos conceitos de Planejamento Espacial Marinho para identificação de áreas disponíveis para desenvolvimento de energia eólica offshore no Brasil*" (HERNANDEZ C. *et al.*, 2022b) and "*Abordagem estratégica sustentável para avaliação locacional de Parques Eólicos Offshore e oportunidades da cadeia de valor no Brasil*" (HERNANDEZ C. *et al.*, 2022) helped to test the practical implementation of the first stages and GIS-based tools that provide insights to improve the robustness and construction of development scenarios.

4.1 Integrated spatial sustainability approach

One of the main issues related to the sustainability of large-scale offshore wind energy is an integrated sustainability approach at all stages, from the strategic planning of the energy sector to the implementation of a specific project (PHYLIP-JONES & FISCHER, 2015). This methodology aims to integrate the sustainability approach into various activities of the strategic planning process, such as: a) the definition of unconstrained areas, b) the identification of non-conflicting areas throughout the marine space, c) sustainability optimization to prioritize the most suitable areas for installation, and d) technological optimization for energy production and the evaluation of the cost potential of the resulting alternatives.

The current methodology is based on various methodological frameworks related to strategic planning of marine and coastal areas and energy technologies. These methodological frameworks include: a) Marine Spatial Planning (EHLER & DOUVERE, 2013; UNESCO, 2021), b) Strategic Environmental Assessment (MAR, 2020; TEIXEIRA, 2008), c) Hydroelectric inventory assessment (MINISTERIO DE MINAS E ENERGIA, 2007), and d) Siting of nuclear plants (EPRI, 2022). These approaches use multi-criteria assessments and geospatial modeling methods to incorporate the spatial dimension into the strategic analyses. Most of these approaches take advantage of the GIS computational tools to assemble a user-friendly Spatial Decision Support Systems (DSS) (BEITER *et al.*, 2016; SCHILLINGS *et al.*, 2011, 2012). A DSS facilitates the implementation of sustainability approaches when environmental, social and economic analyses are integrated into the planning levels to evaluate different strategies and multiple project alternatives (EALES *et al.*, 2003; HERSH, 1999; UNESCO-IOC & EUROPEAN COMMISSION, 2021).

The current methodological framework aims to integrate concepts and experiences to strengthen the strategic planning of offshore wind energy. It also aims to close the gaps identified in the vertical integration of plans and projects in the offshore wind industry. Finally, the approach aims to integrate the sustainability approach from the early planning to the operational phase of an offshore wind project. Table 4-1 summarizes the objectives and contributions of the reference approaches that have been incorporated into the current methodological proposal.

Table 4-1. Theoretical framework for sustainable strategic planning of the offshore wind energy in Brazil.

Methodology	Stages	Goal and application in OWE strategic planning
Integrated Management of Coastal Zone - Marine Spatial Planning (MSP)	1. Preparation 2. Characterization and diagnosis 3. Prospective and environmental zoning 4. Formulation and acceptance. 5. Implementation or execution 6. Monitoring and evaluation 7. Determination of planning standards 8. Identification of existing conditions 9. Identification of future conditions 10. Development of a public information system	Ecosystem-based allocation of marine uses, including human and natural uses. This framework supports the definition of criteria for assessment, data organization and compatibility of activities to allocate areas for OWE projects as recommended uses within a given timeframe as part of a sustainable approach and to identify capacity potentials, targets and industry opportunities. The priority management measure for OWE use is the organization of auctions for renewable energy production. The management measures must define where, how and when the OWE activities should take place (UNESCO-IOC, EUROPEAN COMMISSION, 2021). The point of contact between MSP and SEA is the assessment of conflicts and impacts on biological and ecological resources.
Strategic Environmental Assessment (SEA)	1. Screening 2. Timing 3. Scoping 4. Assessment of the strategic impact 5. Documentation and information 6. Revision 7. Decision 8. Monitoring the implementation of the strategic decision	SEA focuses on the overall assessment of the strategic environmental impacts of a policy, plan or program to ensure the sustainability of the implementation of the instruments or initiatives. As the next step after MSP, the SEA serves as a guide for the environmental assessment of the areas designated for OWE as a result of the MSP application. In this case, the link between the SEA and the hydropower inventory is the assessment of alternatives based on the decaying environmental-economic factors.
Hydroelectric inventory	1. Study planning 2. Preliminary studies 3. Final studies 4. Integrated environmental assessment of the selected alternative	The aim is to assess the energy potential (technological, ecological and social potential) and to integrate socio-ecological aspects into the strategy and management stages. In terms of offshore wind resources and energy potential, this method is used as a decision-making tool for defining alternatives and selecting the most sustainable option or combination of alternatives to identify OWE areas and prioritize projects for leasing bids.
Siting Guide for Nuclear Plants EPRI 2022	1. Definition of region of interest (ROI) 2. Definition of candidate areas 3. Identification of candidate sites	It aims to select the most suitable sites, taking into account a multi-criteria process with successive rounds of evaluation. The aim is to include a large number of criteria in the process and thus reduce the number of suitable alternatives at each stage.

Methodology	Stages	Goal and application in OWE strategic planning
	4. Assessment and selection of candidate sites 5. On-site assessments and site selection	It allows to downscale the area of analysis from regional to local scales. Then, this methodology deals with a similar challenge that in the case of the OWE planning is to find an oprtimal and sustainable location in a vast area coastal and marine zone.
Environmental Impact Assessment	1. Project analysis 2. Screening 3. Impact identification 4. Impact assessment 5. Impact assessment 6. Formulation of an action plan 7. Public participation. 8. Monitoring	The environmental impact assessment is defined as a tool for environmental management and decision-making for certain projects or polluting actions. It aims to mitigate or potentiate the impact on the environment (or on one of its areas). In relation to offshore wind projects, the large-scale attribute and offshore wind projects result in the need to conduct an environmental impact assessment, even though OWE is considered an environmentally friendly and low-carbon technology.

Source: The author.

These methods have several crucial factors in common, such as: an integrated sustainability approach, challenges due to data gaps and challenges in effectively integrating strategic and operational levels, the need to include the spatial dimension and the implementation of GIS-based tools. Another important aspect is the analysis based on scenario planning, which varies depending on the method. Finally, all these methods should include public participation strategies, ideally to support the process of scenario development, follow-up and evaluation of the results. This public participation should take into account the highest possible level of public involvement (ARNSTEIN, 1969). This process could help to avoid strong social barriers in the deployment stages of an OWF, when most capital expenditures are higher.

The concept of "sustainability" is adopted by integrating factors related to the SDGs in all stages of strategic planning and development of offshore wind projects. The methodology includes a robust framework and modeling tools that support strategic activities and provide strategic information for operational stages and local studies for bid rounds, auctions, environmental impact assessments and other local studies or approvals.

This approach seeks to fill the vertical gap between the planning and operational stages. As HERSH (1999) states, vertical integration enhances sustainable decision-making from the project's inception. Here, the sustainability analysis arises, but it is important to understand how the development dimensions interact with each other. Thus, current research identified different criteria related to strategic planning and sustainability factors of offshore wind energy. Investigated factors included wind resource assessment, technological innovations (wind farms and turbines), environmental impacts, economics and finance of wind energy, and supply chain (port and maritime logistics, power transmission systems), among others (see Table 4-4).

Based on state-of-the-art of geoprocessing techniques, a wide range of GIS-based tools were assembled to perform complex spatial multi-criteria analyses within a computational platform.

The MSP approach established a baseline methodology for assessing competition for space and resources in coastal and marine environments. The Ecosystem-based approach utilizes ecosystems and natural resources to analyze the dynamics of human activities. This method was implemented using GIS-based modeling, including Boolean and spatial overlapping analyses. The Strategic Environmental Assessment (SEA) approach focuses on preventing strategic environmental impacts that a policy, plan, or program might cause. Optimized spatial suitability indices were employed to integrate spatial data related to environmental receptors vulnerable to offshore wind deployment activities. The selection of procedures and GIS-based tools was guided by hydroelectric inventory and the siting of nuclear plants to narrow the spatial scope and define a portfolio of feasible and suitable alternatives for offshore wind development. Finally, the Environmental Impact Assessment (EIA) outlined the desired environmental data to support the environmental licensing process. Outputs from each stage of GIS-based modeling serve as crucial input for the EIA and the leasing process for offshore wind areas.

Unstructured interviews and seminars were conducted to gather the knowledge of experts on strategic planning of renewable energy and offshore wind energy and to validate the selection of strategic criteria and geoprocessing methods. Table 4-2 lists the experts consulted and their respective backgrounds and institutions.

Table 4-2. List of consulted experts.

Name	Background	Institution
Eliab Ricarte, D.Sc.	Offshore energy expert	Bureu Veritas - PPE
Carol Lemos, D.Sc.	Biological resources & EIA expert	IBAMA
Cristiano Vilardo, D.Sc.	EIA & O&G expert	IBAMA
Roberta Cox, M.Sc.	Environmental licensing expert	IBAMA
Denise Matos, M.Sc.	Environment expert	CEPEL, Eletrobras
Ricardo Dutra, D.Sc.	Wind energy expert	CEPEL, Eletrobras
Katia Garcia, D.Sc.	Corporative ESG expert	CEPEL, Eletrobras
Sergio Melo, M.Sc.	GIS expert	CEPEL, Eletrobras
Fábio Siqueira Batista	Renewable energy economics and finance expert	CEPEL, Eletrobras
Renan Pinto, M.Sc.	Transmission system expert	CEPEL, Eletrobras
Paula Oliveira, M.Sc.	Transmission system expert	CEPEL, Eletrobras
Myriam Gerk, M.Sc.	Energy planning modeling expert	CEPEL, Eletrobras
Igor Raupp, D.Sc.	Hydropower expert	CEPEL, Eletrobras
Luciana, D.Sc.	Socio-environmental expert	CEPEL, Eletrobras
Cristian Soriano, D.Sc.	Geotechnical substructures expert	U. Gustave Eiffel
Thomas Xavier, D.Sc.	Social & community expert	Centec Institute
Rodrigo Guimarães, M.Sc.	Energy planning expert	EPE – CENERGIA, COPPE
Gordon Wilmsmeier, D.Sc.	Ports, maritime logistics & electromobility expert	Kühne Professorial Chair in Logistics, KLU – Universidad de los Andes
Federico Jensen	Ports and offshore wind logistics advisor	Danish Energy Agency
Luisa Spaggiari, M.Sc.	Port logistic consultant	RAMBOL
Heliana Vilela, D.Sc.	Environmental assessment expert	LIMA, COPPE
Giovanni Luigi, D.Sc.	Environmental assessment expert	LIMA, COPPE
Milad Shadman, D.Sc.	Offshore renewable energy expert	GIRO, COPPE
Mojtaba Maali Amiri, D.Sc.	CFD expert	GIRO, COPPE
Corbiniano Silva, D.Sc.	Mapping expert	LAMCE, COPPE

Source: The Author.

Next, the GIS-based analytical framework was structured to integrate the selected multi-criteria analyses at different scales, spatial methods and tools, taking into account the methodological approach and the characteristics of the available public data in the Brazilian context. The GIS-based DSS was created using ArcGIS 10.6 software, supported by Python programming, and the Power BI Analytics platform. As used in several previous studies (SCHILLINGS *et al.*, (2012), BEITER *et al.*, (2016), CAVAZZI & DUTTON (2016), among others), a DSS aims to automate and standardize the analyses, reducing the time and cost of the assessment procedures.

4.1.1 Multi-criteria approach and methodological considerations

Multi-criteria decision-making methods (MCDM) are widely used in multi-objective decision-making processes and in real-life decision-making situations (HERSH, 1999). The MCDM are mainly applied in planning and management stages in more than 40 countries (MARDANI, ZAVADSKAS, *et al.*, 2017). An important aspect of the MCDM is the identification of the criteria to be used in the analyses. Then, the criteria related to OWE must be identified and analysed, identifying the possible interactions between the technology and the environment (natural, social and economic) in order to structure a robust, holistic methodology.

The criteria were grouped according to the sustainable development dimensions in order to incorporate and integrate the holistic approach into the multi-criteria analysis. This dimensions are:

a) **Technological dimension**: it is represented by the characteristics and parameters of the current cutting-edge technology of OWE production and OWFs at large commercial and demonstration scale according to the classification of Kaiser and Snyder (2012).
b) **Environmental dimension**: it is represented by the natural physical, biological and ecological phenomena of the regions and local areas**.**
c) **Social dimension**: It refers to the social complexity, including human activities, perception and acceptance of energy projects at the local, regional or federal level.
d) **Economic dimension:** It reflects the economic factors that influence the cost and financing of an OWE project, such as bathymetry, distance to shore, distance to ports, cost of structures and equipment or financial costs (discount rate or WACC).
e) **Governance dimension:** It stands for the possibility to implement and manage the strategic planning of the OWE project taking into account different stakeholders such as ministries, public institutions, the civilian population and private institutions or developers.

As discussed in the literature review, multi-criteria evaluations consider several types of criteria that can be integrated (“combined”) with the aim of estimating composite indices representing a large number of variables, in this case spatial variables. It should be remembered that multi-criteria assessments are prone to trade-offs when integrating data. Another feature of multi-criteria assessments is the nature of the criteria, as the same criterion may be assessed differently at different stages of the project or activity depending on the objective of the analysis. An example is the approach of EPRI (2022), where criteria are used in different stages to reduce the scope of the analysis until the most suitable site for a nuclear power plant is found (Figure 4-2.

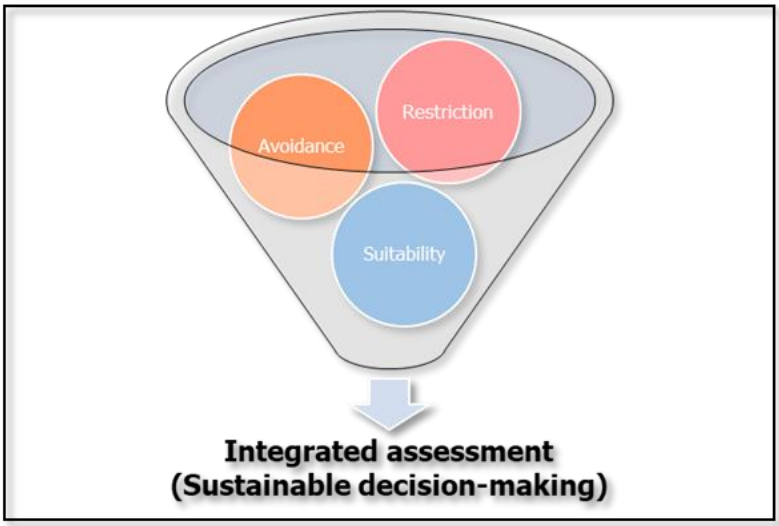


Figure 4-2. Schematic integration of multiple criteria.
Source: The Author.

This multi-criteria approach considers three types of criteria, which are described below:

1) **Absolute restrictive criteria:** They do not allow the implementation of the project or activity, *e.g.*: Conservation Units or areas where the average wind speed is below 7 m/s. The analyses for these criteria are mainly Boolean analyses.
2) **Avoidance criteria:** They allow the project to be implemented, but are not desirable. The current approach uses the MSP approach to assess compatibility conflicts (competition for space or resources) between activities, *e.g.*: Sea- use conflict between industrial fishing and offshore wind energy.
3) **Suitability/sensitivity criteria:** These are not direct constraints, but depending on their value, the relative suitability/sensitivity of each criterion leads to an increase or decrease in the resulting integrated suitability, *e.g.*: the greater the distance to beaches, the greater the suitability for wind farm construction (where a minimum distance of X km is considered a constraint). These criteria have suitability values (continuous, discrete or

categorical) that start at the restrictive threshold and increase or decrease in the “opposite” direction depending on the suitability function defined for the specific criterion.

These characteristics are important because they provide an initial insight into the way in which the criteria and values must be assessed and integrated. Furthermore, the identification of thresholds is crucial for the quantitative definition of parameters for modeling. This process, referred to here as the parameterization process, supports the integration between different types of criteria and serves to quantitatively represent the strategic scenarios.

The identification of strategic criteria that represent the characteristics of offshore wind energy and the interactions with the environment and other dimensions is essential to ensure the sustainability of the projects. In addition, these criteria must take into account the potential social and environmental impacts that the selected technology may cause (see section 3.7). These impacts are primarily influenced by the scale of the OWE projects (CAUSON, GILL, 2018). Therefore, the scope was included for the current study to determine the relationship between the levels of technology, environment, ecology, impact and scope of the instrument. Table 4-3 represents the logical analysis and vertical integration for the sustainability analysis.

Table 4-3. Spatial scales of sustainability planning analyses and impact assessment.

Spatial scale	Level of Multi-criteria analysis	Level of technological analysis	Level of impact analysis		Level of ecologic analysis	Instrument scope
National ↕ Regional	Compartment ↕ Component ↕	Technology ↕	Cumulative and synergetic impacts	Strategic impacts	Ecosystem services Ecological integrity	MSP ↕ SEA
↕	Factor ↕	Activity ↕		↕	Habitats/Populations	↕
Local	Criteria ↕ Parameter	Stressor		Local impacts	Niches Species	EIA

Note: MSP: Marine Spatial Planning; SEA: Strategic Environmental Assessment; EIA: Environmental Impact Assessment.
Source: The author.

In addition, Table 4-4 lists 47 criteria identified on the basis of the extensive literature review in Chapters 2, 3 and 3.8. In addition, the Brazilian context and the availability of data to analyse the sustainability of OWFs in the marine coastal environment were taken into account when identifying and selecting more relevant criteria. The following subsections describe the characteristics of the main criteria and their relationship to the OWE analysis.

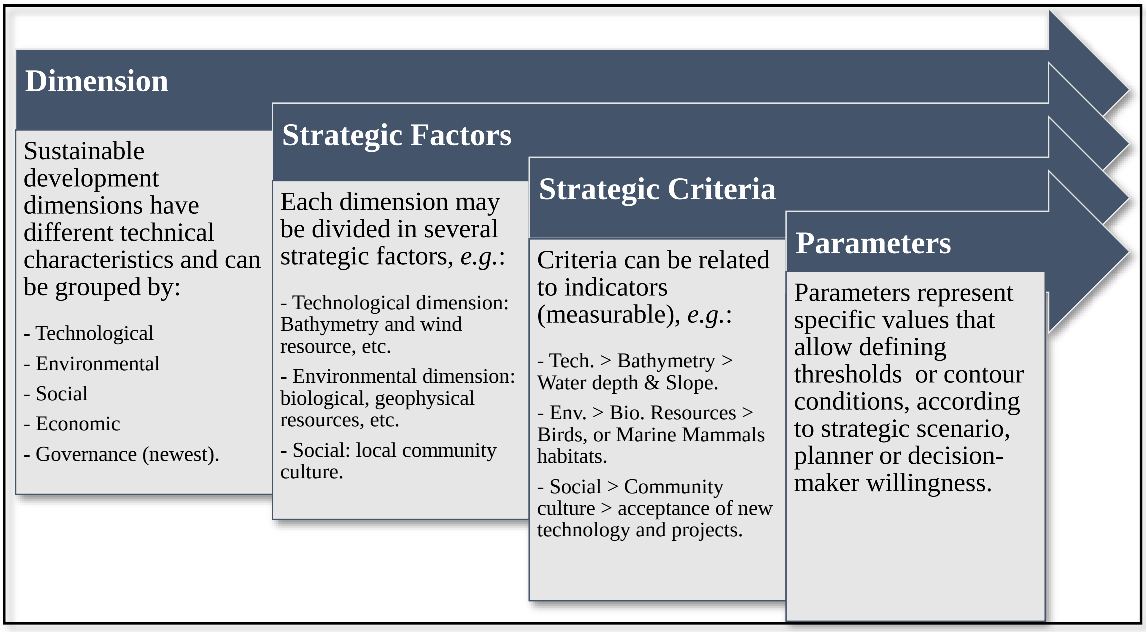
Table 4-4. Analyzed criteria related to spatial analysis of offshore wind energy, considering sustainable development dimensions.

Development dimension	Factor	Criteria (spatial variable)
Technological	Wind resource	Mean wind speed at hub height
	Wind resource	Wind direction
	Wind resource	Capacity factor*
	Geomorphology	Bathymetry/Water depth
	Wave/Currents resource	Wave regime
	Geological	Sedimentary material*
Environmental	Biological resources	Listed threatened spp. areas*
	Biological resources	Seasonal vulnerable areas/habitats*
	Biological resources	Benthonic areas
	Biological resources	Coral reefs areas
	Biological resources	Chelonia areas
	Biological resources	Marine mammals*
	Biological resources	Elasmobranchs*
	Biological resources	Coastal/migratory birds*
	Biological resources	Seabirds/pelagic*
	Ecological resources	Coastal ecosystems*
	Ecological resources	Prioritized areas for conservation
Social	Acceptance	Perception index*
	Tourism	Distance to touristic beaches
	Heritage	Distance to archeologic sites
	Human resources	Universities/Technical institutes
Economic	Logistical	Distance to shore
	Logistical	Distance to port
	Logistical	Port System Readiness
	Logistical	Port’s storage areas
	Logistical	Grid/Connection distance
	Support infrastructure	Grid available capacity*
	Support infrastructure	Substation idle capacity*
	Supply chain	Onshore wind manufactures
	Supply chain	Airports
	Supply chain	Highways
	Supply chain	Railways type/charge type
	Complementary infrastructure	Energy plants type
	Complementary infrastructure	Energy generation/Installed Capacity
	Complementary infrastructure	Capacity factor of energy generation*
Multi-use	Protected Areas	Conservation Units/Fixed vulnerable areas
	Military Areas	Existence of military areas
	Fishery activity (Industrial/Artisanal)	Fishery intensity
	O&G activity	Blocks/Fields
	Tourism activity	Seascape/Recreative sports
	Linear infrastructure	Pipelines/Cables
	Mineral resources	Mineral extraction areas
	Maritime traffic	Cabotage lines
	Maritime traffic	Maritime traffic density
	Future ORE	Offshore Wind Farms

Note: (*) criteria with high complexity for accurate data acquisition.
Source: The Author.

On the other hand, the first challenge in integrating criteria through spatial methods is to define how each criterion should be used in the different assessments. Criteria can be used in one or more stages of project development. The same criteria can be used in different ways depending on different aspects such as: Planning phase, spatial analyses, available data (level of detail) and extension, format and type. In the same way, the selected criteria will guide the characterization of the area and the target activity – consolidation of the basic data – in this case the basic geodatabase for OWE activities. Table 4-4 sorts the factors according to the sustainability approach.

In addition, two key concepts associated with the criteria concept are important: spatial variables and modeling parameters. Spatial variables – also known as spatial indicators in the management context – represent the spatial distribution of a phenomenon in the form of characteristics or values. They can be represented by points, lines or polygons (vector format) or by spatialized matrices of values (discrete or continuous), better known as rasters, *e.g.*, the localization of substations (vectors of point geometry) or the spatialized mean wind speed (raster). Since the vector format can be converted to a raster format, most of the spatial integration must be performed with raster surfaces. Specific modeling suggestions for the current approach are described in Section 4.1.2. Figure 4-3 illustrates the multi-criteria structure to facilitate the understanding of the proposed approach.



Sustainable development dimensions have different technical characteristics and can be grouped by:

- Technological
- Environmental
- Social
- Economic
- Governance (newest).

Each dimension may be divided in several strategic factors, *e.g.*:

- Technological dimension: Bathymetry and wind resource, etc.
- Environmental dimension: biological, geophysical resources, etc.
- Social: local community culture.

Criteria can be related to indicators (measurable), *e.g.*:

- Tech. > Bathymetry > Water depth & Slope.
- Env. > Bio. Resources > Birds, or Marine Mammals habitats.
- Social > Community culture > acceptance of new technology and projects.

Parameters represent specific values that allow defining thresholds or contour conditions, according to strategic scenario, planner or decision-maker willingness.

Figure 4-3. Muti-criteria assessment structure.
Note: examples are related to the offshore wind energy context.
Source: The author.

In spatial multi-criteria modeling, most of the input data must be spatialized to represent the distribution of the phenomenon in space – onshore or offshore – this is the first level of input data or spatial variables. However, these spatial variables can be ambiguous due to the low level of pre-processing and interpretation. Later, the spatial variables need to be interpreted and their values normalized to a standard scale that allows quantitative variables (continuous or discrete data) to be combined with qualitative variables (nominal, ordinal/categorical data), regarding the context of the multi-criteria assessment. These normalized variables become spatial indicators that can have a precise meaning in the context of modeling. In most cases, they should be converted to a raster format for complex geoprocessing and integration procedures.

On the other hand, modeling parameters are values that represent data thresholds with which the same environmental indicator can be subdivided into a restriction criterion or a suitability criterion. This subdivision is necessary to perform spatial analyzes such as the Boolean sum or the suitability overlay analysis. Boolean methods and overlay suitability methods are basic methods used in spatial multi-criteria analyzes for decision making. These can be used to integrate suitability criteria into spatial suitability indices.

Both approaches may or may not refer to the same spatial variable or environmental indicator, i.e. the spatialized mean wind speed in raster format may represent a constraint area where values are below 7 m/s, and it may also represent different degrees of suitability for offshore wind energy generation in areas where values are above 7 m/s, 8 m/s, 9m/s, etc., depending on a continuous or discrete categorization of mean wind speed values.

The modeling parameters must be consistent with the vision of the strategic scenarios in terms of development objectives and the limits of the modeling contours. The modeling parameters make it possible to link general visions of different possible futures. If the process of constructing the strategic scenario is robust, defining parameters that represent key characteristics and system boundaries is a straightforward task.

These parameters can be defined according to different approaches. Basically, one has to stick to literature review (educated guest) or expert consultation. Methods for capturing the visions of strategic stakeholders vary from online or face-to-face surveys (electronic and physical forms), structured interviews, focus groups or social mapping. Ideally, scenario planning for the future development of new technologies must include the active participation of local communities and society during the various planning and project phases.

The current methodology focuses on proposing methods and tools that facilitate the inclusion of a large number of criteria and parameters and allow the planner or decision maker to freely change the values according to the specific strategic scenario or for an infinite number of possible simulations. In the following subsections, the strategic factors and criteria are described, and in sections 4.7 and 7.1 the methods and tools proposed for the implementation of the multi-criteria approach are described.

4.1.1.1 Technological criteria

Technological factors include criteria that determine the feasibility of installing and generating electricity from offshore wind resources, taking into account the level of technological development, including technologies with a low level of development, such as pilots, demonstration plants or pre-commercial plants.

As the most important criterion, offshore wind resources are the first key factor for the selection of the location of an offshore wind farm. The average wind speed is the first criterion to be analyzed. Secondly, the technology of the wind turbines determines the required height of the wind resource data (measurement height). A precise analysis of this criterion is mandatory as a minimum technological requirement. This criterion can be used as a limitation and suitability criterion divided by the minimum wind speed threshold (parameter) required for wind power generation.

The wind direction is important to define the characteristics of the wind farm and the basic design of the turbines (see section 2.2). This criterion is also important to define the spacing factor between the turbines in order to avoid energy losses due to wake effects of the upstream turbines. In the early stages of planning an OWF, planners and decision makers must give due importance to the separation factor parameter. It has a direct influence on the initial estimates of the area required for the project and determines the power density of the wind farm. Currently, several auction procedures require minimum or maximum values for power density as a classification criterion for bids. While wind direction is not a limiting or suitability criterion, it can have an impact on compatibility conflicts between OWFs or between other economic activities due to the wake effect in the surrounding area.

The capacity factor is almost more important than the wind resource, as this criterion represents the net energy potential that can be generated by a turbine at a given site, taking into account the specific wind turbine technology. This criterion could be considered as an accurate indicator and one of the most important technological criteria, but due to the difficulty of generating the spatialized data, it is considered indicative and not an absolute representation of the technological potential. It can be used as a constraint or suitability parameter, depending on the thresholds that the planner or scenario wishes to evaluate. Until 2022, the capacity factor for newly installed offshore wind projects ranged between 28% and 50%, with the lowest CF being characteristic of Chinese projects and the highest found in the North Sea (IRENA, 2023a).

Bathymetry is an essential criterion because it largely determines the foundation technology to be used. In addition, the bathymetry also has a strong influence on the cost of installing the foundations and laying the cables. After the identification of hotspots for offshore wind turbines, bathymetry is the second mandatory criterion and the most important criterion for the analyses. Considering the nature of seabed geomorphology and the new weather trends that are being altered by climate change, bathymetry is the most stable criterion among the nature-based criteria that remains stable over the planning periods. This criterion can be used as a constraint and suitability criterion which is divided by the maximum water depth threshold (parameter) required for the installation of substructures, depending on the current available technology.

The characteristics of the wave dynamics are an important criterion, as the wave height affects the height of the foundations and turbines and can have an impact on installation, operation and maintenance activities. The wave regime was initially identified as a representation of metocean conditions as public data is available for strategic planning activities. This criterion can be used as a suitability criterion divided by the wave height threshold (parameter) required for the installation of the turbines and substructures. Depending on the availability of accurate spatial data, this criterion could be used as a constraint, but in general it is more stable over time at equatorial latitudes and may not represent relevant changes in the velvet areas there.

Sedimentary material may represent the initial seabed conditions for the placement of OWFs or for the selection of the most suitable foundation. However, it was identified as a desirable but not a mandatory strategic criterion, as the extent and accuracy of data along the bast areas is sparse.

This criterion may influence the ability to construct certain foundations, but mainly influences the cost of constructing foundations due to the characteristics of the seabed. Another criterion that could be taken into account is the slope of the seabed as an indicator of seabed stability and as a geotechnical parameter for selecting the most suitable foundation.

Table 4-5 summarizes technological criteria that may influence decision making during the development, installation, O&M or managing stages. Additional characteristics such as variable type, data type and source, and raw geometry determine the selection of criteria used in the spatial analyses.

Table 4-5. Characteristics of analyzed technical and technological criteria.

Criteria	Variable type	Field format	Unit/description	Data Source	Raw Geometry
Mean wind speed at hub height	C	Number	[m/s]	GWA	Raster
Wind direction	N	Text/ number	[°], [N, S, E,W…]	CEPEL	Point
Capacity factor	C	Number	[%]	GWA	Raster
Bathymetry	C	Number	[m]	MARINHA	Raster
Waves regime	D	Number	GWS area	BMT-GWS	Polygon
Sedimentary material	N	Text	[formation, predominant material]	CETEM	Polygon

Note: C: continuous; D: discrete; N: nominal.
Source: The Author.

4.1.1.2 Environmental criteria

Protected areas, defined in the Brazilian regulation as “Conservation units” (UCs) (DEPUTADOS, 2000), were identified as the first and most important environmental criterion.

These areas are legally designated for mandatory protection or special environmental management measures due to their vulnerability or strategic biodiversity.

Priority conservation areas were identified as a strategic criterion due to their importance in Brazilian legislation. Although not defined as “conservation units”, these areas have priority for future conservation units or for the development of biodiversity conservation or protection measures.

Listed threatened species areas were identified as critical and strategic criteria under the sustainability approach. However, mapping at species level (see Table 4-4) is notoriously scarce, difficult, time-consuming and costly. Therefore, this criterion was defined as desirable. In the strategic planning phase, species that are highly threatened must at least be identified in the region of concern in order to prioritize data collection and actions directly related to their protection and impact prevention during the OWF construction phase. Regardless of whether spatial data on threatened species is available, it must be incorporated into strategic planning to improve outcomes for site selection and enable early identification of strategies to avoid impacts. According to ICMBio (ICMBIO, 2023), there are at least 29 endangered species along Brazil's Bioma seacoast.

Seasonal vulnerable areas/habitats have been identified as important strategic criteria within the sustainability approach. In general, sensitivity/vulnerability mapping is less complex than species mapping (see Table 4-4). However, spatial data on these criteria is also scarce, especially in Latin America or in developing countries. Therefore, this criterion was also classified as desirable.

Biological resources associated with coastal ecosystems, Benthonic areas and coral reefs were identified as static strategic criteria due to their potential sensitivity to offshore wind turbines, particularly during foundation installation and cable laying (see Section 3.7). Instead, biological resources associated with Chelonia, Marine mammals, Elasmobranchs, Coastal/migratory birds and seabirds/pelagic birds were identified as dynamic strategic criteria.

Table 4-6 summarizes technological criteria that may influence decision making during the development, installation, O&M or managing stages. Additional characteristics such as variable type, data type and source, and raw geometry determine the selection of criteria used in the spatial analyses.

Table 4-6. Characteristics of the analyzed environmental criteria.

Criteria	Variable type	Field format	Unit or description	Data Source	Raw Geometry
Conservation units (Protected areas)	N N	Text	Type	ICMBio	polygon
Prioritized areas for conservation	N	Text	Type	ICMBio	polygon
Listed threatened spp. areas	N	Text	[species]	ICMBio	polygon
Seasonal vulnerable/habitats areas	N	Number	[presence/index]	ENMs	raster

Criteria	Variable type	Field format	Unit or description	Data Source	Raw Geometry
Benthonic areas	N	Text	[presence]	ICMbio	polygon
Coral reefs areas	N	Text	[presence]	ICMbio	polygon
Chelonia areas	N	Text	[presence]	ICMbio	polygon
Marine mammals	N	Text	[presence]	ICMbio	polygon
Elasmobranchs	N	Text	[presence]	ICMbio	polygon
Coastal/migratory birds	N	Text	[presence]	ICMbio	polygon
Seabirds/pelagic	N	Text	[presence]	ICMbio	polygon
Coastal ecosystems	N	Text	[presence]	ICMbio	polygon

Note: C: continuous; D: discrete; N: nominal; ENM: ecological niche modeling.
Source: The author.

The presence of environmental resources is represented in the form of vector information on the estimated occupied area or as a result of complex computational models that estimate the presence of primary data collected in situ. LEMOS *et al.,* (2023) conducted one of the first approaches to assess the environmental distribution and impacts of seabirds in the Southern Hemisphere by using ENM to identify areas of threatened seabird species in the marine regions south of Brazil.

4.1.1.3 Social criteria

Social criteria mean that they represent the possible problems associated with the social dimension. In emerging markets, these criteria become more important due to the novelty of the technology and the complex communitarian dynamics and culture. Depending on the level of development of renewable and new technologies for power generation, areas with high technological potential may not have a broad knowledge of new technologies, so the acceptance and perception of this infrastructure may be negative. or they may need strong strategies for local community management. These strategies must include experts in the local indigenous communities and active participation in the project from concept to operation. Table 4-7 lists the social criteria and basic characteristics.

Distance to tourist beaches is a relevant criterion due to its relationship to potential impacts on tourism and the visual seascape due to the proximity of the OWF to the coast (HERNANDEZ C. *et al.,* 2021; MASLOV *et al.,* 2017; SULLIVAN *et al.,* 2013).

Archaeological sites are a criterion directly related to traditional communities that are or were located near potential sites for offshore wind development. These sites may be sensitive to impacts caused by construction or land take, particularly in coastal transitional areas where historic or submerged cultural heritage resources may remain (DUTTA *et al.,* 2021; HERNANDEZ C. *et al.,* 2021; HO *et al.,* 2018).

The perception index aims to incorporate the social perception of offshore wind projects into the integrated assessment and support strategic decisions on social acceptance or management of the local community (MÖLLER *et al.,* 2012). However, with regard to the limitations and accuracy of participatory mapping in strategic phases, other approaches can also be applied to avoid social conflicts or impacts on local communities, such as setting the minimum distance to the coast as a boundary for the installation of OWFs. This boundary must be set considering coastal dynamics (*e.g.,* regional coastal trends, administrative boundaries or boundaries between states). It must be updated at the end of the defined timeframe of the roadmap for the offshore wind industry.

Table 4-7. Characteristics of analyzed social criteria.

Criteria	Variable type	Field format	Unit or description	Data Source	Raw Geometry
Perception index	O	Number	Index	Geoprocessing	raster
Touristic beaches distance	C	Number	[km]	Geoprocessing	point
Archeologic sites	N	Text	[presence]	IPHAN	point

Note: C: continuous; D: discrete; N: nominal; O: Ordinal.
Source: The Author.

4.1.1.4 Economic criteria

Numerous aspects can be used as economic criteria that can influence the decision-making process for the use of offshore wind deployment. These criteria relate primarily to technical and logistical features that influence the cost of installing and operating OWFs. Table 4-8 lists the main economic criteria that influence the cost of offshore wind energy deployment.

Table 4-8. Characteristics of economic criteria analyzed.

Criteria	Variable type	Field format	Unit or description	Data Source	Raw Geometry
Distance to shore	C	Number	[km]	Geoprocessing	raster
Distance to port	C	Number	[km]	Geoprocessing	raster
Substation idle capacity	D	Number	[MW] or [%]	ONS-Power flux modeling	point
Distance to Grid/distributed connection	C	Number	[km]	Geoprocessing	raster
Port category/System readiness	N	Text	[category]	MIN INFRAS.	point

Note: C: continuous; D: discrete; N: nominal; O: Ordinal.
Source: The Author.

GILMAN *et al.,* (2011) emphasize that energy costs do not reflect the entire economic potential. Economic viability also depends on electricity prices and local tax regimes. The different regulations can vary depending on administrative boundaries and countries.

4.1.1.5 Criteria for the multiple use of rooms

Criteria relating to the multiple use of coastal and marine areas are used to identify avoidable areas due to potential competition. As defined in the MSP approach, competing use (conflict or compatibility) of coastal and marine areas occurs when two or more activities require the same space or resources for the production of their main product or service. These criteria are considered avoidance criteria as they are not direct restrictions. Avoiding conflicting areas in marine space is preferable and synergistic uses are desirable. These criteria are very site-specific, and depending on local dynamics and legal frameworks, the same activities may or may not be in direct conflict in different areas. Table 4-9 details criteria's characteristic of the multiple use criteria in detail.

Table 4-9. Characteristics of analyzed multi-use criteria.

Criteria	Variable type	Field format	Unit or description	Data Source	Raw Geometry
UCs/Sensitivity areas/Fixed vulnerable areas	O	Text	[type]	ICMBio /MMA	polygon
Existence	N	Text	[m2]	MARINHA	polygon
Fishery intensity	C	Number	[time density]	GFW	raster
Blocks/Fields	N	Text	[O&G activity]	ANP	polygon
Seascape or Recreative sports	N	Number	[type] (beaches, scuba diving, species sighting, leisure housing, sightseeing)	Research (field or secondary)	point
Pipelines and telecom cables	N	Text	[localization]	ANP-EPE-MIN INFRAS.	line
Mineral extraction areas	N	Text	Mineral type	ANM-CPRM	polygon
Maritime traffic	C	Number	[density]	MIN INFRAS.	raster
Offshore Wind Farms or other Ocean renewable energy	N	Text	[Presence]	IBAMA	Polygon-lines

Note: C: continuous; D: discrete; N: nominal; O: Ordinal.
Source: The Author.

4.1.1.6 Optimization criteria

Optimization criteria are used to conduct a geographic assessment to determine higher suitability for offshore wind farm development. Several of these criteria have previously been used as constraint criteria, depending on the parameters of the constraint thresholds.

A large number of scientific publications have applied spatial suitability modeling for site analysis and offshore wind potential in different regions worldwide; most of them used only a few criteria to assess the suitability of the projects (see Section 3.10). However, suitability assessments at the regional level are limited by the available spatial data with a large number of criteria and their coverage. The current approach therefore aims to reduce the scale of the study area at each stage to ensure suitability assessment at a local level.

The optimization criteria are used to compile two optimization indices: the Spatial Environmental Suitability Index and the Spatial Economic Potential Index (as a replacement for the LCOE). Both indices provide insights for decision making in early technical planning and environmental licensing, considering the optimization of the layout and export cable corridors. The following subsection explains the breakdown of all criteria and their allocation along the entire methodology. Table 4-10 presents criteria incorporated into the optimization indices.

Table 4-10. Characteristics of sustainability optimization criteria.

Criteria	Input variable type	Optimization index	Raw Geometry
Prioritized areas for conservation (APCBs)	O	SESI	polygon
Coral reefs	N	SESI	polygon
Turtle areas	N	SESI	polygon
Marine mammals	N	SESI	polygon
Coastal and seabird areas	N	SESI	polygon
Elasmobranch areas	-	-	-
Bathymetry	C	SCPI	raster
Slope	C	SCPI	raster
Distance to installation port	C	SCPI	raster
Distance to connection point	C	SCPI	raster
Seabed material	N	SCPI	polygon

Note: SESI: Spatial environmental Suitability Index; SCPI: Spatial Cost Potential Index; C: continuous; D: discrete; N: nominal; O: Ordinal. These criteria were normalized (into raster with [0,1] values), using *Fuzzy Membership tool*, and different membership functions depending on the spatial distribution and behavior of the input data.
Source: The Author.

4.1.1.7 Breakdown of the strategic criteria

The final analysis of the strategic criteria involved selecting the criteria that were used in each spatial analysis at different stages. The most important factors for the selection of data were the availability of public data, data quality and the evaluation of sources. The data was then spatialized and converted into meaningful criteria for the spatial analysis so that each criterion could be categorized into each phase of the strategic assessment of offshore wind projects. Figure 4-4 shows the breakdown of the criteria to illustrate the use of each criterion in the different stages. Parameterization for performing spatial simulations considering different scenarios for strategic planning and sustainability assessment.

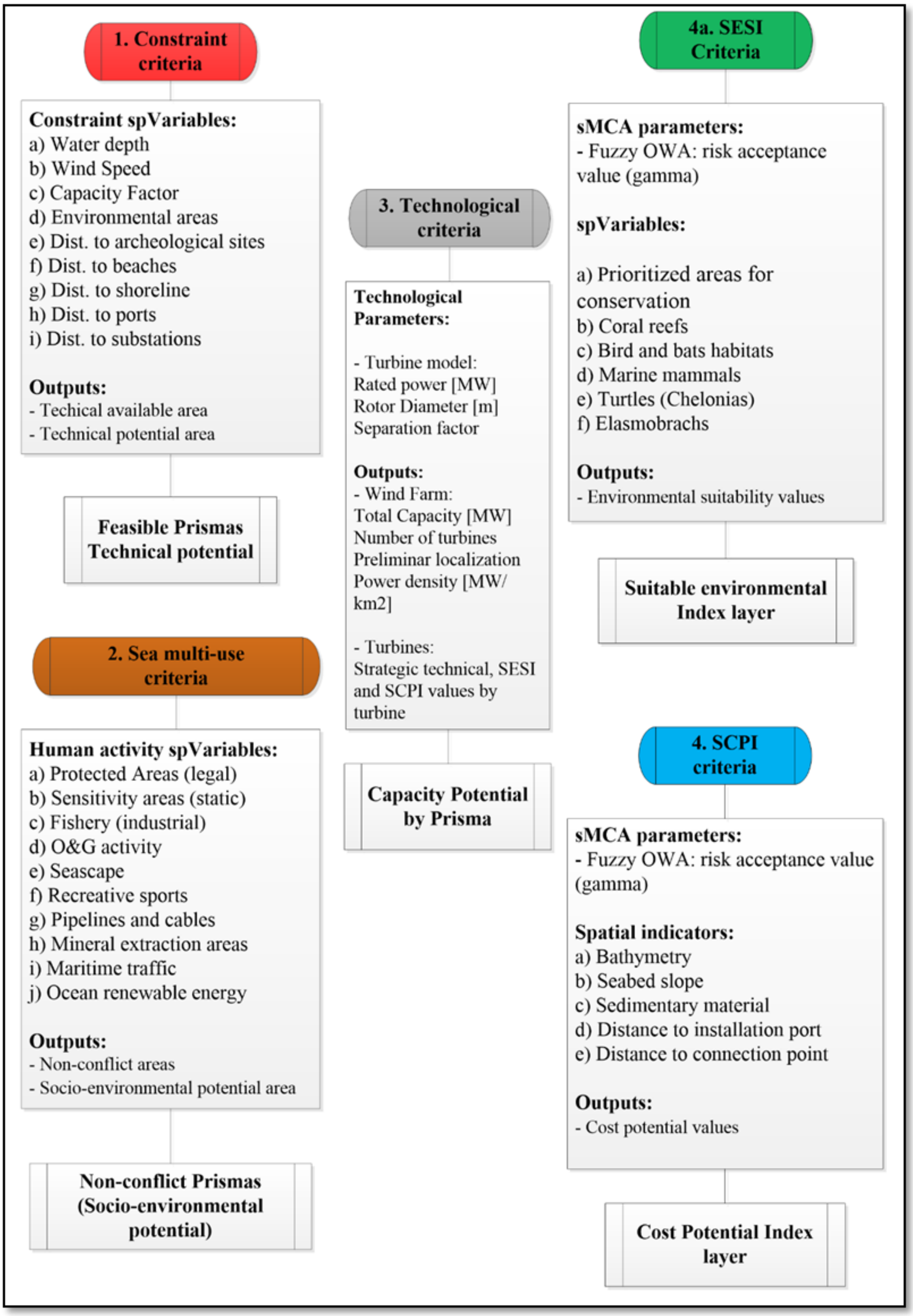


Figure 4-4. Criteria breakdown by GIS-based modeling stage.
Note: SESI: Spatial Environmental Suitability Index; SCPI: Spatial Cost Potential Index; spVariables: Spatial data (georeferenced layer); Parameters: numerical values provided by the user.
Source: The Author.

4.1.2 GIS-based multi-criteria analyses

GIS-based analyses are proposed to support the overall methodological multi-criteria framework for strategic planning of offshore wind energy and to improve the sustainability of projects. GIS platforms and methods are known to support efficient multi-criteria assessment with a large number of spatial criteria (SIMÕES, COUTO, *et al.*, 2023). For this reason, the selection of robust computational tools is essential to ensure the robustness and reliability of the methodology.

Therefore, ArcGIS software, developed by the Environmental Systems Research Institute - ESRI, was chosen as the platform for compiling the spatial data and geoinformation tools. The ArcGIS platform is a comprehensive and scalable digital mapping and analysis software and a leader in the development of spatial modeling and planning software.

Numerous scientific and technical studies have used GIS computing platforms to implement various types of DSS for strategic planning in the energy sector. An example of this is a GIS-based model used for environmental assessment for the optimal location of non-conventional fossil fuel resources (HERNANDEZ C., 2016). Several studies on offshore wind energy planning also rely on GIS software for geospatial modeling. SCHILLINGS *et al.,* (2011) and JONGBLOED *et al.,* (2014) have implemented a specific platform for the North Sea; BEITER *et al.,* (2016) in the United States; OU *et al.*, (2018) in China and recently SIMÕMES *et al.,* (2023) in the coastal zone of Portugal. In several developing countries (such as Colombia and the Philippines), THE WORLD BANK (2022a, 2022b) has supported strategic planning of offshore wind energy development using GIS-based technologies, but without developing robust methodologies or automated calculation systems. Most relevant studies have developed specific robust decision support systems to support strategic planning of the offshore wind industry (BEITER *et al.,* 2016, SCHILLINGS *et al.,* 2012).

In light of previous experience, current research proposes a different approach to strategic planning for the offshore wind industry, focusing on the whole concept of sustainability: a balance between natural, social and economic dimensions; along the whole strategic process to gain insights on sustainability in the operational stages. This approach helps to close the vertical integration gaps identified in the literature – from the formulation of strategic plans to the implementation of offshore wind projects. Each analysis aims to reduce uncertainty in the planning process by adding criteria or deepening analyzes on the same criteria. Figure 4-5 summarizes the conceptual integrated model (logical integration) of the different GIS-based analyses. These analyses are supported by a dedicated GIS-based toolbox – the GIS-SPOWER-BR Toolbox (Appendix D).

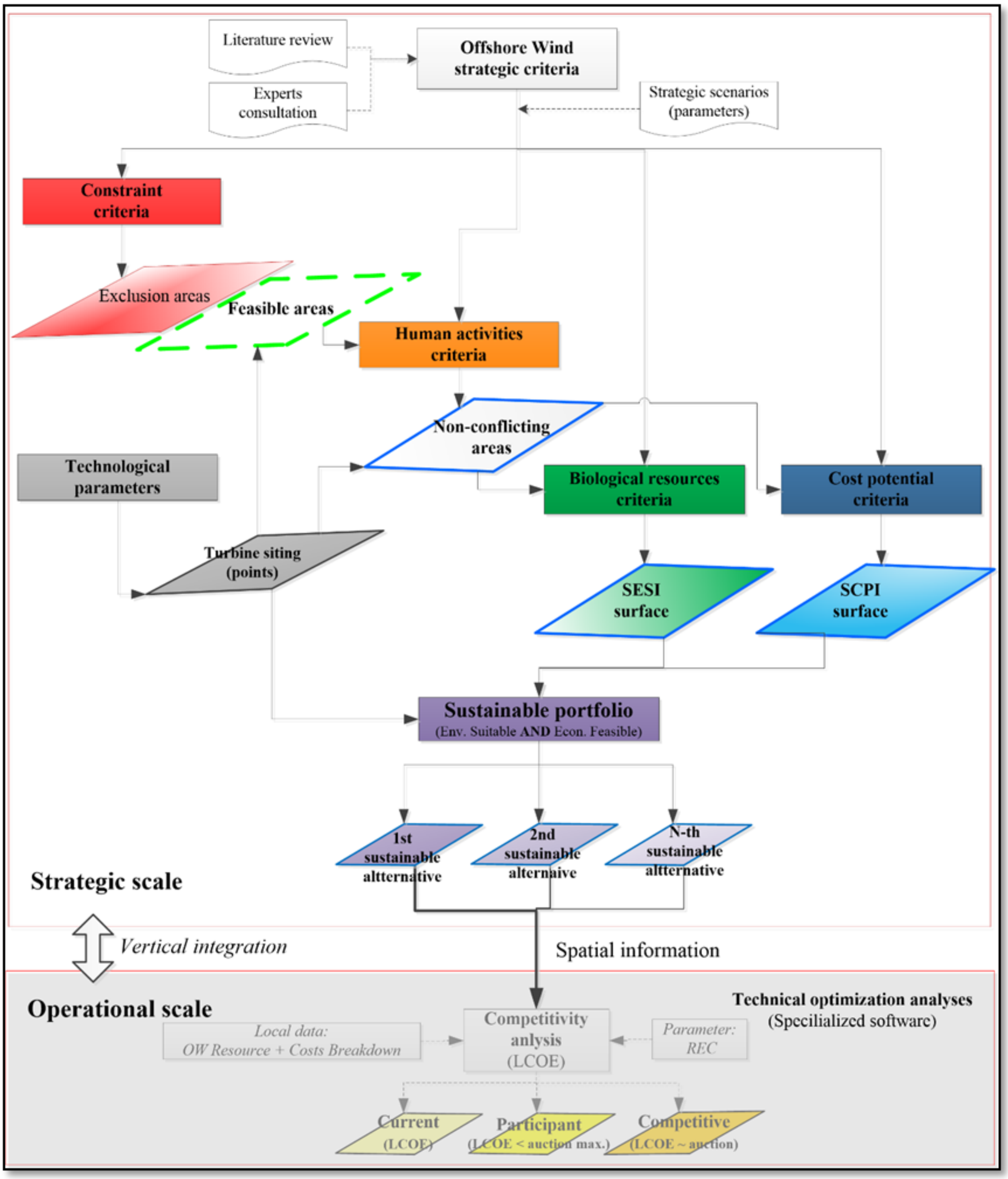


Figure 4-5. Conceptual GIS-based integrated analysis approach for Offshore Wind Energy. Note: SESI: spatial environmental suitability index; SCPI: spatial cost potential index; LCOE: levelized cost of electricity; ERC: Energy Reference Cost
Source: The Author.

This approach evaluates 35 strategic spatial criteria (at different stages of development) and offers greater accuracy than other approaches. A larger number of spatial variables better represent the real world in the context of holistic spatial modelling. The conceptual model also aims to reduce the spatial scale at each stage and analysis. It is similar to EPRI's (2022) approach for nuclear power plant siting, but the current methodology uses this approach due to the spatial scale of EEZs in countries with vast marine areas (such as Brazil) and gaps or available geodatabases of marine space. This GIS-based multi-criteria approach is applied through various analyses, which are explained in more detail in the following subsections.

4.1.2.1 Constraint Mapping Analysis

This analysis calculates the possible area in which an offshore wind farm can be technically located according to the sustainability concept. It uses a Boolean spatial method (presence = 1 and absence = 0) that aims to identify areas that are unsuitable for the deployment of offshore wind farms. The constraint mapping analysis summarizes the constraint layers – negative cumulative effect – to produce a map of exclusion and feasibility areas for offshore wind farms. This procedure is considered within the MSP process (UNESCO-IOC & EUROPEAN COMMISSION, 2021) and was successfully implemented by SCHILLINGS *et al.,* (2012) in the Offshore Wind Energy Decision Support System that supported the elaboration of the OWE Roadmap for the North Sea. However, the latter approach assumed all human activities as a direct constraint, in contrast to the current approach which analyzes the competitiveness of human activities at the local level (see subsection 4.1.2).

The analysis of constraints was automated using the OW Fesible Areas tool as part of the GIS-SPOWER-BR Toolbox (see Appendix D). The calculation is based on the general Equation 4-1.

$$\textbf{Constraint Index} = -\sum_{i=1}^{n} \boldsymbol{C_{i,j}} \begin{cases} \boldsymbol{if\ Constraint\ Index = 0 \rightarrow Feasible\ area} \\ \boldsymbol{if\ Constraint\ Index \leq -1 \rightarrow Exclusion\ area} \end{cases} \qquad \textbf{Eq. 4-1}$$

The constraint index is the area that indicates the number of constraints that the area to be evaluated has (*e.g.,* constraint index = 4 is an area with four cumulative constraints). -Ci stands for a Boolean constraint area (with integer values 0 or 1) and i stands for any constraint type, ranging from i =1 to n=11. The constraint index grid is the result of the summation of all constraint surfaces -Ci. Finally, a conditional evaluation over the constraint index grid assigns the feasible areas for values equal to 0 and the exclusion areas for values equal to or less than -1. Figure 4-6 conceptually illustrates the spatial multi-criteria analysis applied to identify feasible offshore wind areas.

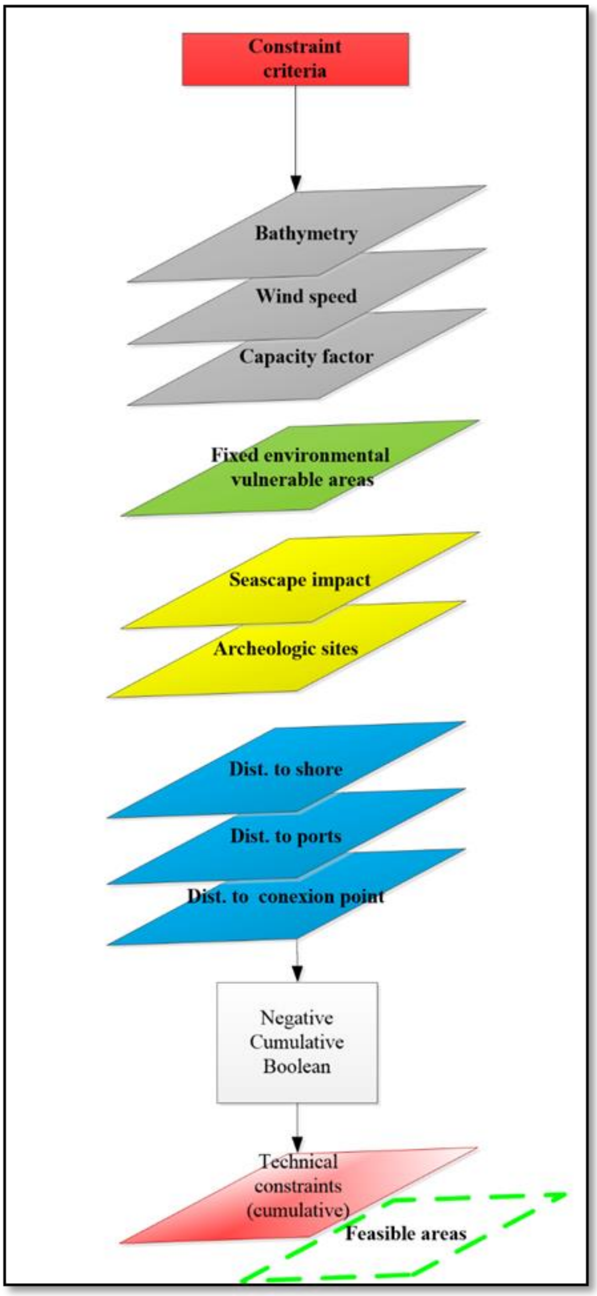


Figure 4-6. Multi-criteria feasible analysis approach for offshore wind energy.
Source: The Author.

4.1.2.2 Spatial-based sea-use conflict analysis

The sea- use conflict analysis aims to assess the competition between OWE activities and other human activities. It is based on the technique of overlay mapping. The spatial levels (polygons or grids) of human activities are compared to assess the relative competition between the individual activities (pairwise comparison). It is assumed that spatial competition arises when more than one activity claims to use the same space or resource. This assessment identifies the potential compatibility or conflict in specific coastal and marine areas, particularly between OWFs and other human activities.

The overlay mapping provides information on which activities have spatial overlaps and the analysis of the activity matrix (see Appendix I) assigns the competitiveness values (see Figure 4-7) (EHLER & DOUVERE, 2013; JONGBLOED *et al.,* 2014; UNESCO-IOC & EUROPEAN COMMISSION, 2021; VAN DER WAL *et al.,* 2010). The assessment of competitiveness is based on legal frameworks, expertise or different conflict assumptions, *e.g.*, different scenario modeling. This assessment identifies the non-conflicting areas (synergetic areas) and the conflicting areas; the priority of Offshore wind development must focus on the former. The conflict areas can be re-evaluated during further assessments or special measures (*e.g.*, negotiations between interest groups).

Overlay mapping supports the assessment of pairwise analysis between human activities by comparing current human activities with the installation of an OWF. Here, the mapping of compatibility or conflict must be done manually by the analyst, based on the competition rules (see Table 4-11), inputs from the scenario(s) of interest (conflict assumptions) and expert knowledge.

Table 4-11. Sea-use competition categories and quantitative values for spatial assessments.

Sea use competition rule	Competition category	Compatibility value
Areas without registered economic activities or associated ecosystem services	Empty areas	10
Both activities can use the space or resource at the same time (coexistence) without the parties involved having to intervene or negotiate. Positive interactions can occur when the presence of one activity improves the conditions for another activity.	Compatible	3
Both activities can use the space or resource simultaneously, requiring intervention or negotiation between stakeholders.	Likely compatible	2
The activities do not compete for the same space or the same resource.	No apparent interaction	0
Both activities cannot use the space or resource at the same time due to legal restrictions or direct conflict between stakeholders.	Conflict	-3
Both activities cannot use the space or resource at the same time due to legal restrictions or direct conflict between stakeholders.	Future Conflict	-2
Low spatial resolution in the input data due to digitalization process or data availability.	Manual digitalized	-88
Areas with spatial data gaps or unavailable public data.	Unavailable public data	-99

Source: The author based on EHLER & DOUVERE (2013); JONGBLOED *et al.*, 2014.

Equation 4-2 is the general function describing the pairwise analysis between coastal or marine activities, with competition categories assigned for each area.

$$\textbf{Competive category}(\mathbf{A}_{\boldsymbol{OWF}}, \boldsymbol{A_h}) = \begin{cases} \mathbf{3}\ \boldsymbol{if\ compatible} \\ \mathbf{2}\ \boldsymbol{if\ likely\ compatible} \\ \mathbf{0}\ \boldsymbol{if\ no\ spatial\ interaction} \\ \mathbf{-1}\ \boldsymbol{if\ conflict} \\ \mathbf{-4}\ \boldsymbol{if\ future\ conflict} \\ \mathbf{-88}\ \boldsymbol{if\ low\ spatial\ resolution} \\ \mathbf{-99}\ \boldsymbol{if\ unavailable\ data} \end{cases} \qquad \textbf{Eq. 4-2}$$

Where:

AOWF is the activity of the offshore wind farm; Ah is the other activity in the pairwise evaluation; h is the possible activity competing with the offshore wind farm for utilization, h varies from 1 to k human activities with possible conflict with OWF deployment; Competitive category(AOWF, Ah) is the pairwise evaluation between the activity AOWF and the activity Ah and assigns the competitive category to each possible interaction.

Equation 4-3 evaluates each area with competitive category values equal to or greater than 0 to classify it as a non-conflicting area for offshore wind energy. Areas with competitive values less than 0 represent the conflict areas.

$$\textbf{Non} - \textbf{conflicting areas} = \textbf{Competive category}(\mathbf{A_1}, \boldsymbol{A_2}) \geq \mathbf{0} \qquad \textbf{Eq. 4-3}$$

Figure 4-7 illustrates the spatial multi-criteria analysis used to identify non-conflicting areas for offshore wind deployment use.

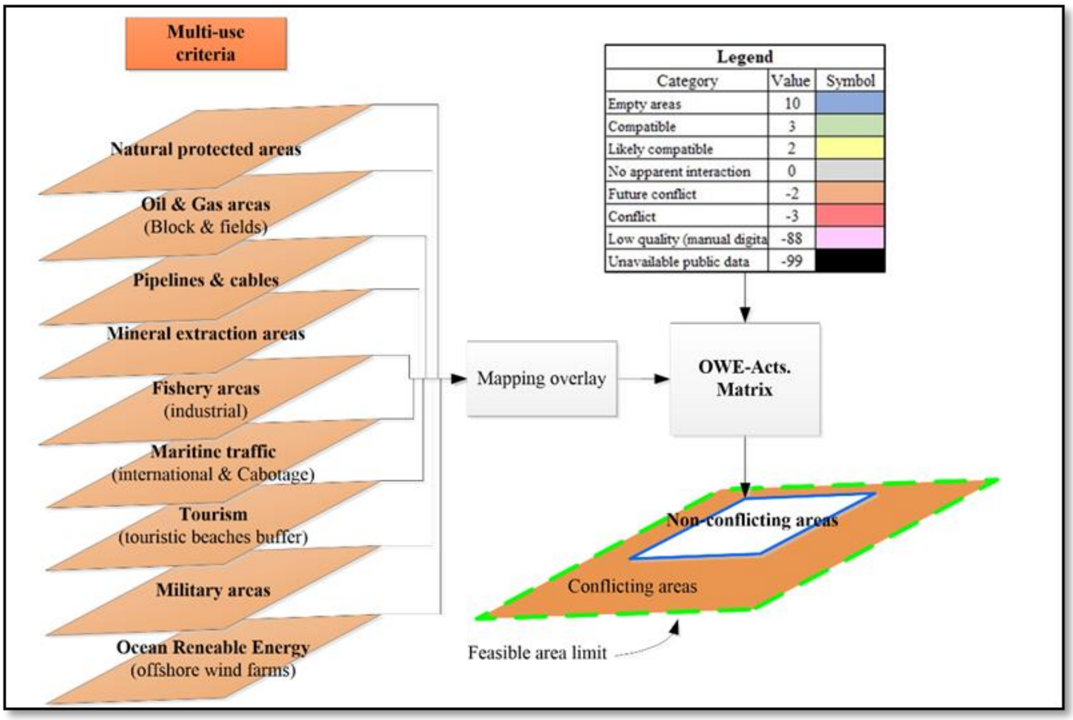


Figure 4-7. Multi-criteria sea-use conflict analysis approach for offshore wind energy. Source: The Author.

4.1.2.3 Sustainable optimization analysis

Sustainable optimization analysis aims to integrate two spatial optimization indices: the Spatial Environmental Suitability Index (SESI) and the Spatial Cost Potential Index (SCPI). Subsequently, the integration of both indices is done by a second-best option(s) approach, where higher scores of both indices intersect in the same space. Areas where occur intersection of high suitability scores suggest higher sustainable areas for the siting of an offshore wind farm – areas with a trade-off between environmental and economic indices – than areas with the highest score of only one index. Equation 4-4 describes the spatial overlap of the two indices.

$$\boldsymbol{Sustainable\ optimization}(\boldsymbol{SESI},\boldsymbol{SCPI})_{(x,y)} = \boldsymbol{SESI}_{(x,y)} \cap \boldsymbol{SCPI}_{(x,y)} \qquad \textbf{Eq. 4-4}$$

Where:

SESI: Spatial Environmental Suitability Index at pixel location x,y.

SCPI: Spatial Cost Potential Index at pixel location x,y.

Figure 4-8 illustrates the spatial multi-criteria analysis used to identify more sustainable areas for offshore wind farm development.

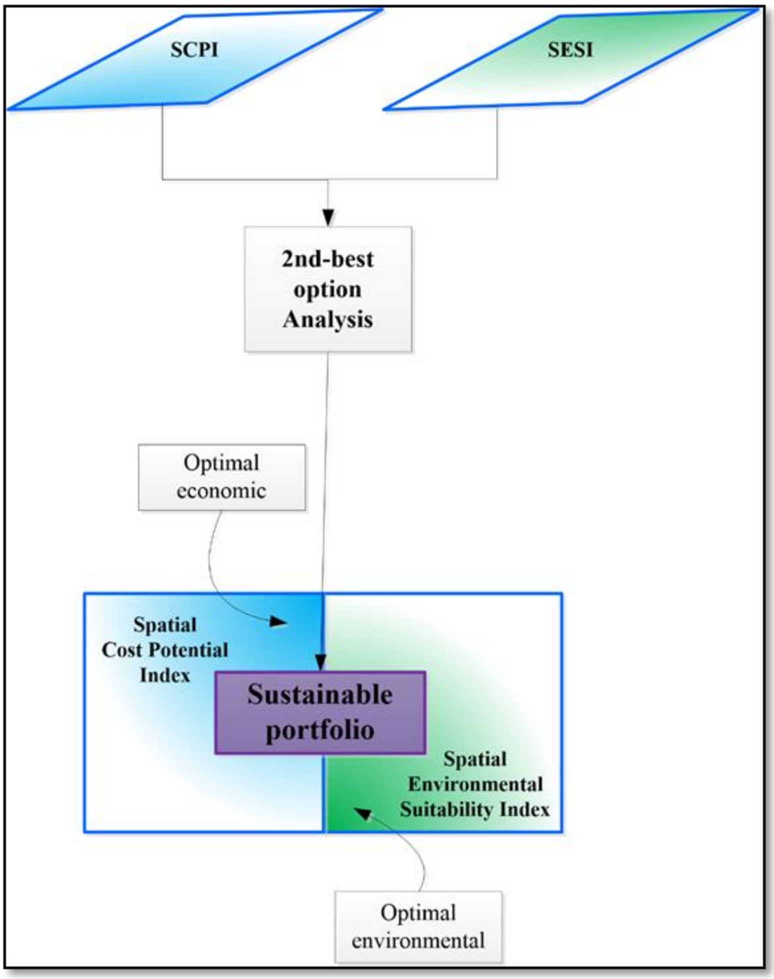


Figure 4-8. Multi-criteria sustainable optimization approach.
Source: The Author.

SESI and SPCI indices can be computed using different spatial multi-criteria approach such as Weighted Linear Combination (WLC) or Analytical Hierarchy Process (AHP). Curremt methodology calculated both indices using spatial Fuzzy Multi-criteria assessment which applies the Ordered Weighted Analysis (OWA) method based on Fuzzy aggregation operators (YAGER, 1988). The Fuzzy multi-criteria analysis was selected due to its ability to cope with decision uncertainty (risk acceptance or rejection) and reduce the subjectivity of qualitative weighting or trade-off between criteria (GORSEVSKI *et al.*, 2012).

The OWA method considers two weightings: a) the relative weighting of the individual criteria and b) the weighting of the order of aggregation (GORSEVSKI *et al.*, 2012). This weighting approach performs the optimization process under risk acceptance profiles that depend on the selected fuzzy operator. The AND operator stands for the lowest risk (all criteria must be met) and the OR operator for the highest risk (at least one criterion must be met) (HERNANDEZ C., 2016). The calculation is based on the general equation 4-5.

$$\mathbf{OWA} = \sum_{j}^{n} \boldsymbol{v_j b_{ij}} \qquad \textbf{Eq. 4-5}$$

Where:

The calculation of the OWA is based on the ordered weighting of the criteria values a_{ij}, $i = 1,2, ..., m$ and $j = 1, 2, ..., n$, with two weighting vectors: weight of the importance of the criterion w_j (with $j = 1, 2, ..., n$) and weight of the order of the criterion v_j ($j = 1, 2, ..., n$), using a set of fuzzy operators. The weights w_j are assigned to the j-th criterion for each pixel. The ordered weights are associated with the values of the weighted criteria ($w_1a_{i1}, w_2a_{i2}, ..., w_na_{in}$) on a pixel-wise basis i, $i = 1, 2, ..., m$. The values of the weighted criteria are $b_{ij} = w_ja_{ij}$, arranged in a predefined descending order $b_{i1} \geq b_{i2}... \geq b_{in}$, without consideration of the initial criterion (RINNER & MALCZEWSKI, 2002).

This procedure is referred to as reordering. It connects the ordered weight v_j ($v_1, v_2 ... v_n$; $0 \leq v_j \leq 1, \sum v_j = 1$) with a certain ordered "position" j ($1, 2, ..., n$) within the vector v_j, v_n. The first weight v_1 is assigned to the highest weighted criterion value $\max(w_1a_{i1}) = b_{i1}$. The second ordered weight v_1 is assigned to the second highest value, and so on. The v_n is assigned to the lowest value $\min(w_ja_{ij}) = b_{in}$.

The OWA has been implemented by ESRI in the Fuzzy Overlay and Fuzzy Membership tools, which are part of the ArcGIS Software Suite geoprocessing tools. Fuzzy Overlay uses the fuzzy operator based on risk profiles, which is represented by the parameter Gamma. Section 7.1.4 explains its implementation in the spatial analysis in more detail.

4.1.2.3.1 Spatial Environmental Suitability Index - SESI

This analysis performs the spatial optimization process by integrating environmental criteria based on spatial Fuzzy OWA. This analysis must incorporate the available spatial data focused on vulnerable biological and ecosystemic resources, including at least: priority protected areas (APCBs) (highest priority), coral reefs, turtle areas, marine mammals, shorebird and seabird areas, and elasmobranch areas. Figure 4-9 illustrates the spatial multi-criteria analysis used to identify suitable environmental areas for offshore wind farm development.

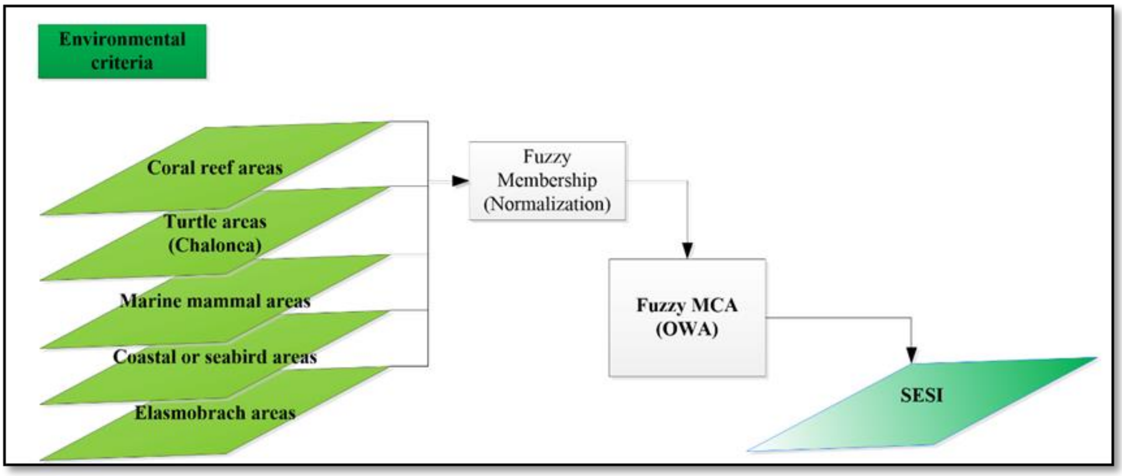


Figure 4-9. Multi-criteria environmental suitability index approach for offshore wind energy. Source: The Author.

4.1.2.3.2 Spatial Cost Potential Index - SCPI

This analysis performs the optimization process of environmental criteria integration based on spatial Fuzzy OWA. This analysis must incorporate the available spatial data of the biological resources, including at least: bathymetry surface, seabed slope surface, distance to installation port surface, distance to connection point surface, material surfaces on the seabed. Figure 4-10 illustrates the spatial multi-criteria analysis used to identify areas with better cost potential (lower cost) for offshore wind farm development.

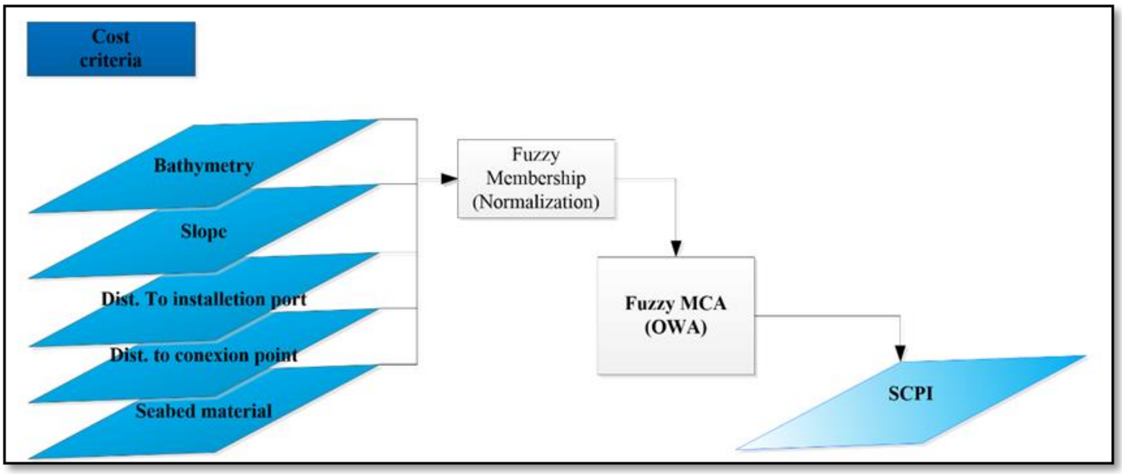


Figure 4-10. Multi-criteria cost potential index approach for offshore wind energy. Source: The Author.

4.1.2.4 Technological analysis

This analysis applies basic concepts of layout design and technological characteristics of offshore wind turbines (EL-SHARKAWI, 2017). In spatial modeling, a quadratic layout is calculated where all possible turbines are placed in a given area without considering site optimization or strategic scale micro-siting calculations. In this analysis, the turbine model is used as a reference for the technological characteristics to define the rotor diameter (RD). In addition, the separation factor (SF) between the turbines is used as a proxy to reduce the wake effect between the turbines. As shown in subsection 2.3.1.4, 2-10 shows that the total area for the location of an offshore wind turbine depends on three variables: the number of turbines *T*, the distance between the turbines *D* (related to the separation factor) and the length of the rotor blades r (EL-SHARKAWI, 2017). The Rotor diameter (RD) = 2*r* has a direct influence on the distance between the turbines, therefore *RD* influences the total area of an OWF; it is the independent variable and an important input parameter for technological modeling. As a reminder, Equation 2-10 calculates the total area for a square layout as follows:

$$\boldsymbol{A_{Sq} = [(T-1)D + 2r]^2} \qquad \textbf{Eq. 2-10}$$

Where A_{Sq} is the total area of the wind farm in a square arrangement, *T* is the number of turbines in a row, *D* is the distance between adjacent turbines within a square arrangement and *r* is the length of the rotor blades. In addition, the distance between the turbines (separation factor) is calculated by the Eq. 2-8 (EL-SHARKAWI, 2017):

$$\boldsymbol{SF = \frac{D}{2r}} \qquad \textbf{Eq. 2-8}$$

Where *SF* is the separation factor, *D* is the distance between two neighboring towers and r is the length of the blade (taking into account *R* ~ *r*, but *R* > *r*).

Considering that previous spatial analyses focused on defining the boundaries for OWE development, the total area is calculated using geoprocessing tools. The general equation 4-6 explains the basic calculation of the total number of offshore wind turbines in a given area, as a simplified form of equation 2-10 (EL-SHARKAWI, 2017) in terms of the number of turbines *T*.

$$\boldsymbol{T = \sqrt{\frac{A_{sq}}{SF * RD}} - \frac{1}{SF} + 1} \qquad \textbf{Eq. 4-6}$$

However, this equation only calculates the total number of turbines. Spatial modeling makes it possible to determine the total number of turbines in a given area and achieve the same result, but with the inclusion of the preliminary localization (coordinates x,y) of each turbine. Figure 4-11 illustrates the spatial analysis based on technological parameters applied for the placement of offshore wind turbines based on Rotor diameter and separation factor for a square layout in the selected area of interest, *e.g.*: Total Area, Feasible Area, Non-conflicting Area or Sustainable Offshore Wind Areas, etc. This analysis was automated as an OW Turbine Grid Tool in the GIS-SPOWER-BR Toolbox. Additionally, the Wake buffer tool is available for modeling

20H rotor diameter buffers of different reference turbines as indicative wake effect areas upwind and downwind of the wind farm to estimate the area of influence of the offshore wind farm during the strategic planning stage.

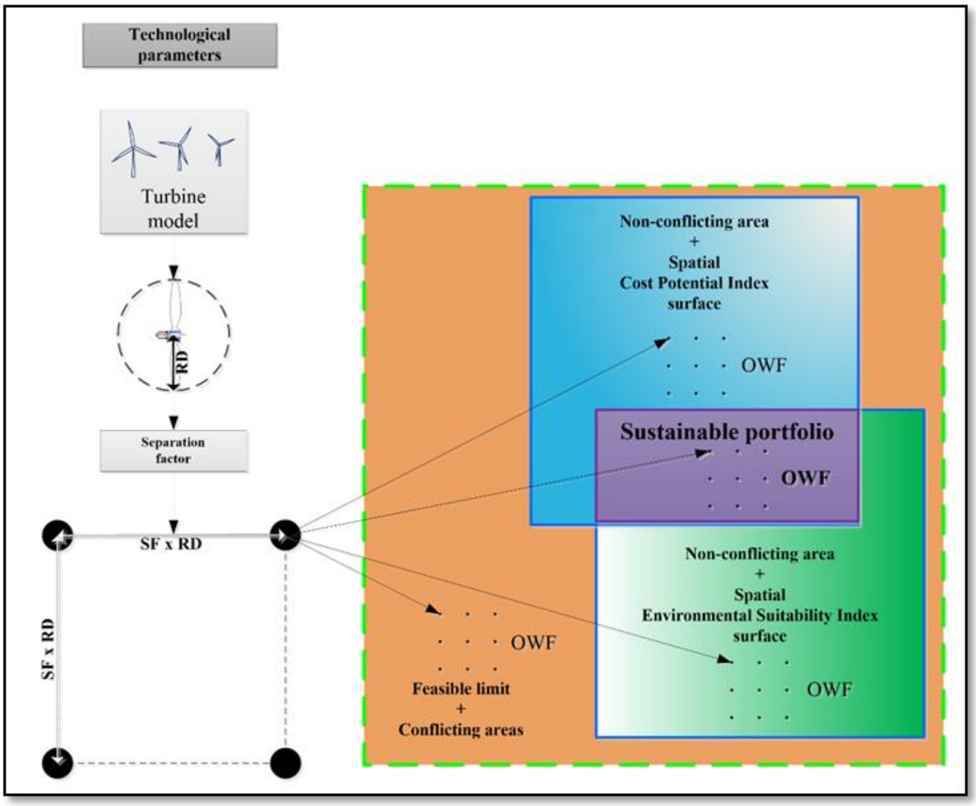


Figure 4-11. Spatial-technical modeling framework for offshore wind energy.
Note: Spatial modeling for a square offshore wind farm layout. RD: rotor diameter; SF: separation factor; OWF: offshore wind farm.
Source: The author.

All previous GIS-based analyses are based on prior strategic scenario planning. This prior step aims to integrate the holistic visions of the strategic stakeholders into an overall vision for the development of offshore wind energy. Scenario planning must guide the entire strategic planning process. The parameterization of the strategic scenarios enables the quantitative representation of scenarios of interest for modelling the probable future of the study area (LIMA-COPPE, 2007). The parameterization process consists of defining quantitative values or assumptions as contour conditions for each scenario of interest. These values can be determined by experimental, technical or experience-based findings (data) from scientific literature, technical reports or expert advice. Section 4.2 presents this activity, which is embedded in the SPOWER-BR methodology.

4.2 Methodology for Strategic Planning of Offshore Wind Energy, Brazil – SPOWER-BR

This section presents the stages of the methodology for the Strategic Planning of Offshore Wind Energy in Brazil (SPOWER-BR). Components, methods, tools, assumptions and data requirements. The stages were developed to integrate sustainability concepts and GIS-based multi-criteria methodologies into strategic decision-making for offshore wind energy development and to improve vertical integration with operational project phases at the local level. The current methodology also aims to support the implementation of other studies, such as marine spatial planning or strategic environmental assessment, environmental licensing or renewable energy auctions. Figure 4-12 shows the general stages of the methodology.

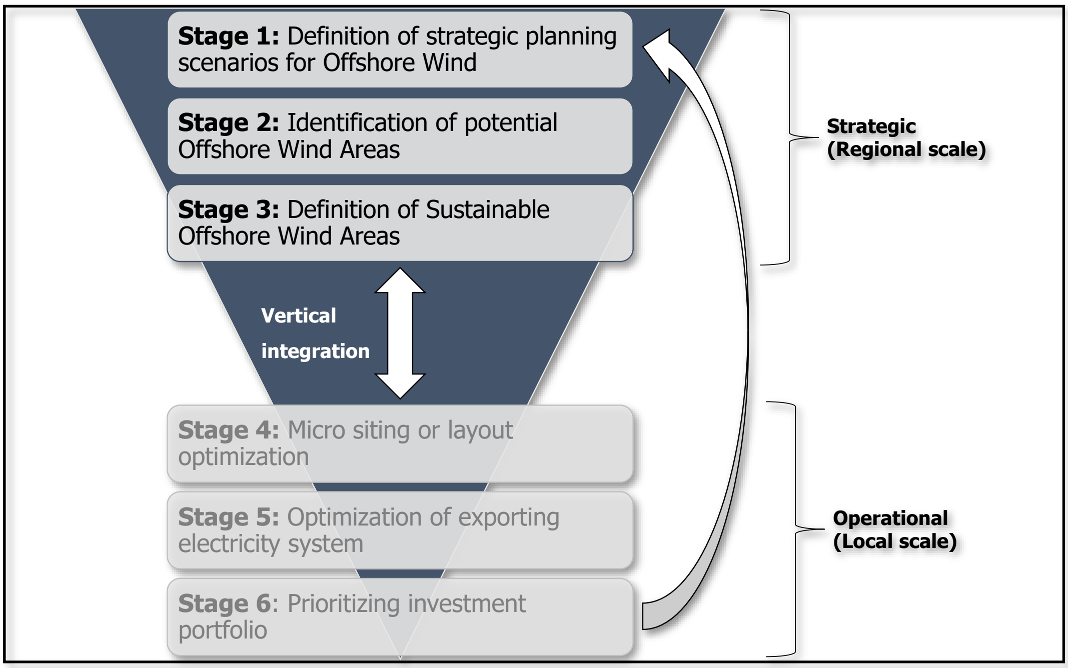


Figure 4-12. General stages of the SPOWER-BR methodological framework.
Note: the cyclic data flux fosters improvements in vertical integration between strategic and operational stages in long-term and periodic planning processes.
Source: The Author.

The proposed methodology has three main objectives: 1) vertical integration between the strategic and operational stages focused on the development of offshore wind energy projects; 2) overcoming obstacles due to gaps in the available data by reducing the amount of work in each phase within a structured framework; and 3) reducing time bottlenecks by providing specialized GIS-based tools for computer simulations of likely scenarios of planning. The last objective is directly supported by the compilation of the GIS-SPOWER-BR Toolbox (HERNANDEZ C. *et al.*, 2022), a GIS-based toolbox specifically developed for offshore wind energy planning. The general stages of the methodological approach are presented below.

Stage 1 – Definition of strategic planning scenarios for offshore wind

Scenario(s) of interest must be defined in relation to the vision and objectives of the evaluation. In this case, they must take into account the strategic factors that influence the offshore wind project planning process. Strategic planning of offshore wind energy is influenced by technological and economic factors, but if the planning process is embedded in a sustainability approach, strategic environmental and social factors must also be included. Strategic scenarios then need to represent likely futures that OWFs might encounter during the project life cycle.

In addition, other factors such as technology and market maturity must be taken into account in order to obtain a more comprehensive picture of the possible future in which an OWF will be embedded (BERGERSON *et al.,* 2019, DEDECCA *et al.,* 2016). Due to the specific characteristics of offshore wind farm technology (*e.g.,* fix-bottom and floating foundations or rotor blades), developing countries often lack a supporting infrastructure and an established supply chain.

The importance of analyzing strategic factors during the scenario planning process is based on the ability to link the strategic factors to the specific strategic criteria. Strategic criteria define the level of detail at which the assessment can be conducted and the framework conditions that constrain or differentiate the strategic actions to be implemented in the planning periods or geographic regions.

The scenarios must provide a clear vision of the context in which decision-makers might develop the offshore wind industry or projects, so that the quantitative technical parameters (values defining constraints and suitability thresholds) can be linked to these future contexts. This activity creates a solid basis for estimating energy production forecasts, targets and goals. Scenario planning must take into account the sector's strategic objectives, market development trends (supply and demand) and technological developments of core structures or equipment (such as offshore wind turbines, offshore foundations, installation techniques, logistics dynamics, supply chain development and others). The steps to create robust scenarios are described below.

Scenario conceptualization

It must represent the decision-maker's vision for the long-term development of the offshore wine industry (public sector) or a portfolio of individual projects (private developer). This activity is necessary due to the maturity of the technology and the market in developing countries. Table 4-12 explains the elements to be considered in the conceptualization of scenarios.

Table 4-12. Elements of Strategic scenarios for development offshore wind energy.

Element	Description
Title	Conveys a general idea of the scenario, the vision of the future and, optionally, the decision-maker and the time horizon.
Objective	State the vision and scope that the current scenario/alternative will achieve.

Element	Description
Decision-maker	Responsible for the decision or action to solve the problem.
Risk profile	This element represents the risk profile of the decision maker in relation to the development of the offshore wind energy industry or project.
Timeframe	Available time horizon for achieving the objective(s), targets and goals. It should take into account the state of technology and market development in order to synchronize the targets with the governance timeframes.
Geographical localization	Selection of an initial geographical localization for the development of the strategic scenario
Strategic constraints	Defines direct or absolute restrictions that limit the development of the industry or a project. Technological, environmental, social and economic factors and criteria are taken into account.
Strategic sea use conflicts with human activities and natural resources at coastal-marine zone	Identify the human activities and natural resources (geophysical or biological) that may affect the development of an offshore wind farm. These conflicts are not absolute constraints, as several activities or resources can be negotiated, managed or developed at the same time.
Offshore wind farm optimization assumptions	Consider the technological parameters that make it possible to digitize, model and optimize the layout of the wind farm to maximize energy production.
Transmission and connection optimization assumptions	Takes into account the technological parameters that make it possible to optimize the transmission from the offshore substation to the onshore connection (grid connection or decentralized point). It is important to consider the environmental and social problems that the transmission corridor may cause.
Port infrastructure and logistics	Ports and logistics are strategic factors for the development of offshore wind energy. For the selection of installation and O&M ports, assumptions about technological characteristics and legal constraints need to be defined.
Potential solution alternatives	Hypothetical results that the scenario can produce depending on the overall assumptions.

Source: The Author.

The outcome of this activity is a set of conceptual scenarios that may be of interest for analysis and modelling to drive the strategic development of offshore wind energy.

Compatibilization with regulatory framework and strategic plans and programs

After defining the conceptual idea of strategic scenarios of interest, it is highly recommended to align these scenarios with the current and evolving legal framework, policies, plans and programs. This step supports the consolidation of scenarios based on sectoral, regional or national trends. Regulatory and policy frameworks may include current specific regulatory instruments that have been enacted or are under development (*e.g.,* Decree 10.946-2022 or Project Law 576-2021), as well as strategic plans for the energy sector (*e.g.,* National Power Plan 2050 or Decennial Transmission Expansion Plan), strategic plans for the development and improvement of strategic infrastructures (*e.g.,* port development and land use plan) and spatial planning plans such as marine spatial planning – currently most Latin American countries are at an early stage of development, as the MSP Roadmap 2030 (2023) shows. Historical growth rates (*e.g.,* the development of the onshore wind industry in Brazil) and projected growth rates (international trends) of the industry need to be taken into account to help with the distribution of targets along the planning horizons. Figure 4-13 depicts the compatibilization process producing a strengthened aligned vision.

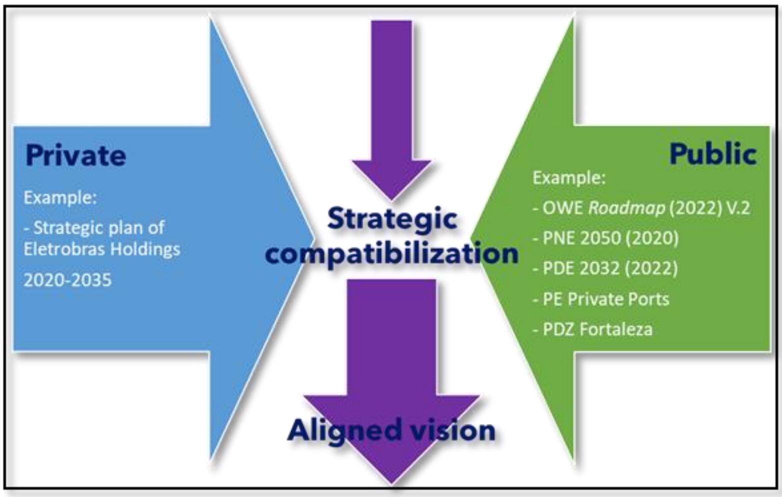


Figure 4-13. Schematic representation of compatibilization of scenarios.
Source: The Author.

The main outputs of this process are references and bases for the parameterization of scenarios in relation to objectives, targets or interests of public or private partners. The selection of a specific scenario for the development of OWE that is compatible with marine spatial planning approaches can be based on the following aspects (EHLER & DOUVERE, 2013):

- Physical, chemical and biological impacts over time, including cumulative impacts.
- Economic impacts and their distribution, *e.g.*, direct and indirect costs and benefits, who gains and who loses.
- Time considerations, *e.g.*, the time needed to achieve results.
- Political considerations, *e.g.*, public acceptance, relationship to other management plans.
- Financial feasibility, *e.g.*, economic requirements for implementation.

Parameterization of the conceptual scenarios

Based on scenario planning and the Harvard case method (BERGERSON *et al.*, 2019; DEDECCA *et al.*, 2016; HAMMOND, 2002), the elements and parameterization of the strategic scenarios are proposed in Table 4-13. This activity aims to provide a structured process for the definition of planning scenarios that facilitates compatibility with complementary strategic scenarios at sectoral, regional or national level. In the event that the fundamental issues of the table cannot be clearly identified, it is recommended to review the decision-making process and to complete the supporting information, as this gap may indicate a potential weakness in decision-making.

Table 4-13. Parametrization of Planning Scenarios.

Component	Parametrization
Objective	Establish a timeframe, limits or thresholds for reducing geographic expansion and a planning approach such as: economic, environmental, social or sustainable/trade-off, etc.
Decision-maker	Public or private.
Risk profile	High acceptance, low acceptance, neutral profile.
Timeframe	Year in which the vision is to be achieved *E.g.,* overall target for installed capacity of floating wind energy (or milestone) by 2050, with sub-targets for installed capacity in the short, medium and long term.
Geographical localization	Choice of location and planning approach depending on the situation, *e.g.,* resource hotspot, federal, regional or local.
Strategic restrictions	Numerical values representing thresholds that must not be exceeded (parameters), taking into account the strategic factors and criteria, represented by spatial variables. The strategic factors and criteria for offshore wind energy are explained in more detail in the following subsection.
Strategic sea use conflicts with human activities and natural resources at coastal-marine zone.	Numerical values required for the spatialization of human activities or natural resources. Different activities such as offshore oil and gas platforms may represent a conflict, but at a strategic level they are represented by a point. Therefore, buffering is recommended as a spatialization strategy. It applies to linear infrastructure or the protection of special areas. The factors and criteria for offshore wind turbines are explained in more detail in the following subsection.
Offshore wind farm optimization assumptions	Numerical values related to layout design, physical characteristics, technical parameters or future technology and market evolution *e.g.,* wind capacity factor, turbines separation factor. It is recommended to set ideal reference parameters based on scientific literature and specialized optimization software.
Transmission and connection optimization assumptions	Numerical values for identification of grid connection points (origin and fate). Additionally, parametrization must take into account future procedures (criteria, and weights for modeling) for optimization of transmission corridor, considering scenario assumptions. It is recommended to set ideal reference parameters based on scientific literature and specialized optimization software.
Port infrastructure and logistics	The characteristics of ports in terms of available space for storage and assembly (shunting), channel depth, pier length, vertical clearance, availability of services and legal/contractual provisions should be evaluated to identify ports for installation and/or operation. Based on the port selected, an acceptable maximum distance for modeling must be determined (*e.g.,* 100 km from the port of installation).
Solution alternatives	Reference values that allow a comparison or indicate the expected result. (*e.g.,* PNE 2050 has calculated an installed capacity of 16 GW by 2025).

Source: The Author.

At this point, a series of strategic scenarios must be created, ideally consisting of a maximum of four scenarios with different concepts, rather than different versions of the same scenario containing alternatives and challenges (CAPLICE & PHADNIS apud CHEN, 2020).

The set of scenarios must include the trend or baseline scenario and the additional scenarios that represent most of the possible future realities in the area or stakeholder bias (UNESCO-IOC & EUROPEAN COMMISSION, 2021). It is recommended to consider at least three additional scenarios with different preferences to identify possible trade-offs and complementary stakeholder visions. Suggested scenarios include: high profitability (economic orientation), high environmental protection (ecological orientation) and high sustainability (trade-off between dimensions). The construction and modeling of different scenarios can also be helpful in the evaluation of project alternatives in the EIA and operational stages.

Validation of strategic scenarios

As an international best practice, it is recommended to introduce a collaborative approach into the scenario development process. This process aims to incorporate the visions of strategic stakeholders on what and how they envision the development of the industry and the implementation of projects in a country or region. The visions need to complement each other to create a solid, holistic perspective. For this, multidisciplinary approaches such as workshops, expert interviews (structured interviews, ad hoc or Delphi methods) (GONZÁLEZ & CONNELL, 2022; HO *et al.,* 2018) or surveys (online or in-situ forms) (XAVIER *et al.,* 2020) can be used. This process should seek a holistic opinion and, above all, incorporate society's perception as early as possible in the early planning stages.

Stage 2 – Identification of potential Offshore Wind Areas

This stage summarizes the activities to identify different possible areas or sites for the offshore wind farm, taking into account a variety of strategic criteria. Two main outcomes must be achieved: feasible and non-conflicting areas that represent potential offshore wind areas.

Characterization and definition of coastal environment units for strategic planning

In this phase, the input data – as spatial variables – are organized following the classification of the drivers of the MSP process into: a) international and political boundaries, c) biomes and ecosystems, d) human activities (UNESCO-IOC, EUROPEAN COMMISSION, 2021), as described in subsection 4.4.3. This mapping helps to characterize the area of interest, where the characterization should prioritize the most important/relevant layers for environmental, social and economic assessments and the study of future scenarios (MINISTERIO DE MINAS E ENERGIA, 2007), with a current focus on strategic scenarios related to OWE development.

Subsequently, the coastal/marine environmental units (basic planning units) must be defined, which have homogeneous spatial characteristics along the coastal/marine zone (depending on the MSP approach) (MMA, 2017).

These units are very important due to the lack of small-scale planning units in the marine environment, unlike the onshore environment where municipalities, provinces or states are defined by law. Here, absolute technological factors that limit the development of activities can help to define the boundaries of the planning unit and limit the analysis to the area of interest. In addition, these units can guide the prioritization of actions along the time frame based on economic activities, infrastructure development or natural dynamic relationships, etc.

In this case, the geodatabase and key drivers mapping (see 4.4.3) support the definition of the individual coastal environment units for the strategic planning of offshore wind power. These boundaries support strategic decision-making in terms of management approach, timeframe, objectives and risk acceptance.

Identification of Feasible Areas

In this phase, the first complex spatial assessment is carried out. Here, the selected constraint criteria are integrated to identify the area where OWF is technically feasible – with a sustainability approach – using 8 spatial variables as input data and 11 numerical parameters. The numerical parameters represent different approaches depending on the strategic planning scenario (see Table 4-4). This activity is carried out using the OWE Feasible Areas tool (see subsection 7.1.1), which is included in the DSS GIS-SPOWER-BR Toolbox developed by HERNANDEZ *et al.*, (2022). The results include the feasible areas (restriction = 1) and the restricted areas (restriction = 0). In addition, a restriction index provides information on which border areas must be avoided due to a high number of restrictions. This index adds up the restrictions from 1 to 11 within the restriction areas.

Some of the restriction areas may also be technologically feasible, but this depends on: a) the defined scenario of the analysis and b) the sut up of the associated restriction parameters for each criterion.

Identification of non-conflicting areas

In this phase, the conflicts of use between the sea and other human activities in the marine area are identified. In this phase, the OWE activity matrix (see Appendix I) is used to identify potential conflicts between OWE and other human activities. At least four categories of conflict must be considered: Direct conflict (-1), Potential conflict (2), Compatibility (3), Non-spatial overlap (0) and No public data available (99). However, if desired, other values for compatibility can also be used, such as Future conflict (-2) or Low quality data (88). The numbers represent a numerical value for each conflict category. These specific numeric values are suggested because they can help organize the data during geoprocessing and spatial analysis.

In areas with overlapping polygons, the category with the most conflicts must be selected according to the "precautionary principle". Polygons within feasible areas and outside direct conflicts or possible conflict areas are classified as non-conflicting areas. These non-conflicting areas represent a lower risk of overlapping absolute technical restrictions and conflicts with other human activities. The non-conflicting areas then form the basis for "preliminary" optimization assessments by SESI and SEPI indices.

Stage 3 – Definition of Sustainable Offshore Wind Areas

This step aims to reduce the scope of the analysis and incorporate spatial optimization techniques into the sustainability approach through integrating two indices: the Spatial Environmental Suitability Index (SESI) and the Spatial Economic Potential Index (SEPI).

Due to the higher uncertainty in strategic stages caused by the market maturity and low quality of local data, both spatial indices are proposed to provide spatial optimization insights into small-scale integrated multi-criteria analysis. Risk profiles can be assumed to normalize and integrate optimization criteria into the environmental and cost indices. Integrating both spatial optimization indices generates an integrated sustainability optimization index providing additional sustainability information to prioritize and group turbines into more sustainable wind farms or areas.

Spatial Environmental Suitability Index - SESI

SESI integrates the five most important biological resources in the coastal zone related to potential impacts caused by OWFs (HERNÁNDEZ C. *et al.*, 2021; LEMOS *et al.*, 2022; MAXWELL *et al.*, 2022; LEMOS, 2023). Depending on data availability, these biological resources prioritize spatial indicators on the following themes: **priority areas for conservation, birds and bats, marine mammals, turtles (chelonians), elasmobranchs and coral reefs**. Bentos, large marine mammals and other important or threatened biological resources must be carefully managed. Due to the potential impacts identified during installation (pile driving, reef protection, and cable installation), these resources must be carefully managed.

Spatial Cost Potential Index - SCPI

The SEPI needs to integrate the five key economic criteria that influence LCOE and economic potential, as suggested by GILMAN *et al.* (2018). Depending on data availability, these economic criteria should prioritize spatial indicators: bathymetry**, distance to port of**

installation, distance to grid connection (grid or decentralized depending on connection concept), **seabed slope** and seabed material.

The areas resulting from the collection of turbines according to homogeneous characteristics in the comparison between SESI and SEPI represent the proposed sustainable projects. These analyses thus support the definition of conceptual projects within a robust holistic approach.

Technological analysis

The technological analysis consists of modelling the total number of possible turbines in a desirable area with a preliminary localization. This analysis is based on a quadratic layout approach and considers the distance factor between the turbines as an input parameter for the estimation and placement of the offshore wind turbines. The GIS-SPOWER-BR Toolbox includes the OW Turbine grid tool (see Appendix D), which calculates the distribution of turbines based on the rotor diameter of the selected turbine and the desired separation factor for the OWF (the user must provide the technical data). In addition, the classification scale for offshore wind farms given by SNYDER & KAISER (2012) has been updated as follows to take into account new market trends, wind turbine and farm sizes and total installed capacity:

- Demonstration (pilots): < 50 MW
- Pre-Commercial: 50 – 100 MW
- Small Commercial: 100 – 250 MW
- Full Commercial: 250 – 750 MW
- Large Commercial: 750 – 1,500 MW
- Mega Commercial: > 1,500 MW

This analysis provides the total number of wind turbines in the selected area and their initial localization, and depending on the total number of turbines, the total potential installation capacity is calculated. This strategic level siting estimate must be based on primary data collected (in the field), processed and modeled with dedicated software for offshore wind farm layout optimization.

Definition of installation targets and specifications

Technological modeling of offshore wind turbine sites within feasible and non-conflicting areas – at a strategic stage – provides data and robust insights for defining the installation target and deployment goals for an offshore wind area or a farm. Targets and goals must consider a suitable spacing between farms to avoid power losses caused by the influence of the wake effect in downwind sites.

Feasible and non-conflicting areas are suggested boundaries for defining the overall installation target and assigning development goals and project pipelines in the short, medium and long term. This procedure follows the NREL's approach for resource classification in the – U.S. National Offshore Wind Strategy (GILMAN *et al.*, 2018).

Stage 4 – Micro-siting (Layout optimization)

The optimization of micro-sites or layouts is based on complex numerical modeling, which software such as OpenWind, WindSIM, WAsP and others already perform. The OpenWind software stand out for its interoperability with GIS-based software (BEITER *et al.*, 2016). The current methodology aims to support all development stages, including project optimization activities, by providing the best possible inputs and complementary data along the process. The current methodology proposal does not address this phase as micro-siting is outside the scope of the research. However, the basic activities are listed below to describe the basic steps during full sustainability planning. When structured and robust contour data (after application of earlier stages) on sustainable OWF is available, the micro-siting activities are more accurate and timesaving.

Micro-siting activity comprises following activities (MELO, 2023):

a) Selection of modeling platform or software
b) Acquisition of topography and roughness data
c) Acquisition of local wind resource data
d) Calculation of local wind resource (wind micro atlas)
e) Definition of wind farm preliminary layout (provided by prior stages using GIS-SPOWER-BR)
f) Layout optimization using specialized software. Stage 3 provides strategic input data.
g) Calculation of energy generation

This stage must provide detailed data on energy production, turbine selection and the micro-location of individual turbines.

Currently, strong links between GIS and specialized calculation software are required. Data compatibility must be handled carefully to avoid errors in data transfer between programs. Specialized software for wind resources must be up to date in software development.

Stage 5 – Optimization of the electricity export system

The optimization of the power export system aims to obtain more accurate information about the export cable and the grid connection. Two steps are considered: the selection of the optimal connection point and the optimization of the export cable corridor.

Selection of the optimum connection point

Selecting the optimum connection point for an OWF is not a trivial decision. It requires a complex analysis of the connection scheme (to the grid or to an independent consumer), the available connection capacity and the location of the substation. Optimization is not the subject of the research, but basic activities and considerations are also proposed.

The choice of connection model depends on the developer's interest, the local market price of energy and the company's strategic planning. When selecting the optimal point for connection to the grid, the available connection margin at the possible grid connection points (substations) must be taken into account. Depending on the available data on the available connection margin, specific modeling of the power flow and the impact on the power transmission system must be carried out as soon as possible to ensure this.

Optimization of export cable corridor

To optimize the cable export, it is recommended to use special software and tools that are designed for linear projects. Here it is recommended to GIS-based tools such as AMBIENTRANS ®, developed by CEPEL (2013) (Brazil), which focuses on optimizing the corridors of transmission lines with a sustainability approach. This tool comprises four modules:

a) Geodatabase assembling
b) Preprocessing and normalizing spatial data
c) Weight importance allocation
d) Data visualization

Micro-siting is outside the scope of the research, however, fixed links between systems are possible at the current state of software development and it is strongly recommended to integrate linear optimization tools into WebGIS platforms.

Stage 6 – Prioritization of the long-term offshore wind farm pipeline

This stage aims to prioritize the proposed OWFs in a long-term pipeline of projects for investment.

Once a sustainable OWF portfolio has been defined, the local economic potential must be determined. The economic potential must include accurate data on energy production (calculated from micro-siting optimization), cost elements (a robust and detailed cost breakdown approach is proposed by IOANNOU *et al.*, 2018), energy prices (LACE) in the local market (BEITER *et al.*, 2016) and accurate data on supply chain and logistics (SHIELDS *et al.*, 2023), specialized technology and labor costs (from local surveys) (ARAUJO *et al.*, 2023).

To illustrate the application of the proposed methodology, the state of Ceará is presented as a selected case study in section 4.3. The validation of the methodology tested on the state of Ceará is presented in detail in Chapter 5.

4.3 Assembling the baseline geodatabase

Data is essential for decision making in policy making and investment in renewable energy. However, gaps in available data are the main obstacle when it comes to strategic decision-making, especially when considering new technologies (BERGERSON *et al.*, 2019). The data-analysis-decisions nexus describes the relationship between data and final decision making, with data at the core of robust and accurate decision making. Stakeholders who use the right data perform better analysis in support of four strategic lines of action: Goal Setting, Policy Making, Energy Sector Planning and Investment (see Figure 4-15) (COX, 2017).

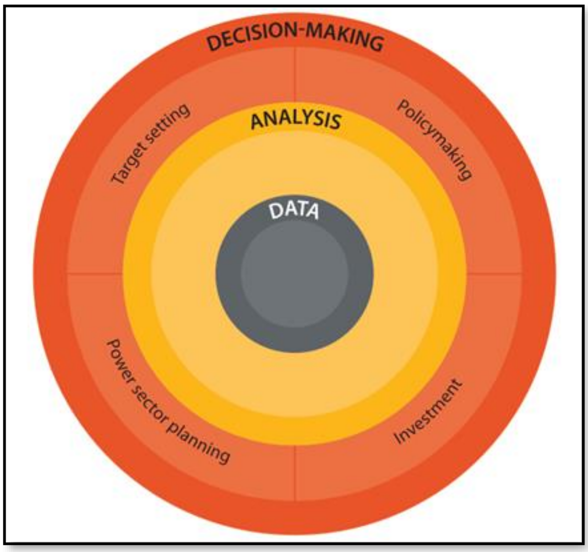


Figure 4-14. Data-analysis-decision nexus.
Source: Cox (2017).

The following subsections describe four key steps for the creation of the geospatial database: a) data source verification, b) data acquisition, c) data exploration and pre-processing, d) mapping of key marine spatial features. These steps guide the process of updating the baseline geodatabase for future assessments or modeling of complementary scenarios.

Collecting the spatial data and integrating it into a system is a very time-consuming task (IMAGEM, 2024; SIMÕES *et al.*, 2023). In some cases, this process can become a planning bottleneck or even a direct obstacle to the development of new technologies. For this reason, the creation of the baseline geodatabase was an attempt to close this initial data gap.

4.4 Case study: the State of Ceará

The case study focused on the state of Ceará due to its geographical location and its importance for the Brazilian wind industry. The test of the methodological framework is applied in the development of this case study for several reasons. First, the state of Ceará is located in the northeast of Brazil, one of the three hotspots with excellent offshore wind resources in Brazil (HERNANDEZ *et al.*, 2021). Secondly, the state of Ceará is a leading state in wind energy generation due to its importance in the historical development of Brazilian onshore wind energy (DUTRA, 2001, FELIPE, 2014) and its significant supply chain maturity for the onshore wind industry (ABDI, 2018; HERNANDEZ C. *et al.*, 2022). Finally, national and international developers have shown their interest in the northeastern offshore wind hotspot since 2016 (LAUXEN, 2021), when BI Energia Ltda. submitted the first conceptual offshore wind project to Brazilian Institute of Environment and Renewable Natural Resources – IBAMA.

By 2023, there were 27 conceptual projects in the coastal zone of the state of Ceará, comprising 14,499 offshore wind turbines with a cumulative installed capacity of 21.9 GW in an area of approximately 18,030.4 km^2. However, these values do not represent the actual potential of installed offshore wind capacity as the areas overlap – approximately 6,341.4 km^2, 35% of the total area required. Other restrictions such as the proximity between wind farms, the minimum distance to the coast or conflicts of use at sea were also not taken into account. Figure 4-14 shows the location of the state of Ceará, including its EEZ. The selected study area covers the Exclusive Economic Zone (EEZ) and the coastal zone of the state of Ceará. In defining the boundaries of the EEZ and the maritime boundaries with other states, the maritime boundaries for the distribution of offshore O&G royalties in Brazil were taken as a reference (BITAR, PAULON, 2011). The marine boundary assumptions are particularly important as the boundaries and delineations for the analysis of marine space remain unclear. Deviations in the total area can cause significant differences – over- or underestimations -in the estimation of energy potential at different levels, i.e. technical, socio-environmental and economic. The case study is presented to contextualize the following sections.

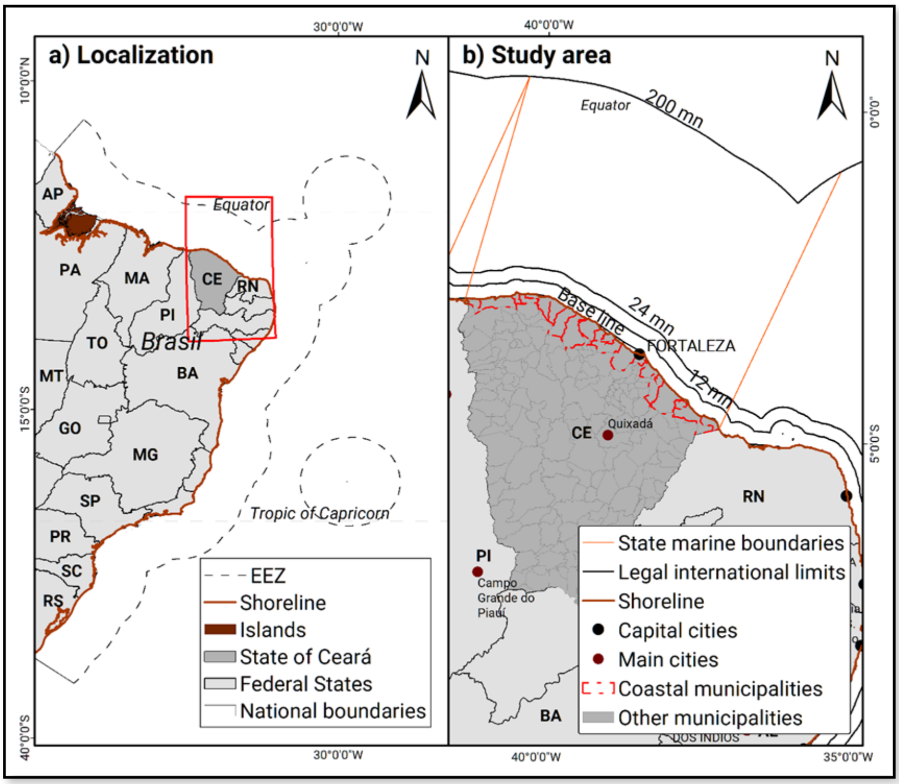


Figure 4-15. Localization of the study area: State of Ceará.
Note: study area comprises the Economic Exclusive Zone (EEZ) and coastal zone of the State of Ceará.
Source: The Author based on raw spatial data (MARINHA DO BRASIL, 2020).

4.4.1 Data sources

It is important to identify the stakeholders associated with the strategic criteria for sustainable offshore wind development, as outlined in subsection 4.1.1.

An analysis of public data sources, data availability, quality and reliability was then carried out. The availability of public geospatial data plays a key role in the strategic planning of identifying offshore wind areas: feasible, non-conflicting and sustainable areas for offshore wind energy (the most suitable area) (HERNANDEZ *et al.*, 2021).

More than 46 public national and international data sources were analyzed in the current study. Table 4-14 lists the main data sources and the basic characteristics of availability and quality. The quality was assessed on the basis of experience in dealing with geodata. Reviewing the scale of each raw data layer is a best practice to set the suitable scale and spatial resolution of the spatial modeling.

Table 4-14. Consulted national and international institutions consulted during the analysis of strategic criteria and spatial data collection.

Consulted data sources	Platform name	Data format	Registered update	Availability and Quality
ANA	GIS: HIDROWEB 3.0	*.xls	-	3
ABDI	Web doc	*.pdf	2018	2
ANEEL	GIS Esri: SIGEL	*.shp; *.kml	2019	3
ANP	GIS Esri: GeoANP	*.shp	2018	3
ANP_stats	Web	*.xls	2020	3
BirdLife Internacional	Web	*.csv	2020	2
CEPEL	-	Raster; *.pdf	2017	3
CETEM	Web	*.pdf	1974	2
CPRM	GIS: GEOSGB	*.shp	2009-2013	2
DNIT	Web folder	*.shp, *.kml	2015	2
EPE	GIS: Web Map EPE	*.shp	2019	2
IRENA_EPE	NA	*.tiff	n/d	2
CEPEL_EPE	GIS: Novoatlas	*.shp, Raster; *.pdf	2017	2
EMBRAPA	external website	*.shp, *.jpg	2011	2
FORESTGIS	external website	*.gpkg	2017	1
GLOBAL WIND ATLAS	Web	*.GeoTIFF	2018	3
IBAMA	SEI	*.shp	2018	1
IBGE	Web folder (Geoftp)	*.shp	2010	2
IBGE	Statistics	*.xlsx	2016	1
ICMBio	Web folder + private	*.shp, *.kml	2019	3
INDE	GIS: visualizador.INDE	*.shp, *.kml	2018	2
INPE	GIS: Webmapit	*.GeoTIFF	2009	3
IPHAM	GIS: visualizador.INDE	*.shp	2018	2
MININFRA	Web folder	*.shp, *.kmz	2019	2
MARINHA	Web folder	*.GeoTIFF	2019	3
MARINHA/REMPLAC	-	-	-	0
MMA	Web folder	*.shp	2004-2014	1
MMA_ZCM	Web folder	*.shp	2018	1
MINTUR	GIS: Mapa do turismo 2019-2021	website, .*pdf	2019-2021	1
Save Brasil	Website	*.shp + *.pdf	2009	2
GEBCO	GEBCO 2019 Gridded	*GeoTIFF	2020	2
ANTAQ	-	*.shp	2015	1
Open StreetMap	GIS: OpenStreetMap	*.osm	2019	2
IPEA	IpeaGEO	*.xlsx, *.shp	-	1
Base de Dados Georreferenciados PNLT 2010	web folder	-	-	2

Consulted data sources	Platform name	Data format	Registered update	Availability and Quality
PETROBRAS	Scielo	*.pdf	-	0
ONS	GIS: SINDAT	*.shp	2013	0
PETROBRAS	-	-	-	0
PGGM	-	documents	-	0
CGEE	-	-	-	0
ClickGeo	NA	*.shp	-	0

Note: Data readiness and quality – 0: not available or unusable; 1: no spatial data or very raw data; 2: raw spatial data; 3: spatial and usable data with minor pre-processing.
Source: The author.

Updating spatial data must be a cyclical process. This practice improves the input data and the modeling results and reduces the uncertainty of the results. The development of a baseline geodatabase as the foundation of the methodological framework is proposed to ensure a functioning decision support system. The data collected is by no means absolute data. Rather, the baseline data create the minimum requirements for carrying out geomodeling. These efforts need to be improved and supplemented in order to improve the sustainable strategic planning process. Due to the number of criteria and the enormous amount of geospatial data, data collection was limited to the data and sources available until 2022.

4.4.2 Data collection process

The collection of the best quality publicly available data was crucial to ensure the applicability and consistency of the geospatial modeling. A GIS baseline model and a decision support system (DSS) differ in that the models do not contain data; instead, the DSS usually contains input data to ensure the functionality of the system and to efficiently model different assumptions or scenarios (SCHILLINGS *et al.*, 2011, 2012). The consolidation of a baseline geodatabase also leads to time savings, as data collection is the most time- and resource-consuming activity.

Initially, the data was examined using the Google search engine, previous studies and consultation with specialized experts from identified data sources (Table 4-14). Different platforms were examined, with a focus on spatial data in shapefile format (*.shp), raster format (*.tif or *.GeoTIFF) and Google Earth files (*.kmz). Other formats were in text format (*.txt, *.csv), technical publications and official reports in document format (*.pdf).

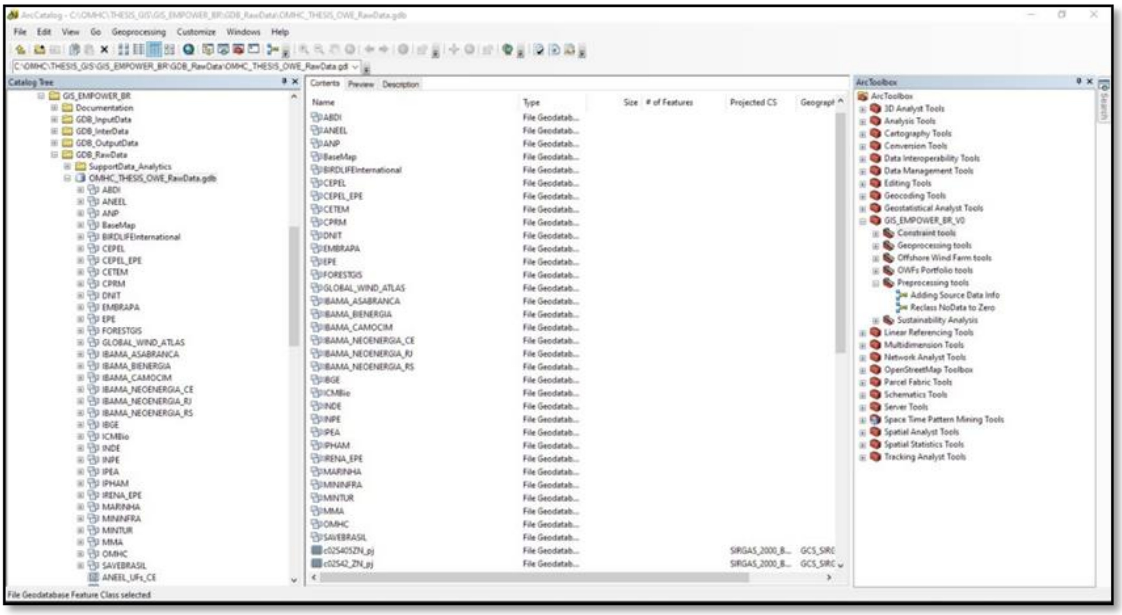
More than 80 raw data layers were collected. Using the ArcGIS 10.6 Suite (ArcMap and ArcCatalog 10.6) and Google Earth Pro, 60 datasets were added to the base geodatabase. These datasets includes more than 45 spatial variables (see Table 4-4) linked to the selected criteria and other complementary spatial information.

4.4.3 Process of data exploration and pre-processing

After data collection, the organization of the data in a structured geodatabase is essential due to the amount of data collected. The geodatabase was then organized by source, theme, geometry, field values and cartographic guidelines (or standards).

The process of data exploration was carried out to identify and interpret attributes (field columns) of interest. This activity required the application of symbolization and mapping techniques to ensure that the spatial variables and features included in the geodatabase were an appropriate representation of the real-world phenomenon in the OWE context. In addition, individual features (rows), duplicates, typos, validations and additions of null data were cleaned.

After the process of data exploration and pre-processing, 60 datasets were consolidated in the geodatabase. Figure 4-16. illustrates the quantity and variety of spatial data related to offshore wind energy, organized by data source.



Name	Type	Size	# of Features	Projected CS	Geograpl
ABDI	File Geodatab...				
ANEEL	File Geodatab...				
ANP	File Geodatab...				
BaseMap	File Geodatab...				
BIRDLIFEInternational	File Geodatab...				
CEPEL	File Geodatab...				
CEPEL_EPE	File Geodatab...				
CETEM	File Geodatab...				
CPRM	File Geodatab...				
DNIT	File Geodatab...				
EMBRAPA	File Geodatab...				
EPE	File Geodatab...				
FORESTGIS	File Geodatab...				
GLOBAL_WIND_ATLAS	File Geodatab...				
IBAMA_ASABRANCA	File Geodatab...				
IBAMA_BIENERGIA	File Geodatab...				
IBAMA_CAMOCIM	File Geodatab...				
IBAMA_NEOENERGIA_CE	File Geodatab...				
IBAMA_NEOENERGIA_RJ	File Geodatab...				
IBAMA_NEOENERGIA_RS	File Geodatab...				
IBGE	File Geodatab...				
ICMBio	File Geodatab...				
INDE	File Geodatab...				
INPE	File Geodatab...				
IPEA	File Geodatab...				
IPHAM	File Geodatab...				
IRENA_EPE	File Geodatab...				
MARINHA	File Geodatab...				
MININFRA	File Geodatab...				
MINTUR	File Geodatab...				
MMA	File Geodatab...				
OMHC	File Geodatab...				
SAVEBRASIL	File Geodatab...				
c025405ZN_pj	File Geodatab...			SIRGAS_2000_B...	GCS_SIRC
c02542_ZN_pj	File Geodatab...			SIRGAS_2000_B...	GCS_SIRC

Figure 4-16. Baseline geodatabase for OWE planning, structured by data sources.
Source: The Author based on HERNANDEZ C. *et al.*, (2022).

Several features have been spatialized into vector polygons and surfaces in raster format, as their original format (*e.g.*, tabular data or geometry: points or lines) may not match the specialized tools. This process is time consuming as spatialization must attempt to represent the spatial variation of the phenomenon, taking into account intrinsic features (*e.g.*, spatial interpolation) or spatial relationships representing interactions with other features (*e.g.*, distance raster). Spatial interpolation uses geostatistical methods (*e.g.*, kriging, spline natural neighbor) to estimate values for which no data of the same feature is available. These techniques require representative samples of data. Alternative spatial relationships can use continuous distances (*e.g.*, Euclidean methods) to represent the presence and possible interaction between features.

For the initial strategic analysis, the spatial data were mapped according to key factors. According to the MSP manuals (EHLER & DOUVERE, 2013; UNESCO-IOC, EUROPEAN COMMISSION, 2021), the strategic data should be divided into four groups of key factors, as follows:

a) Basic spatial data of the study area
b) International and political boundaries
c) Marine and coastal biological resources (biomes, ecosystems, habitat areas)
d) Human activities in the sea and on the coast

To illustrate the key drivers mapping, an example of the spatial data collected for the study area in the state of Ceará is presented in the following subsection.

4.4.4 Mapping of marine and coastal key spatial factors

The mapping of key drivers focuses on consolidating, complementing and symbolizing the integrated spatial data into a meaningful mapping of the study area. The mapping of key drivers integrates information on: the localization of the study area, international and national boundaries and constraints, ecosystems and biological resources, and human activities. All these factors were mapped in the coastal and marine zone of the state of Ceará (see Figure 4-17).

The marine spatial planning area is composed of marine (offshore) and terrestrial (onshore) regions. The identification of the marine zone is of strategic importance to allocate the available areas for the OWFs and their relative occupancy of the total marine spatial planning area. Instead, the terrestrial region (onshore) of the coastal zone is important due to the socio-ecological complexity and the available data focuses on this zone (onshore and offshore areas with the coastline as the interaction axis). The coastal zone of the current case study was defined between 60 km from the hinterland to the coast and 1,000 m.a.s.l. (about 50 km from the coast).

Finally, mapping of key factors was required to define the coastal environment units (CEUs). These units share natural resources and human dynamics and represent the strategic planning units of the coastal zone. Common characteristics form the basis for the assessment and formulation of strategies with an ecosystem-based approach (UNESCO-IOC & EUROPEAN COMMISSION, 2021).

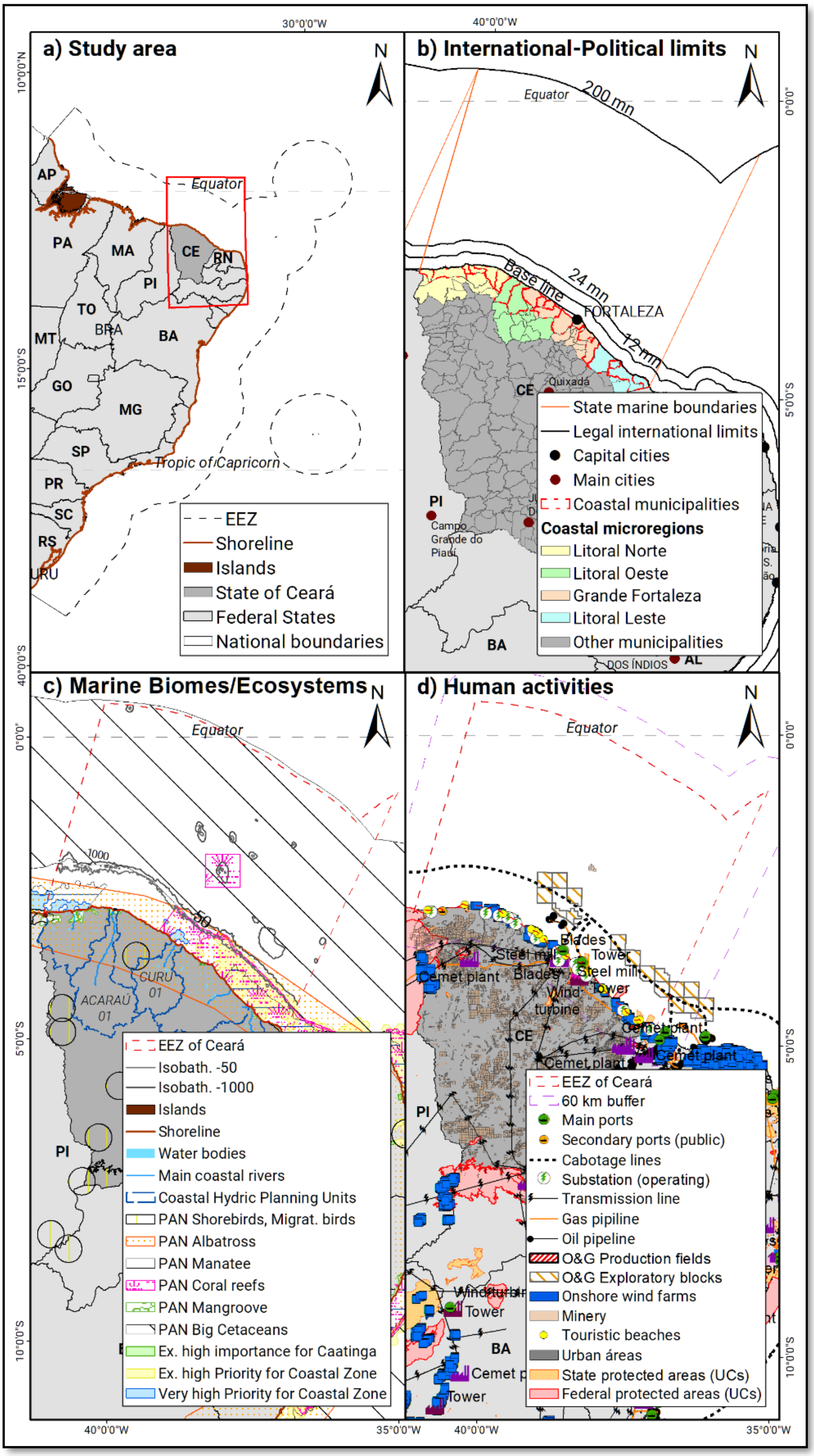


Figure 4-17. Summarized collected data sorted by MSP key-drivers. Source: HERNANDEZ *et al.*, (2022).

Key-drivers mapping generated the spatial indicators (spatial data layers) that are directly related to the strategic planning of offshore wind energy.

4.4.4.1 Basic data of the study area

This map contains the basic elements for the study area. It shows the localization and general boundaries of the study area. The basic elements for this map are the international boundaries of the exclusive economic zone (EEZ) of the study area, administrative boundaries, neighboring countries or states. Natural accidents or reference locations can complement the mapping of the location of the study area. Figure 4-18 shows the base map of the study area. The maritime boundaries between states are essential as these boundaries delimit the overall area of the analysis. The relative analysis depends on the definition of the total area of marine space.

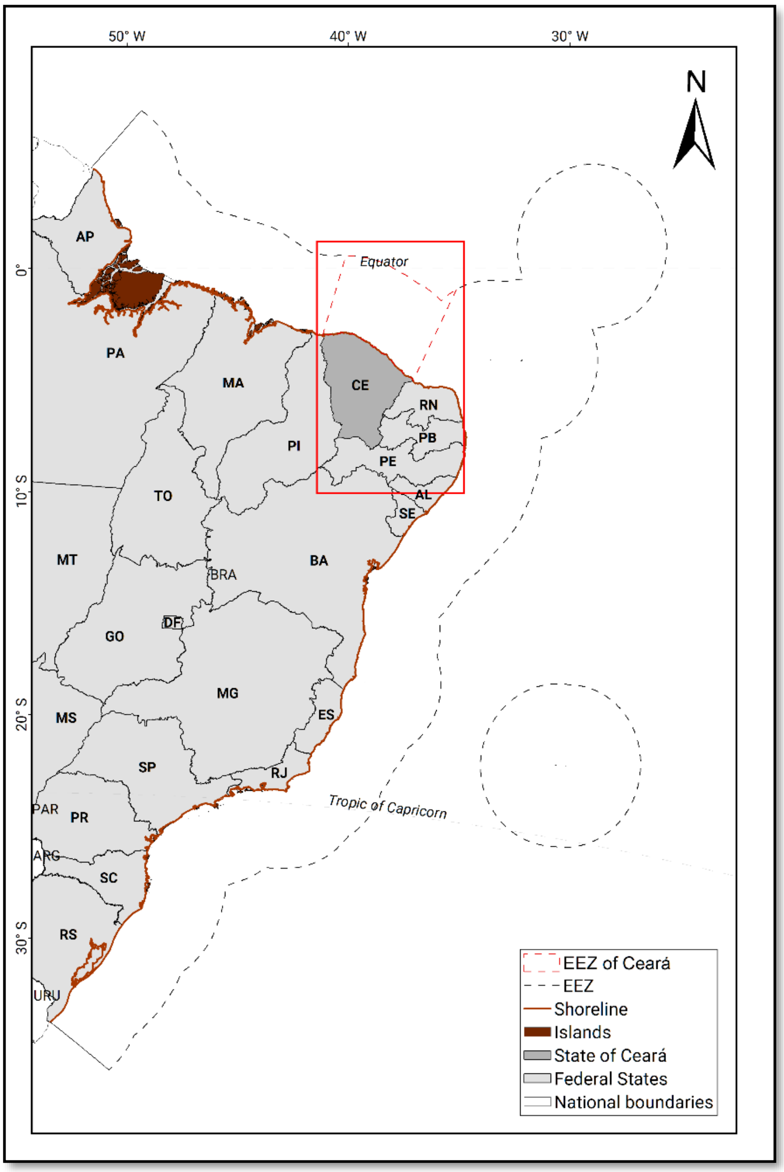


Figure 4-18. Localization of the study area.
Source: The Author base on public data sources (see Table 4-14).

The current methodology is based on the marine boundaries established by the IBGE for the allocation of royalties for offshore O&G production (BITAR, PAULON, 2011).

4.4.4.2 National and international political and administrative boundaries

Political and administrative boundaries are important because of their close connection to the marine spatial planning process (Figure 4-19). International and national boundaries define the spatial boundaries for the strategic planning process. This key factor includes different marine boundaries (MARINHA DO BRASIL, 2020): the territorial sea boundary (12 nm or ~24 km), the boundary of the contiguous zone (24 nm or ~44 km), the Exclusive Economic Zone (EEZ, 200 nm or ~370 km) and the coastal baseline – the baseline is essential for defining marine boundaries based on the orthogonal method.

For the current case study, the marine boundaries between the states of Ceará and Piauí (west) and Ceará and Rio Grande do Norte (east) were defined based on the orthogonal boundaries for offshore O&G royalties (BITAR, PAULON, 2011). Using these boundaries, we were able to estimate the total marine area (EEZ) of the state of Ceará at 215,977.5 km^2.

In addition, in the case study of Ceará, the Minister of Planning defined four planning macro-regions that represent areas (onshore) with similar characteristics for the territorial planning of the coastal zone.

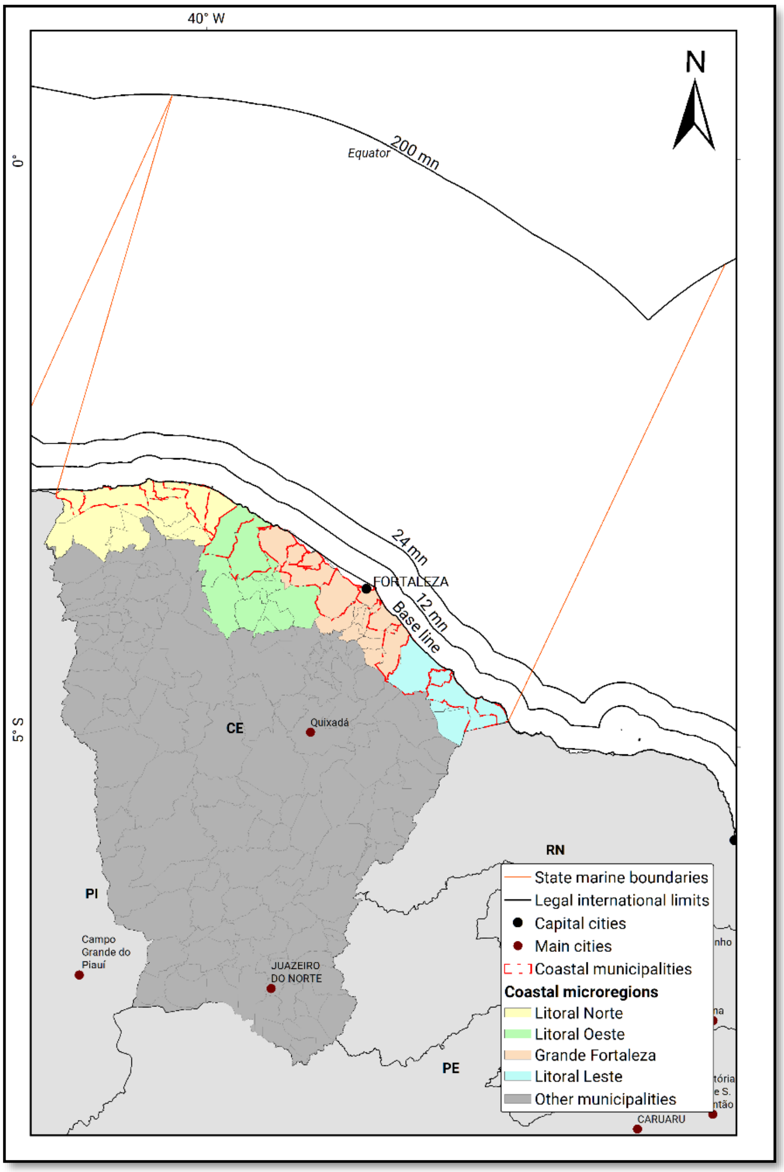


Figure 4-19. Coastal and marine limits and boundaries mapping of the study area. Source: The Author base on public data sources (see Table 4-14).

This information is important because in some cases offshore wind projects or associated structures may be located in the jurisdiction of two states or countries, and decision makers need to be aware of potential administrative issues with permits or license fees.

4.4.4.3 Ecosystems and biological resources

Ecosystem and biological resource mapping captures all available spatial data related to the natural environment, particularly in relation to strategic coastal and marine ecosystems or biological resources, depending on the extent of available data. This key driver map should focus on mapping the natural resources that could be affected by the exploitation of offshore wind energy, as identified by HERNANDEZ *et al.*, (2021).

Figure 4-20 shows the ecosystem and biological resources in relation to: Waters, main coastal rivers, mangroves, coastal hydric planning units, birds, coral reefs, manatees, large cetaceans and priority protected areas (caatinga and coastal and marine biomes).

These data were the best publicly available for the Northeast region of Brazil due to the lack of primary data collected in situ or presence/absence databases of higher quality. In the South and Southeast region, a few studies estimated the distribution of threatened seabirds, marine mammals and one turtle species using the Ecological Niche Modeling and Richness Index (LEMOS, HERNÁNDEZ, *et al.*, 2023). However, gaps in primary data and robust databases collecting primary telemetry or campaign data need to be established.

In addition, geomorphological data such as the spatial distribution of bathymetry, seabed slope, seabed composition or stratigraphic data also need to be mapped.

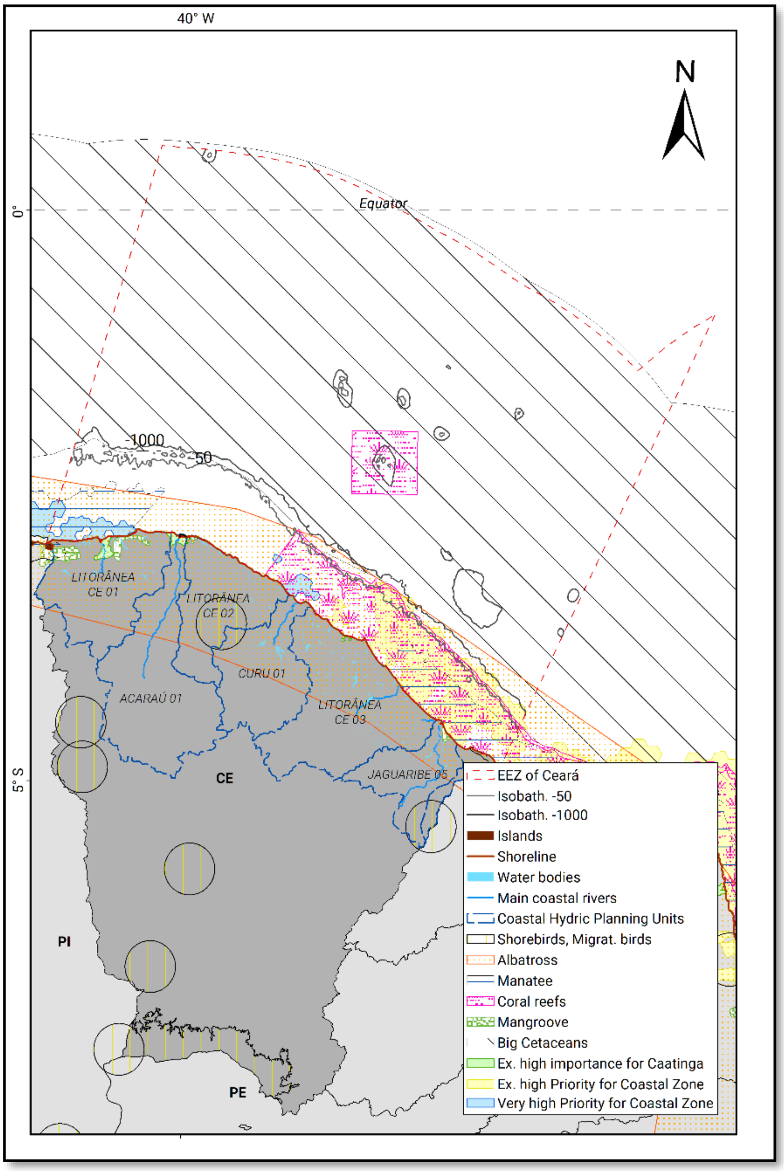


Figure 4-20. Ecosystems and biological resources of the study area.
Source: The Author base on public data sources (see Table 4-4).

4.4.4.4 Human activities

Human activities include all anthropological activities associated with potential competition for space or resources with offshore wind activities (see Figure 4-21). Most data are publicly available; a few are only available in low quality or at coarse scale. At a minimum, this map needs to include human activities in the coastal zone (onshore and offshore). The most important features in this mapping area are port and grid connection infrastructure, categorised by their ability to support offshore wind deployment (*e.g.*, marshalling and O&M ports). Other important human activities that need to be mapped are environmental protection areas, urban areas, military areas, mineral extraction, O&G (onshore and offshore), industrial fishing, maritime and cabotage traffic, linear infrastructure, tourist beaches, etc.

Detailed data on the expansion of telecommunication cables, for example, is only available for a fee. The data on telecommunication cables vary depending on the scale of the official maps. The area covered by the cables was mapped using the official base map, which takes into account the regional scale of the north coast: Fortaleza and Natal (Plate 21030 - MARINHA DO BRASIL, 2020). In the current case study, spatial data with a coarse scale were marked as warning areas.

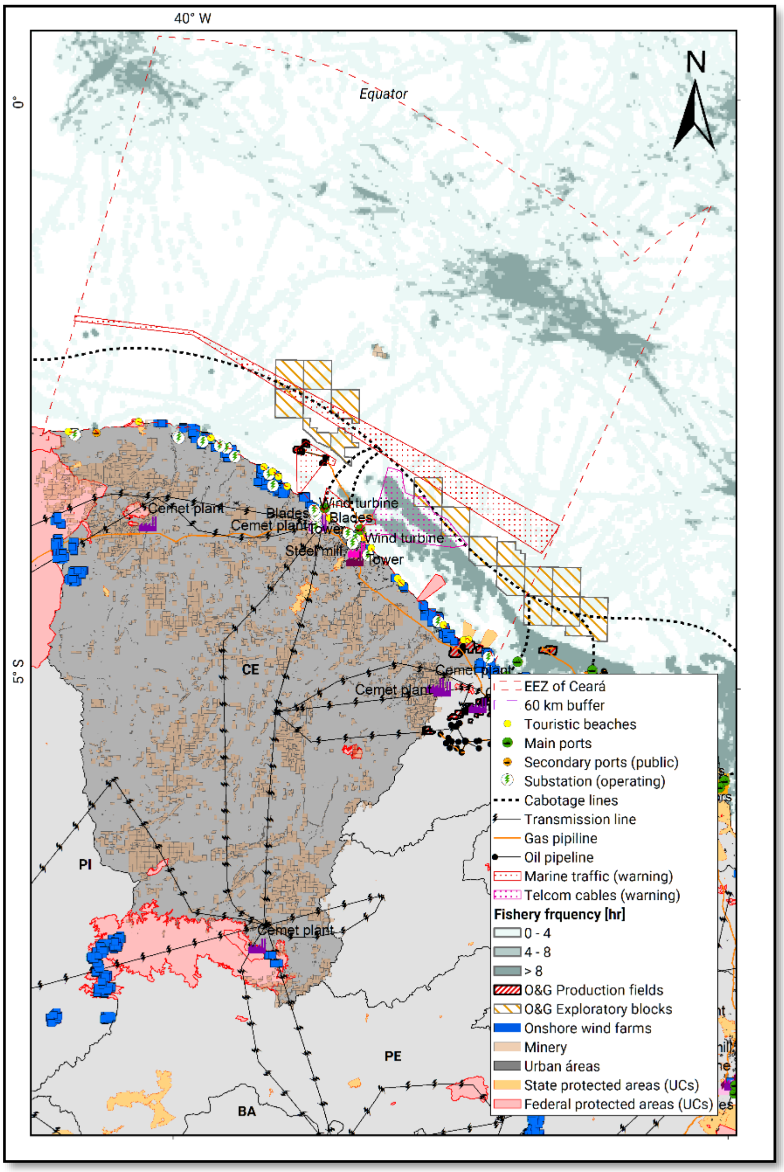


Figure 4-21. Human activities with potential competition for space or resources for the study area. Source: The Author base on public data sources (see Table 4-4).

4.5 Strategic planning of offshore wind energy in the state of Ceará

This section presents the practical application of the methodological framework for the sustainable development of offshore wind energy in the state of Ceará. The current case study focuses on the strategic planning phase, Stages 1, 2 and 3 of the methodology, and indicates how the output data must be linked to the micro-siting phase, Stages 4 to 6 (optimization of energy production and grid connection corridors).

4.5.1 Strategic scenarios for the development of offshore wind energy in Ceará

As a practical implementation of the methodological framework, five strategic scenarios were created for the case study of the strategic planning of offshore wind energy in the state of

Ceará. These strategic scenarios aimed to represent different visions of a current innovation market (first stage market) with a clear extreme orientation; in addition, the baseline scenario 2023 takes into account the current regulatory framework and developer trends. Table 4-15 consolidates the visions of the proposed strategic scenarios. Table 4-17 present parametrization of Scenario A1 and Scenario B1; Appendix G contains the parameterization values for all scenarios.

Table 4-15. Conceptual description of proposed scenarios[10].

Scenario	Vision
Base Scenario 2023 (Scenario A1)	Describes the current situation of planning and regulatory framework. There is no integrated instrument or tool to address the strategic planning of offshore wind energy development. Assumes minimal restrictions, minimal analysis of conflicts of use in the sea and no minimum distance from the coast as a strategy to avoid future environmental problems or social opposition. It does not take into account any restrictions on total installed capacity or distancing between projects. The technology is based on current projects (by 2023).
Economic maximization (Scenario A2)	Describes the situation where higher profitability is the main goal and shows a clear bias towards developers. It follows the minimum mandatory environmental and social restrictions and strive for more cost-effective conditions and higher energy production and profitability. The technology is geared towards mega-commercial projects and maximum installed capacity.
Sustainable Optimization (Scenario B1)	Describes the situation with a balance between factors, integrating the concept of trade-off in the environmental, social and economic dimensions to ensure the sustainability of the industry's development. Based on sustainable development, this scenario aims to reduce environmental and social impacts while increasing economic growth. The technology focuses on a large-scale technology with high performance.
Smart investor (Scenario B2)	Describes the conditions for higher profitability and follows the environmental constraints. This scenario aims at the goal of higher profitability, including environmental constraints, mandatory and non-mandatory, and follows the guidelines based on the scientific findings of the environmental planning of OWE. Technology is based on mega-commercial farms and high-rated power.
Socio-environmental precaution (Scenario C)	Describes a scenario with higher environmental protection and looks for the lowest environmental risk for the development of the offshore wind industry. Includes all possible areas that intend to protect or conserve natural environmental resources, such as biodiversity areas, strategic ecosystems and endangered species. Economic growth is of minimal importance. Technology focuses on pre-commercial farms with proven technology or pilot projects.

Source: the Author.

To illustrate the difference between the biases, these scenarios were assigned to a level that compares economic growth with social environmental protection; this level represents the trade-off between economic growth and social environmental protection, because the higher the social environmental protection, the lower the economic growth. The sustainable optimization

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[10] These scenarios were proposed on the basis of an educated guess based on a literature review and industry practices, and validated as research practice based on private technical discussions with the experts consulted. Scenarios for real-world planning should be discussed, reviewed and validated by multidisciplinary boards, including the active involvement of local communities in strategic planning, using participatory surveys (unlike the public consultation in the EIA).

scenario strives to optimize both axes and is the ideal scenario for the development of offshore wind energy. Figure 4-22 illustrates the conceptual distribution of the strategic planning scenarios.

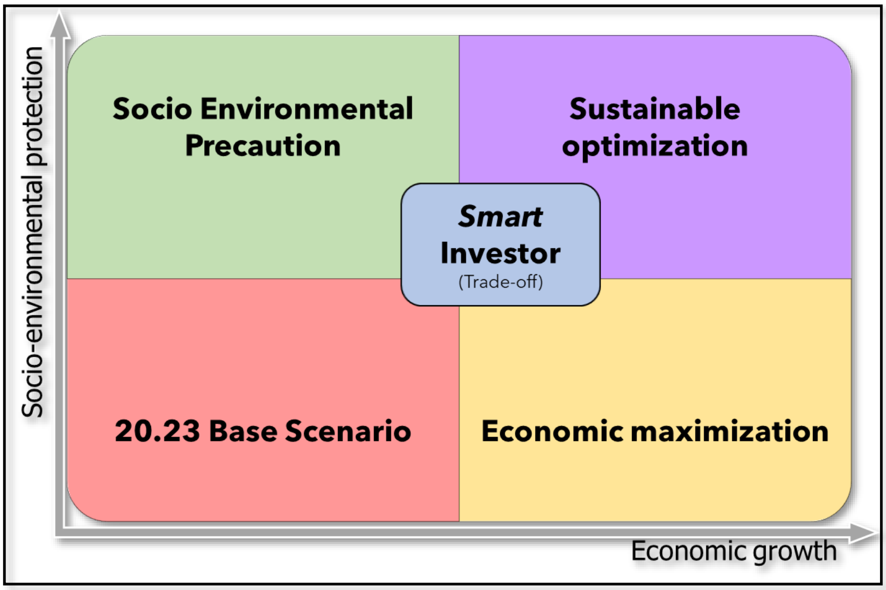


Figure 4-22. Conceptual distribution of strategic scenarios.
Source: The Author.

The scenarios were then compared with the federal and regional strategic planning in the areas of energy and infrastructure development.

The National Energy Plan 2050 (MME, 2020) only considers 16 GW by 2050 assuming decreasing costs on Capex (20%) by the same period. Decennial Transmission System Expansion Plan 2032 (MME/EPE, 2023) reported a cumulative installed capacity of 19 GW in operational solar PV and onshore wind this plan projected 6 GW granted in auctions and 9 GW of signed access in the free/distributed market. The IV Federal Action Plan for the Coastal Zone (MINISTÉRIO DO MEIO AMBIENTE, 2017) has not prioritized actions or programs focused on offshore wind power. The report on employment and job creation in the wind industry (ARAUJO, SAAVEDRA, *et al.*, 2023) already considers the incorporation of the OWE industry into the labor market, which is projected in three market development stages: Invention, Adaptation, Stabilization.

At regional level, only four initial OWF projects were considered as part of the ecological-Economic Zoning for Coastal Zone of Ceará (ESTADO DO CEARÁ, 2022) (by 2023, 27 project proposals were submitted to the Brazilian Institute of Environment and Renewable Natural Resources – IBAMA). The Master Plan for the Port Complex of Fortaleza and Pecém (MINISTÉRIO DA INFRAESTRUTURA & UFSC, 2020) was intended to define strategies and measures for the development of the two ports, including measures for the use of offshore wind energy. However, this document was not yet available at the time of the consultation. Finally, the Plan for the Development and Zoning of the Port of Fortaleza (COMPANHIA DOCAS DO

CEARÁ, 2022) does not define specific strategies or measures for onshore or offshore wind energy. Instead, this plan describes several measures to expand the storage of general cargo, with an estimated energy supply capacity of 10.8 MVA from 2021 to 2031, with a projected energy demand of 5.86 MWA by 2031.

In summary, the strategic planning framework has not defined explicit targets (installed capacity, timeframe or region) for the deployment of offshore wind energy. Therefore, an analysis of generic measures is proposed to guide the distribution of installation targets across different timeframes. Table 4-16 outlines the proposed measures and time horizons for the development and deployment of offshore wind projects that are consistent with both the federal and sector-specific strategic plans.

Table 4-16. General actions to guide strategic planning in different timeframe horizons.

Timeframe	Very short-term	short-term	mid-term	long-term
Deadline	2026	2030	2040	2050
Total time for deployment (years)	2	6	16	26
Market	Technology adoption	Market adaptation	Market stabilization	Market massification
Strategy/Action scope	Development of minimal conditions for deployment of OWE industry.	Strengthening the supply chain and logistics infrastructure (focused on ports and transmission system).	Scaling up national supply chain (manufacture, workforce, and job market).	Consolidating the offshore wind energy market.
Examples	*E.g.,* consolidation of a sound regulatory framework (including auctions and permitting), data collection and sampling of local offshore wind, biological and ecosystem resources, workforce training, implementation of supporting information systems for development, integration of the local community into the strategic planning process; formulation and investment in R&D projects for pilot development.	*E.g.,* testing pilots or small-commercial projects; consolidating projects pipeline and auctioning schedules, based on industry growth trends.	*E.g.,* deployment and installation of first large commercial projects.	*E.g.,* achieving the planned installation capacity; updating the targets and objectives for installed capacity and energy generation for the following planning horizons.

Note: base year 2024.

Source: The Author based on ARAUJO *et al.,* (2023); BERGERSON *et al.,* (2019); DEDECCA *et al.,* (2016); WILMSMEIER *et al.,* (2022).

On the other hand, the historical growth of onshore wind energy in Brazil was used as a past trend and international projections for OWE growth (*e.g.,* the projections of GWEC) as future growth references based on the planning year 2023. The parameterization of the scenarios was based on the literature review and the referenced restriction and conflict thresholds.

The validation of the proposed scenarios and assumptions was supported by CEPEL's Energy Transition and Sustainability (DTS) team, which includes wind energy and sustainability of energy generation research groups (see Table 4-2). The validation process consisted of seminars in which the scenarios, criteria and parameters were presented in the context of the experts' background knowledge. The responses were then discussed, and the proposed changes were incorporated into the assumptions.

Table 4-17 summarizes the parameterization – assumptions about spatial variables and parameters – for Scenario A1 and Scenario B1 according to the scenario's vision (see Table 4-15); Appendix G contains the parameter assumptions of the five scenarios.

Table 4-17. Example of the parameterization of strategic scenarios for the development of offshore wind energy.

Element	Scenario A1	Scenario A2	Scenario B1	Scenario B2	C
Concept	Minimum constraints (current situation)	Higher profitability	Sustainability balance (environmental, social, economic)	Higher profitability under environmental constraints	Minimum environmental risk
Title	Base Scenario 20.23	Economic maximization	Sustainable Optimization	Smart investor	Socio-environmental precaution
Objective	Assess current trends and regulatory framework	Higher profitability	Achieving Sustainable Development	Economic and Environment tradeoff	Higher environmental and social protection
Decision-maker	Private/Public	Private	Public-Private	Private	Public environmental agency
Risk profile	High	High	Neutral	Neutral	Low
Timeframe	very short-term: 2028	Short-term: 2030	Target by 2050	Short term: 2035	very short-term: 2030
Geographical localization	Ceará, NE	Ceará, NE	Ceará, NE	Ceará, NE	Ceará, NE
Strategic restrictions:					
Bathymetry	> 1000 m.u.s.l.	> 30 m.u.s.l.	> 200 m.u.s.l.	> 50 m.u.s.l.	> 50 m.u.s.l.
Average wind speed	< 7 m/s	< 8 m/s	< 7 m/s	< 8 m/s	< 8 m/s
Capacity Factor	No constraint	< 36% (> coastal value)	< 30 %	< 40% (on Ceará's coast)	< 50%
Environmental vulnerability	UCs (All: State)	UCs (All: Federal)	UCs + UCs + Ex. High APCB/VHRI	UCs + Ex. High APCB	UCs + APCB + VHRI
Min. distance to shore	No constraint	3 km and < 5 m.u.s.l.	< 10 km	< 20H	22 km
Archeological sites	No constraint	< 3km	< 3 km	< 3 km	< 6 km
Touristic beaches buffer	No constraint	< 3 km	< 14 km	< 8 km	< 24 km
Max. Distance to shore	> 500 km	> 70 km	> 150 km	> 100 km	N/C
Max. Distance to	>500 km	> 50 km	> 300 km	> 200 km	N/C
	> 150 km	> 50 km	> 100 km	> 80 km	N/C

Element	Scenario A1	Scenario A2	Scenario B1	Scenario B2	C
ports					
Max. Distance to grid connection (SS)					
Strategic sea use conflicts Protected areas Military areas Oil and Gas Infrastructure Mineral extraction Fishery Industrial Maritime traffic Tourism Offshore RE	Fed. & Ste. UCs (IP) All areas Block and production fields Buffer 500m from pipelines N/C N/C N/C N/C Planned OWFs	All UCs All areas Blocks and fields Buffer 500m from pipelines All "fases" N/C 500 m Cabotage Buffer 10 km (TB) N/C	All UCs All areas Block and production fields Buffer 500m pls + cables Operative (Lavra) > 8h Operaion density 500 m Cb + Sh (WA) Buffer 14 km (TB) >750 km^2	All UCs + APCB-Eh. All areas Block and production fields Buffer 500m pls + cables All "fases" (Regimes) > 8h Operaion density 500 m Cb + Sh (WA) Buffer 14 km (TB) > 1.000 km^2	All UCs, APCB, BioRes All areas Block and production fields Buffer 500m pls + cables All "fases" > 4h Operaion density 500 m Cb + Sh (WA) "Buffer 25 km (TB) >250 km^2
Offshore wind farm optimization assumptions	15 MW, 5*RD	21 MW, 5*RD	10-12 MW, 8*RD	15 MW, 7*RD	8 MW, 10*RD
Transmission and connection optimization assumptions	no optimization	Closest distance to Substation	Optimized to connection	Optimized distance to Substation	Optimized-High availability
Port infrastructure and logistics	Closest port	Closest port	Installation-O&M	Closest port	High System Readiness level
Potential solution alternatives	Total available area	Least cost-highest generation	High generation-Low cost-Low environmental risk	Optimal cost	Minimum area

Note: Scenario A1 (baseline scenario 2023) vs. B1 (environmental optimization scenario) for the development of offshore wind energy in Ceará. IP: Integral protection; ExH: Extremely high; APCB: Priority areas for biodiversity conservation; VH: Very high: RI: Richness index; pls: ; Cb: ; Sh: Shipping; WA: Warning areas: TB: Tourist beaches. A complete list of scenarios and parameterization can be found in Appendix G.
Source: The author based on an extensive literature review (see Appendix G).

These values were the input parameters for carrying out geospatial modeling and simulations using the GIS-SPOWER-BR toolbox. In the following, the development of the case study is presented by comparing scenario A1 (Base scenario 2023) and scenario B1 (sustainability optimization). Detailed assumptions and maps for each scenario are included in the appendices.

4.5.2 Potential offshore wind areas in the State of Ceará

4.5.2.1 Coastal Environmental Units of Ceará

In defining coastal environment units for strategic planning, the distribution of key factors was considered, local clusters (led by port infrastructure) driven by the ecosystem-based approach. Figure 4-23 illustrates this process, considering the following assumptions:

a) **Marine spatial planning area:** considering the EEZ boundary and the four coastal micro-regions that make up the marine spatial planning area (light green), a bathymetry of 1000 m.u.s.l. was considered as a technical constraint for the current state of the art of offshore wind turbines (fixed bottom and floating). Then the preliminary shapes of the coastal planning units were drawn (yellow lines).
b) **Coastal environment units:** Trends in spatial distribution were identified and grouped into three areas: Northwest, Central and East units. Ecosystem-based analysis of mapped biological resources (quality available in the region) was taken into account when grouping these areas.
c) **Study clusters:** clustering of human activities was led by harbors and offshore O&G distribution (red circles), while additional coastal study clusters were defined based on environmental protection areas (dark green lines).
d) **Coastal and marine spatial planning areas:** overlapping Ecosystem-based areas and industrial clustering confirmed spatial trends in the proposed Coastal Environmental Units (CEUs): Northwest with low industrial development, recognized tourism activities near the municipality of Jijoca de Jericoacoara and traditional fishing; Center with high industrialization in Porto do Pecém and urbanization in the city of Fortaleza; East with high coral reef resources and associated industrialized fishing. The marine spatial planning area (light green) and the marine study cluster were defined as areas of interest for the future expansion of offshore wind energy towards the deep-water horizon.

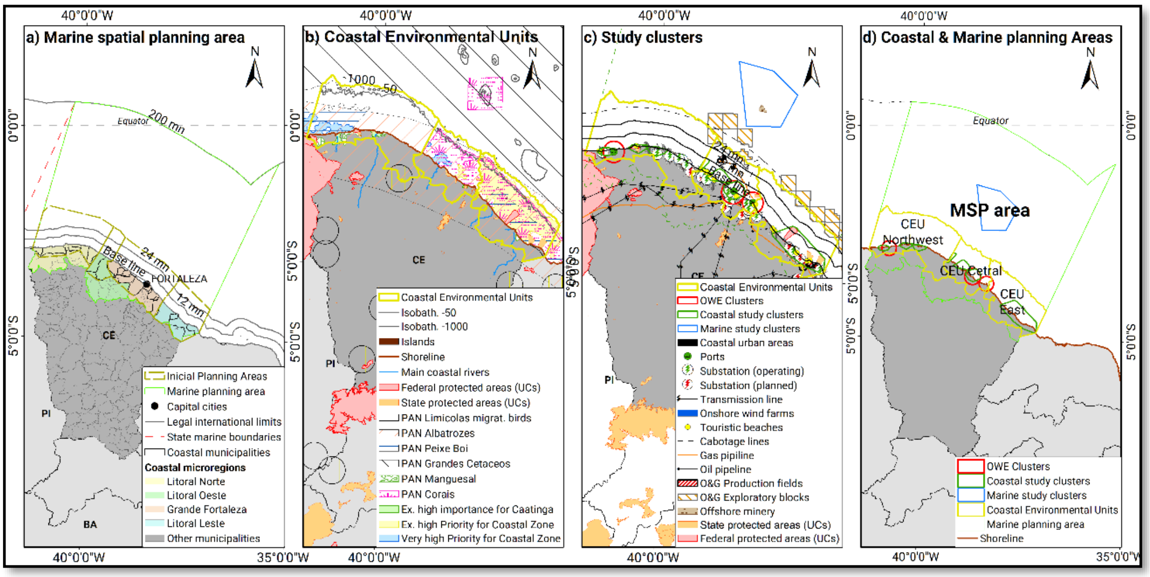
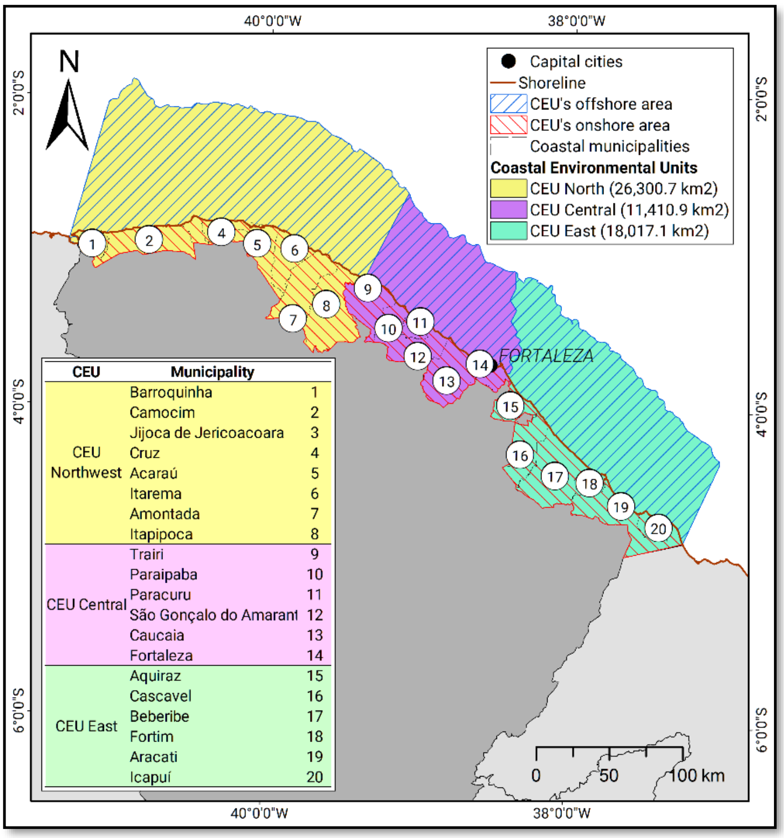


Figure 4-23. Definition of marine and coastal planning areas.
Source: The Author.

Figure 4-244 details the Coastal Environmental Units (CEU) for strategic planning of the offshore wind energy industry in the coastal zone of Ceará: CEU Northwest, CEU Central, CEU East. As mentioned before, CEUs are not absolute boundaries, but local trends and distribution of the spatial data suggested concentration or absence of infrastructure and natural resources.



CEU	Municipality	
CEU Northwest	Barroquinha	1
	Camocim	2
	Jijoca de Jericoacoara	3
	Cruz	4
	Acaraú	5
	Itarema	6
	Amontada	7
	Itapipoca	8
CEU Central	Trairi	9
	Paraipaba	10
	Paracuru	11
	São Gonçalo do Amarant	12
	Caucaia	13
	Fortaleza	14
CEU East	Aquiraz	15
	Cascavel	16
	Beberibe	17
	Fortim	18
	Aracati	19
	Icapuí	20

Figure 4-24. Proposed Coastal Environmental Units for strategic planning in the State of Ceará.
Source: The Author.

Table 4-18 summarizes areas shares by coastal environmental unit in the State of Ceará.

Table 4-18. Summary of Coastal Environmental Units.

Planning area		Area [km^2]	[%]	
CEU Northwest	Onshore	6,526.5	24.8%	Subtotal
	Offshore	19,752.0	75.1%	26,300.7
CEU Central	Onshore	4,043.5	35.4%	Subtotal
	Offshore	7,367.4	64.6%	11,410.9
CEU East	Onshore	5,057.2	28.1%	Subtotal
	offshore	12,960.0	71.9%	18,017.1
CEUs	Subtotal onshore	15,627.1	28.1%	
	Subtotal offshore	40,079.3	71.9%	
	Total	55,706.5	100.0%	

Source: The Author.

The cumulative offshore area (40,079.3 km^2) corresponds to 18.6% of the EEZ of the state of Ceará. This result shows how, with an ecosystem-based approach and a structured framework that considers the OWE scale, the analysis of the coastal zone reduces the study area; this is necessary due to the overall extent of the EEZ and the gaps identified in the spatial data. These are common features in mapping the marine space of emerging and developing countries.

Furthermore, the definition of CEUs supports the prioritization of measures and OWF projects along timeframes in terms of system readiness – industrial development status versus socio-ecological presence. Subsequently, a proposed prioritization for the current case study is presented as follows:

CEU Central is prioritized due to the industrial and infrastructure cluster associated with the Capital city (Fortaleza). The presence of offshore industries such as O&G, and maritime transport due to the existence of Porto de Fortaleza and Porto do Pecém (green point between municipalities of Caucaia and São Gonzalo do Amarante), and important onshore wind industry suppliers (blades manufactures in Caucaia and wind turbine manufactures in Eusébio municipalities). However, this CEU also has coral reefs resources (magenta polygon) and significant biological resources related to extremely high (light green polygons) and very high (light blued polygons) importance areas for conservation (see Figure 4-25).

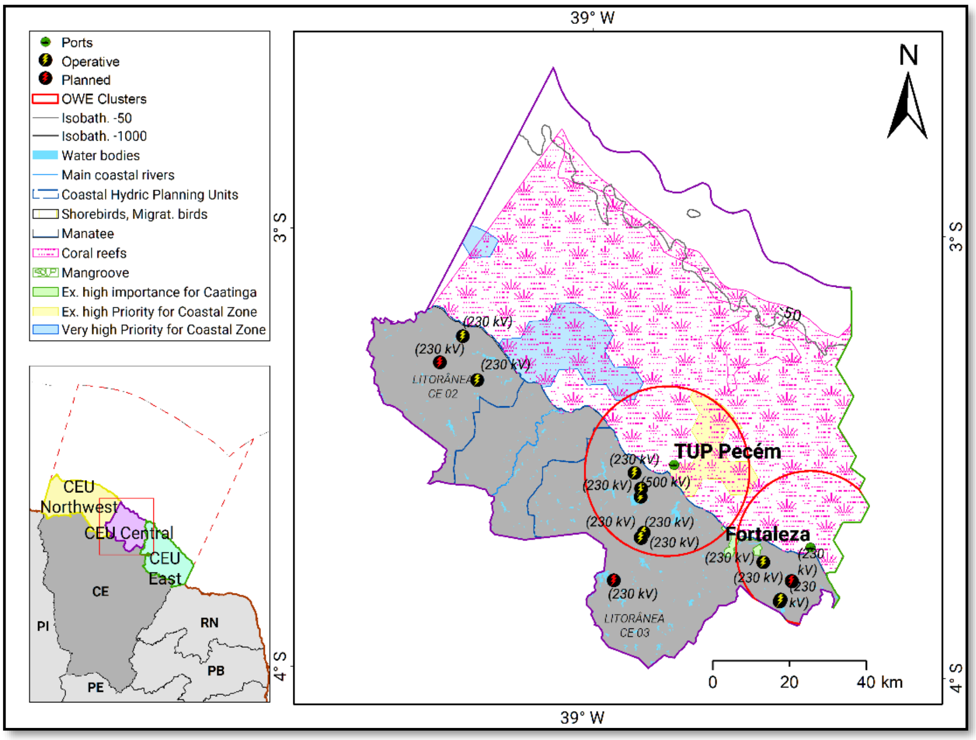


Figure 4-25. Detailed map of CEU Central.
Source: The Author.

CEU Northwest is characterized by a low level of infrastructural development in connection with the inland port of Camocim. Additionally, tourism, protected areas (Jericoacoara National Park, APA do Delta Parnaíba and APA da Serra do Parnaíba), extremely high (light green polygon) and very high coastal areas (light blue polygon) for protection from the municipality of Camocim (see Figure 4-26).

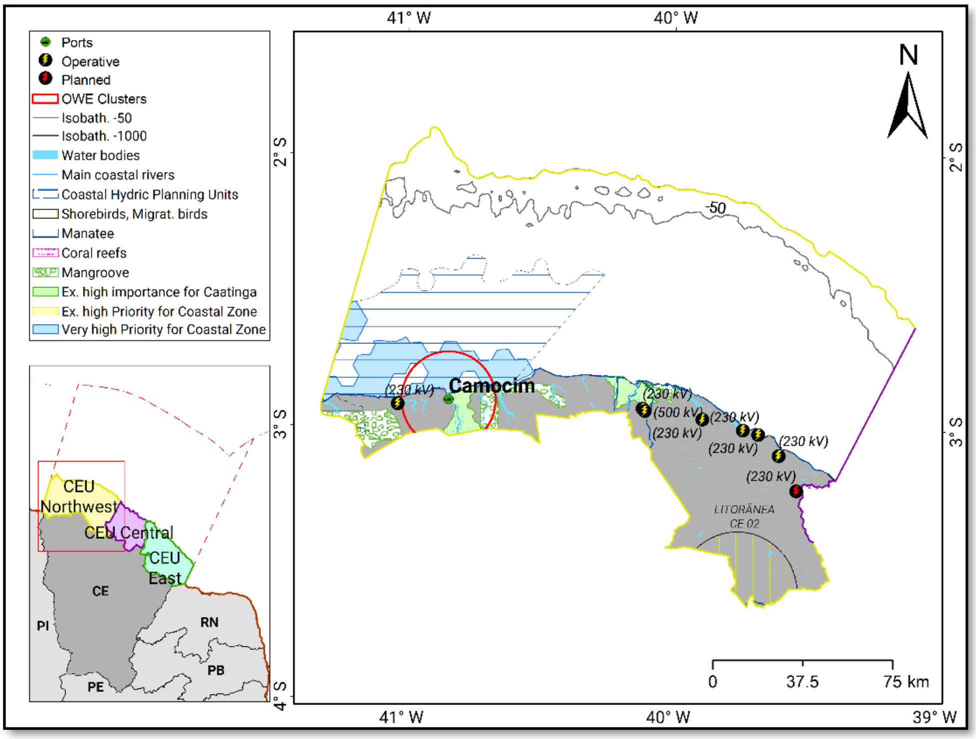


Figure 4-26. Detailed map of CEU Northwest.
Source: The Author.

CEU East is characterized by the presence of biological resources related to coral reefs (magenta polygon), extremely high priority (yellow polygon) areas for conservation (probably related to fish resources), which extend over most of the CEU area, from the municipalities of Fortaleza to Icapuí, from the coastline to a water depth of more than -50 m; this is confirmed by the strong development of industrial fishing in this area. In addition, there are protected areas in the coastal zone of the municipalities of Icapuí and Beberibe (federal in light red and state in light orange UCs) (Figure 4-27).

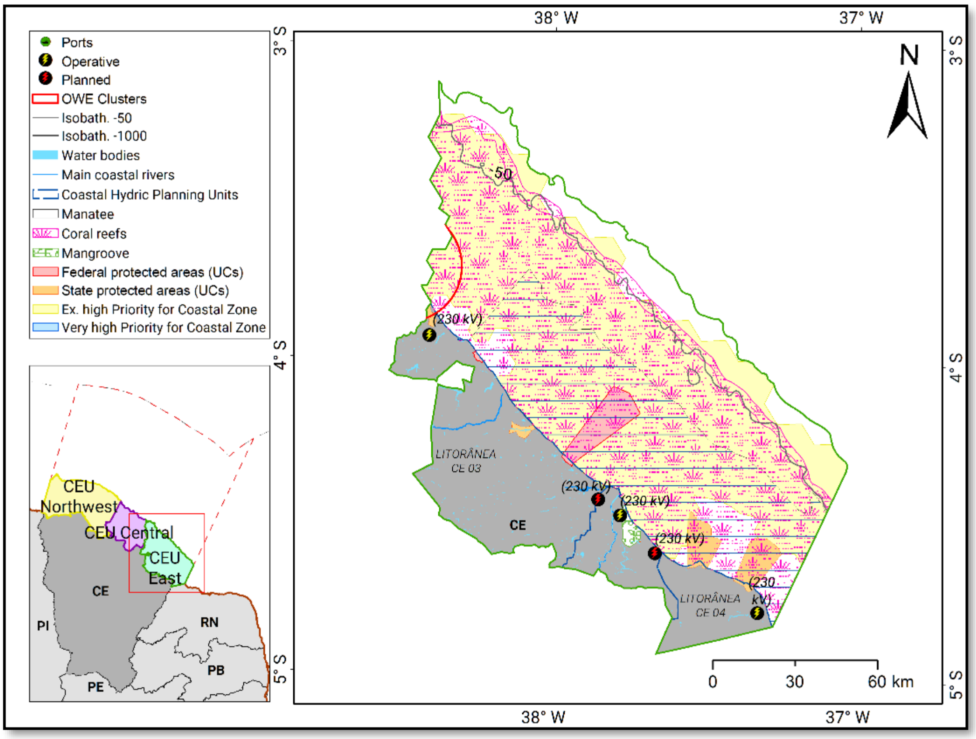


Figure 4-27. Detailed map of CEU East.
Source: The Author.

The prioritization of CEUs as a guideline for the allocation of strategic measures does not restrict the simultaneous implementation of different measures. At the same time, it is possible to define different strategies for sustainable development, a specific pace and timeframe to achieve the specific installed capacity targets for each CEU.

Figure 4-28 shows the base map for the Ceará EEZ with the boundaries of the proposed Coastal Environmental Units, containing strategic features related to offshore wind development. The base map includes: Bathymetry, marine territorial boundaries, ports, onshore substations (operating and planned and grid connection), gas pipelines, cabotage transportation corridors, urban areas and archeological sites. This map confirms the concentration of strategic features in the coastal zone, confirming the need to reduce the scale of the analysis through a robust process.

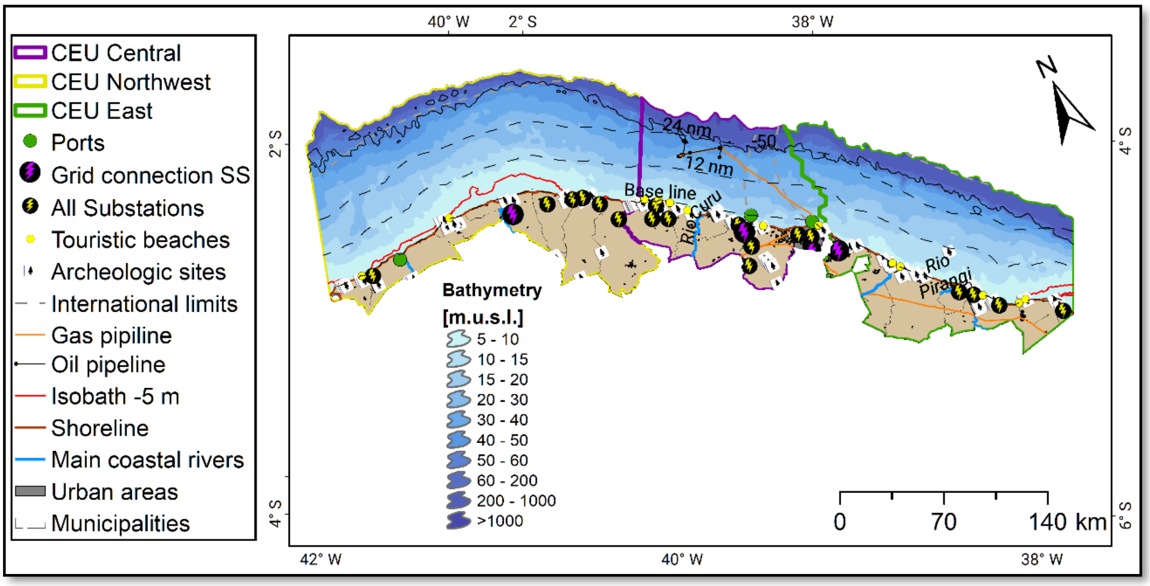


Figure 4-28. Base map of the coastal zone of Ceará for strategic planning of the Offshore Wind Energy.
Source: The Author.

Figure 4-29, Figure 4-30, and Figure 4-31 show detailed base maps for CEU Central, Northwest and East respectively. These base maps are used for detailed analysis due to the scale of the maps and the image resolution.

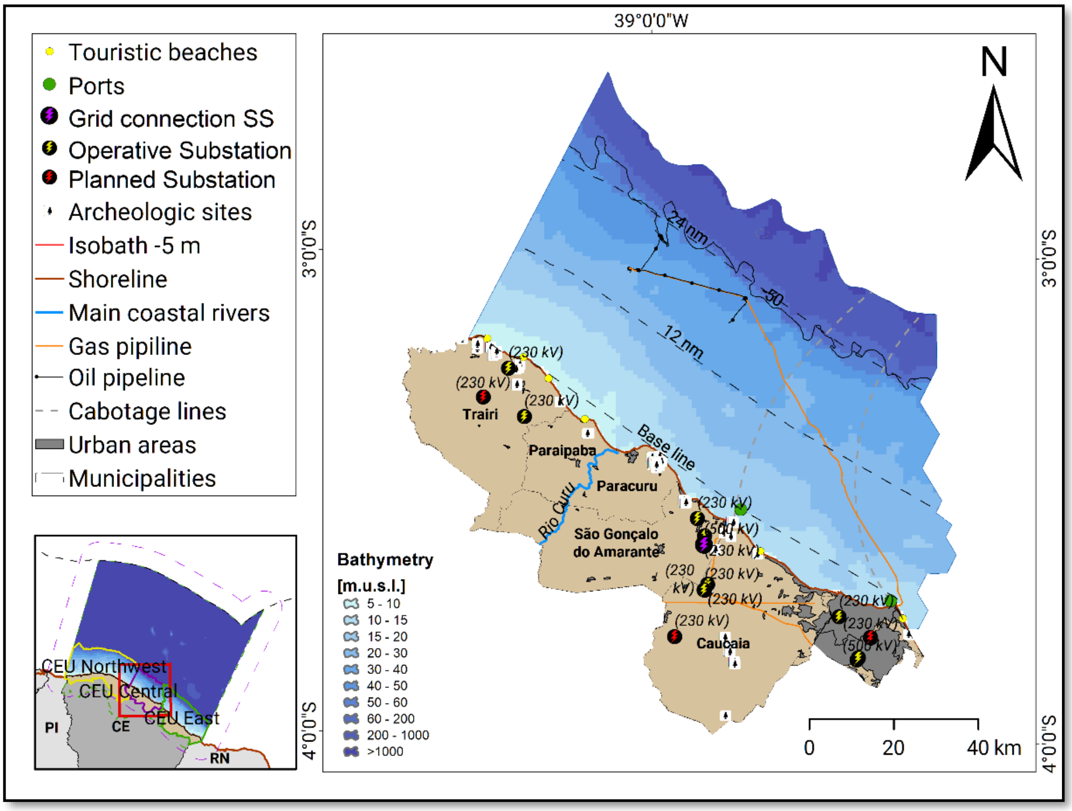


Figure 4-29. Base map for strategic planning of Offshore Wind Energy in CEU Centro.
Source: The Author.

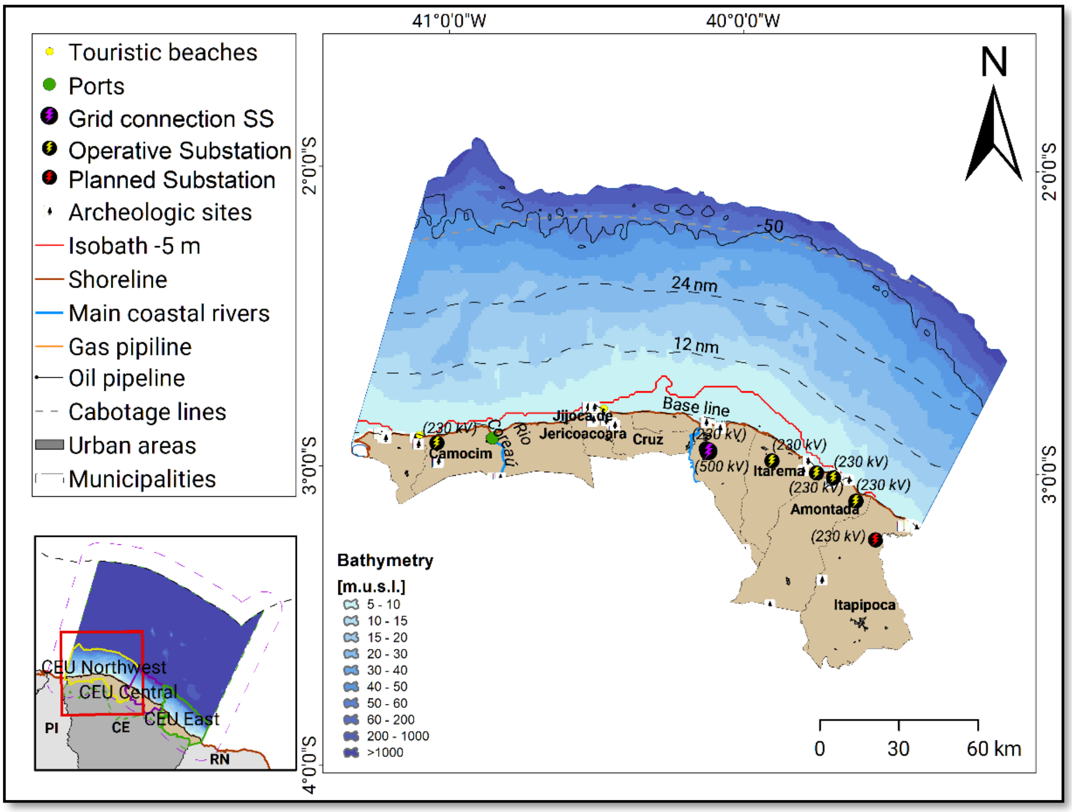


Figure 4-30. Base map for strategic planning of Offshore Wind Energy in CEU Northwest. Source: The Author.

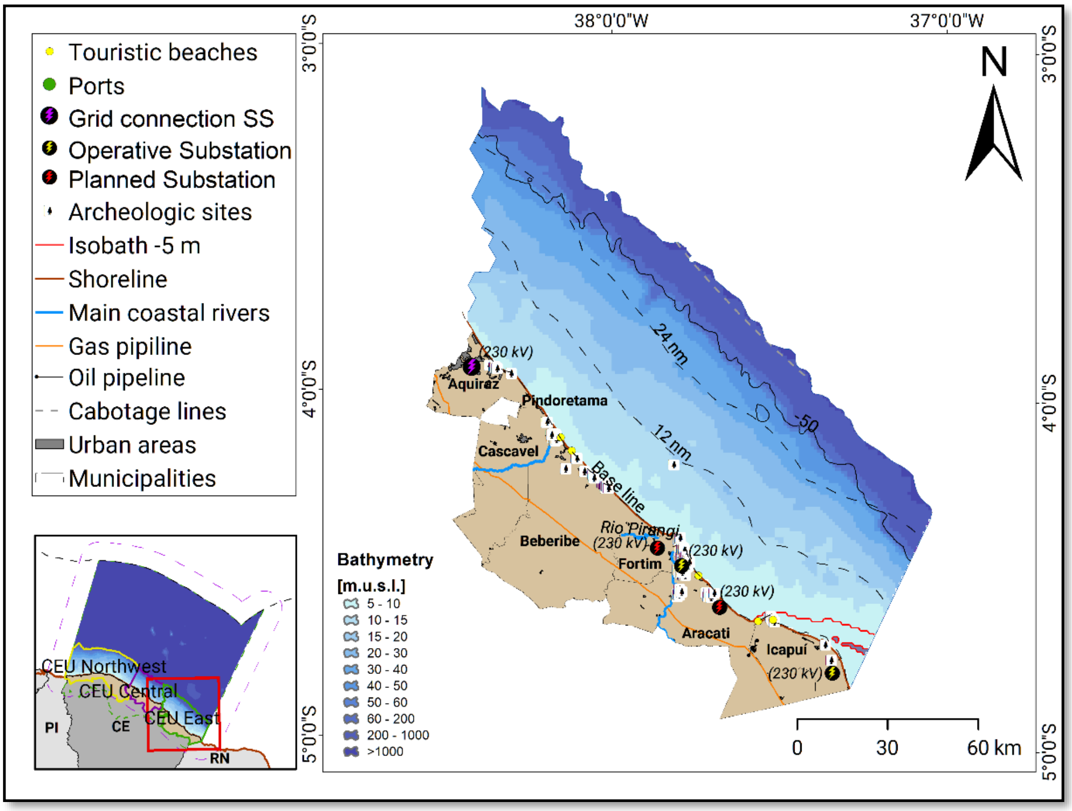


Figure 4-31. Base map for strategic planning of Offshore Wind Energy in CEU Centro. Source: The Author.

4.5.2.2 Feasible Areas for Offshore Wind Energy in Ceará

A Feasible Offshore Wind Areas (FeOWA) represents an area where there are no direct constraints on offshore wind development. Constraint mapping analysis was applied to integrate various direct constraints based on cumulative geoprocessing techniques, using spatial variables and parameterized constraint thresholds (see 4.1.2.1); five scenarios were modeled as defined in Table 4-14 (see detailed parameters in Appendix G).

The results of the constraint mapping are Constraint Index, and polygons representing restricted and feasible areas for offshore wind deployment under the assumptions of the desired scenario (input parameters).

In this stage, the FeOWAs for each scenario were modeled using the OW Feasible Areas tool (included in the GIS-SPOWER-BR Toolbx). The input data are spatial variables (formatted in raster surface format) extracted from the mapping of key drivers (*e.g.,* restrictive human activities such as protected areas or), strategic features (*e.g.,* port or substations) and spatial resource variables (*e.g.,* offshore wind resources or bathymetry). Figure 4-32 depicts a visual example of the input layers (spatial variables) for the constraint mapping analysis considering the assumptions of Scenario B1 (see Appendix G).

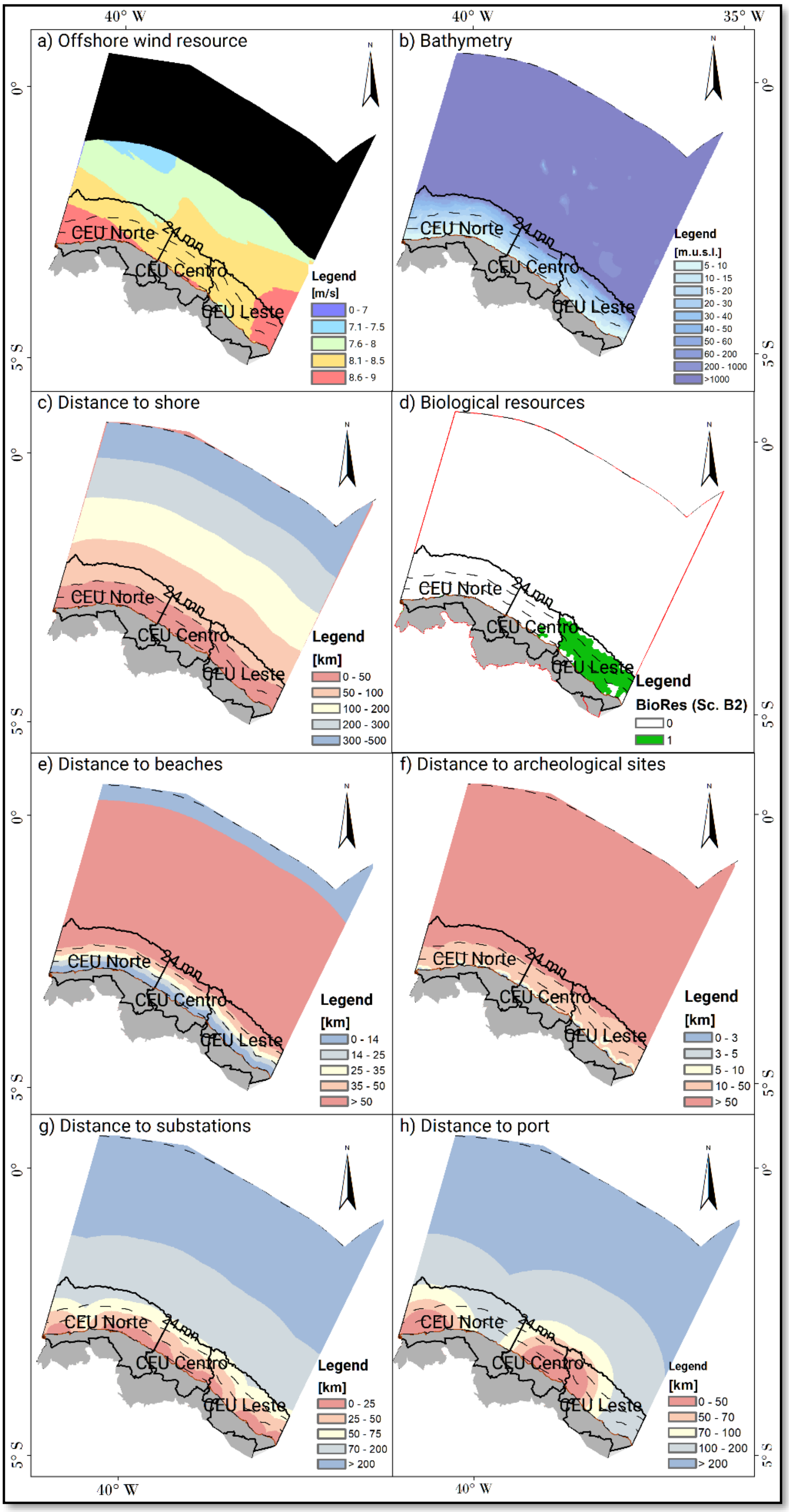


Figure 4-32. Strategic constraint variables for the development of offshore wind energy in the sustainability optimization scenario (Sc.B1).
Note: see Appendix G.
Source: The Author.

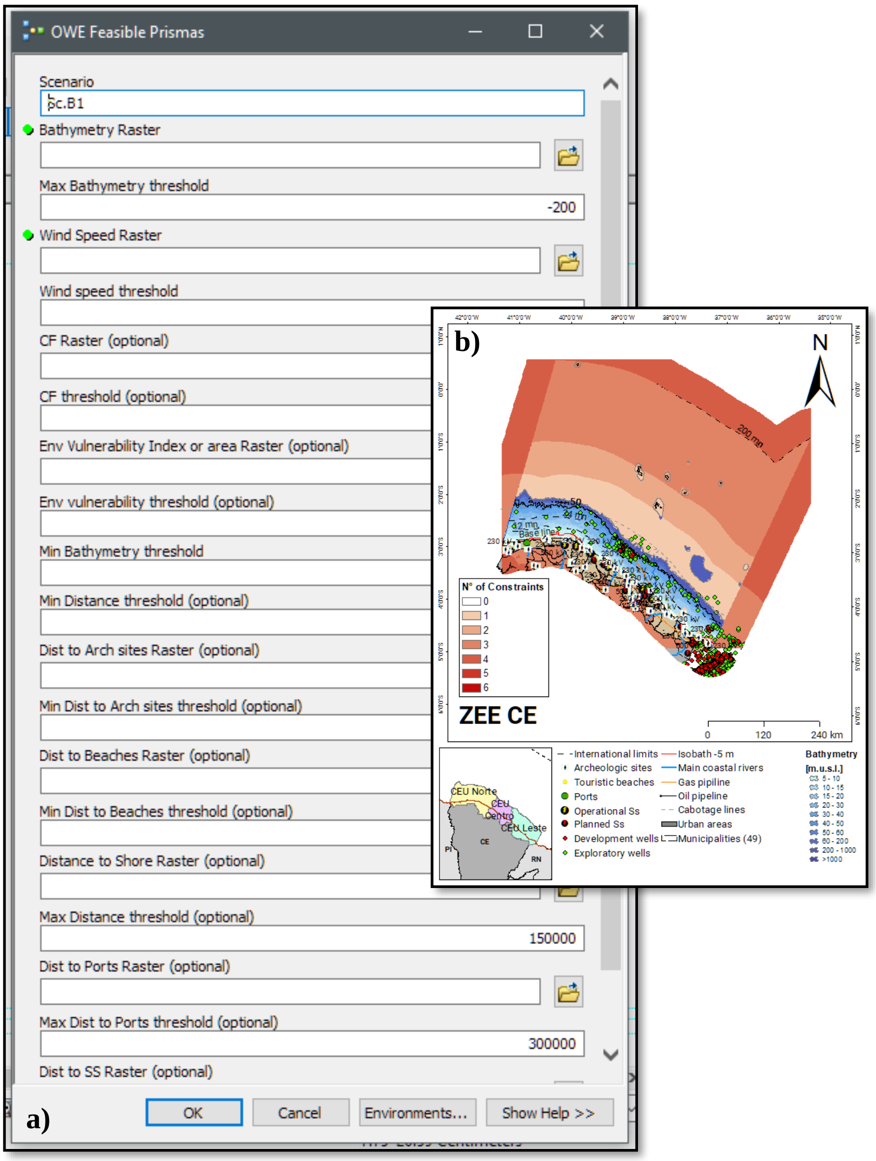
Next, the conceptual scenarios provided the strategic planning vision (bias) and input parameters (threshold assumptions) to model the spatial constraints that define the areas eligible for offshore wind in the coastal zone of the state of Ceará for all scenarios.

For practical reasons, only the maps comparing two scenarios are presented in this section: The 2023 baseline scenario, referred to here as Scenario A1, and the sustainability optimization scenario, referred to here as Scenario B1. These scenarios were selected to illustrate the differences between modeling feasible areas in the currently emerging offshore wind market (by 2023) and a hypothetical scenario of ideal sustainability.

The parameters of scenario B1 are presented as an example for the execution of the GIS-based tools in the GIS-SPOWER-BR Toolbox. The OWE Feasible Areas Tool was executed with eight spatial variables and 11 constraint parameters. The constraint mapping was set up for scenario B1:

a) **Scenario (mandatory):** Sc.B1
b) **Bathymetry layer (mandatory) + parameters:** minimum: 5 m.u.s.l.; maximum: 1,000 m.u.s.l.
c) **Offshore wind resource layer (mandatory) + parameters:** minimum: 7 m/s
d) **Offshore wind Capacity Factor layer + parameters:** minimum: 0.36 (36%)
e) **Distance to shore + parameters:** minimum: 10,000 m; maximum: 500,000 m.
f) **Biological resources layer + parameters:** 1 (restricted areas based on Federal UC, State UC, APCBs of extreme importance).
g) **Distance to archeologic sites layer + parameters:** minimum: 3,000 m.
h) **Distance to beaches layer** (touristic beaches) **+ parameters:** minimum: 14,000 m.
i) **Distance to ports layer** (any port) **+ parameters:** maximum: 300,000 m.
j) **Distance to substations layer + parameters:** maximum: 100,000 m.

The *OWE Feasible Areas tool* run with at least two mandatory layers: Bathymetry and Wind speed, but the modeling for the current case study (including the five scenarios) was run with the eight spatial variables. Figure 4-33 shows *OWE Feasible Areas tool* setting.


OWE Feasible Prismas

Scenario: Sc.B1

Bathymetry Raster

Max Bathymetry threshold: -200

Wind Speed Raster

Wind speed threshold

CF Raster (optional)

CF threshold (optional)

Env Vulnerability Index or area Raster (optional)

Env vulnerability threshold (optional)

Min Bathymetry threshold

Min Distance threshold (optional)

Dist to Arch sites Raster (optional)

Min Dist to Arch sites threshold (optional)

Dist to Beaches Raster (optional)

Min Dist to Beaches threshold (optional)

Distance to Shore Raster (optional)

Max Distance threshold (optional): 150000

Dist to Ports Raster (optional)

Max Dist to Ports threshold (optional): 300000

Dist to SS Raster (optional)

Figure 4-33. ***OW Feasible Areas*** **tool set up. Note: a) Modeling Sc.B1 – Optimizing sustainability; b) Example of constraint mapping for the Ceará EEZ. Source: The Author.**

Figure 4-34 shows Feasible Offshore Wind Areas (light green contour) and the consolidated restricted areas (red shaded surface) and Cumulative constraint Index (red gradient) with the summation of direct restrictions in the coastal zone of the state of Ceará for the example scenarios: a) Scenario A1 and b) Scenario B1.

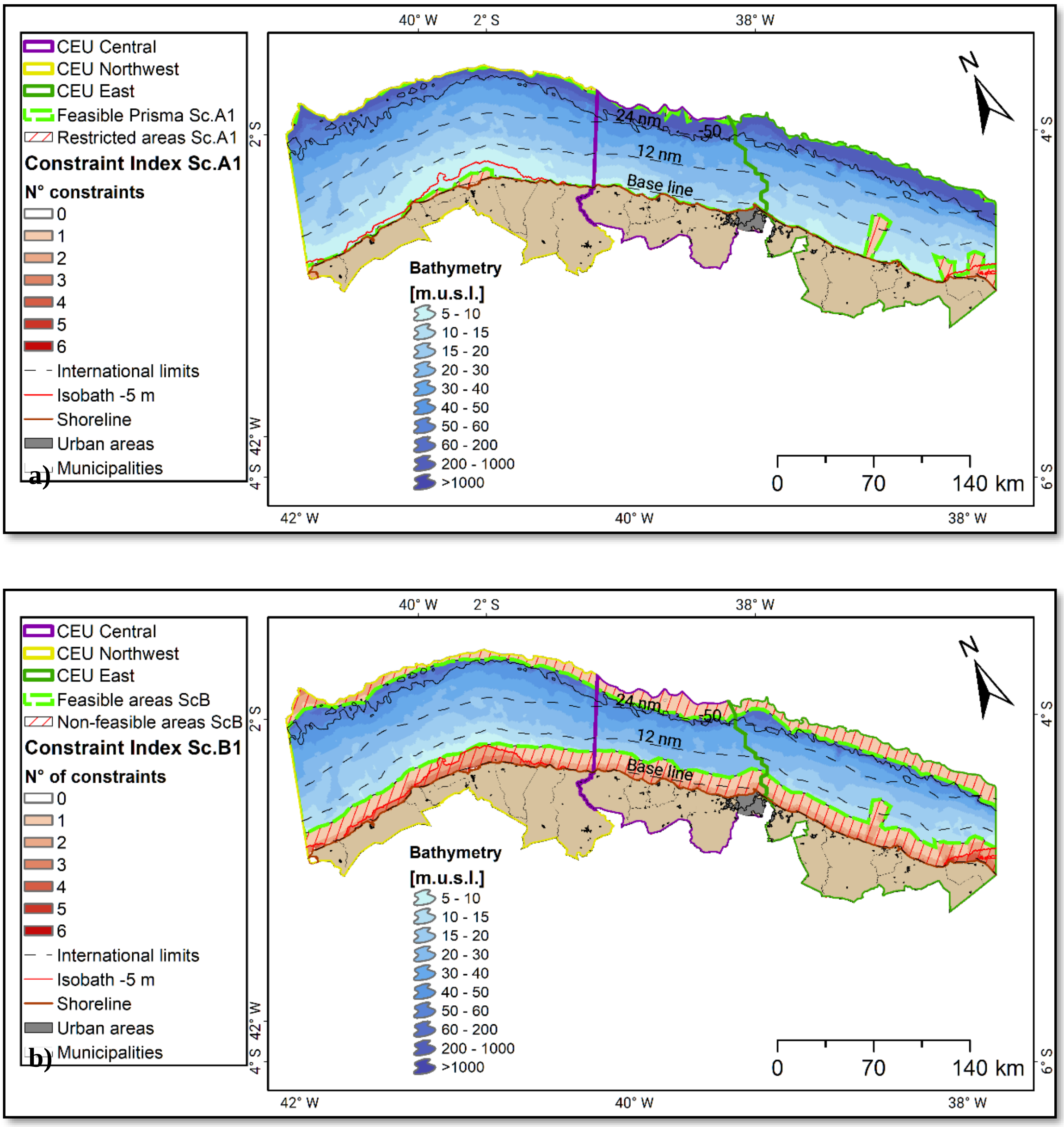


Figure 4-34. Feasible Offshore Wind Areas (FeOWAs) for the State of Ceará:
a) Scenario A1 vs. b) Scenario B1.
Source: The Author.

The comparison shows a significant variation of whole feasible area if additional restrictions are applied (scenario B1). For the Base scenario 2023 (reference scenario), almost the entire coastal area could be available for OWE deployment, which would lead to an overestimation of the capacity potential.

As shown in Figure 4-35, Feasible areas may be sensitive to input constraint threshold parameters The minimum distance to the coast has been shown to be particularly important as it may include other constraint thresholds such as distance to archeological sites or tourist beaches, which may vary from state to state. Furthermore, this parameter is not very well studied in the literature and the assumptions about its value do not have convincing arguments. For example, roadmaps such as the Colombian and Philippine roadmaps (RCG, ERM, 2022, WORLD BANK, 2022) estimate the offshore wind energy potential in the entire EEZ with no minimum distance to the coast. These potentials tend to be overestimated due to a simple limitation to 2 km. The Brazilian coastline, for example, is 7,124 km long, which corresponds to a difference of 42.7 GW of installed capacity. This sensitivity is therefore analyzed in Section 4.6 – Sensitivity analysis.

As far as the theoretical potential of installed capacity is concerned, it was calculated assuming a power density of 3 MW/ km^2 (BEITER *et al.*, 2016; DE ASSIS TAVARES *et al.*, 2020, FERREIRA *et al.*, 2021). However, BOSCH (2018) reports that the power density can vary between 2.47 and 12.8 MW/ km^2 , depending on the separation factor between the turbines and the characteristics of the selected turbines (rotor diameter – RD). These variations are analyzed in the technological analysis (see section 4.5.2.4). Table 4-19 shows total feasible area for offshore wind energy in the coastal zone of the state of Ceará, considering all strategic scenarios.

Table 4-19. Theoretical installation potential in Feasible Areas for each strategic scenario.

Planing scenarios	Feasible Offshore Wind Area [km^2]	Share of coastal zone of Ceará [%]	Theoretical capacity potential [GW]
Sc.A1*	38,433	95.9 %	115.3
Sc. A2	6,397	16.0 %	19.2
Sc.B1*	27,357	68.3 %	82.1
Sc. B2	17,689	44.1 %	53.1
Sc.C	1,704	4.3 %	5.1
Coastal offshore area	40,079	100 %	120.2

Note: (*): selected scenarios for analysis; Theoretical capacity potential was calculated based on capacity density of 3 MW/km^2.
Source: The Author.

With the aim of reducing the areas of investigation and the robustness of the analysis, two scenarios were selected to apply the following steps of the methodological framework. Scenarios A1 and B1 were selected because the scenario represents the status of the Brazilian market and scenario B1 represents the proposal for sustainable development of offshore wind energy in the marine area of Ceará, both in the context of an innovation market.

4.5.3 Non-conflicting offshore wind areas in the State of Ceará

The Non-Conflicting Offshore Wind Areas (NcOWA) represent areas where there are no conflicts between offshore wind energy and other anthropic activities or natural resources. Multi-use mapping and spatial analysis of conflicting uses were applied to integrate offshore wind activities with other anthropogenic activities. This analysis used multi-use mapping and the activity-activity matrix technique, here called the OWE-activity matrix (see Table 4-22), to assess competition between activities, using the competition categories defined in Table 4-11.

Multiple-use mapping was performed in the coastal zone of Ceará with spatial data on human activities that could compete with OWE activities, as follows:

a) **Protected areas**
b) **Military areas**
c) **Oil and gas (exploration blocks, production fields, pipelines)**
d) **Infrastructure (telecommunication cables, harbors)**
e) **Mineral extraction**
f) **Fishing Industry**
g) **Maritime transport (traffic density and cabotage corridors)**
h) **Tourism (area of influence of tourist beaches)**
i) **Offshore RE**

Based on the key drivers mapping of human activities, the multi-use mapping was created to support the assessment of competing uses of marine space (see detailed mapping in Appendix A – Multi-use mapping). As a practical example, Figure 4-35 shows the example of CEU's multi-use mapping for Scenario B.1 – Sustainable Optimization Scenario.

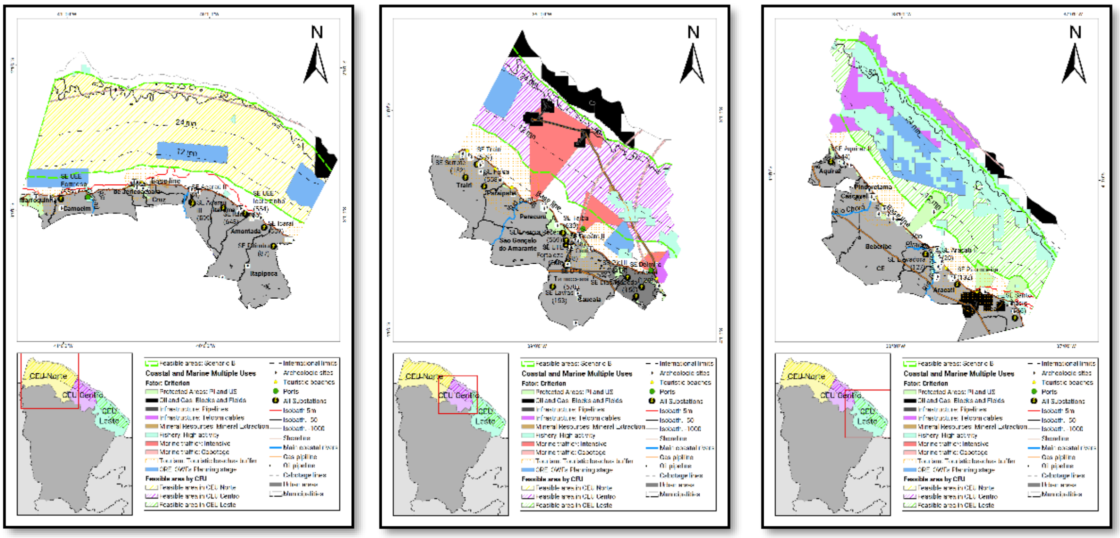


Figure 4-35. Multi-use mapping to assess the OWE-Activity Matrix by CEU.
Note: see full size maps in Appendix A – Multi-use mapping.

Next, sea-use conflict analysis – competition for space or resources – was applied to the potential offshore wind areas (FeOWAs) (see Section 4.1.2.2) for each CEU. The OWE activity matrix was used to assign compatibility conflict categories to the human activity areas (geo-referenced polygons) using the symbology shown in Table 4-20. The detailed procedure is explained in Appendix I. Consequently, the non-conflicting areas include areas with compatible activities (3), no obvious interaction (0) and all other areas within the assessment area to which no activities are assigned – "empty" areas – (10).

Table 4-20. Assessment criteria for OWE-Activity Matrix.

Category	Value	Symbology
Empty areas	10	🟦

Compatible (3)	3	🟩
Likely compatible (2)	2	🟨
No obvious interaction (0)	0	⬜
Future conflict	-2	🟧
Conflict	-3	🟥
Low quality (manual digitalization)	-88	🟪
Unavailable public data	-99	⬛

Source: The Author.

In particular, the assessment of competition varies depending on the vision of the respective scenario (bias). In general, offshore wind energy projects (early planning stage) were assessed as future conflict (-4). However, depending on the vision, different project areas may be in conflict or compatible with a new development within a planned regime (also called centralized regime), *e.g.*, in scenario A1 according to Decree 10.946-2022 (current legal framework) all conceptual projects were assessed as future conflict areas (-4). Instead, in Scenario B1 only the larger OWFs (areas with an extent of more than 750 km^2) were considered as future conflict areas (-4). Table 4-21 shows the assumptions for selected scenarios for comparison (see Appendix G for details of competition assumptions for the other planning scenarios).

Table 4-21. Competition assumptions for Sea-use.

Human activities in offshore coastal zone	Competition assumptions Scenario A1	Competition assumptions Scenario B1
1. Protected areas	1. All areas Fed. & Ste. UCs (IP)	1. All areas All UCs
2. Military areas	-	-
3. Oil and Gas	3. Blocks and production fields	3. Block and production fields
4. Infrastructure	4. Buffer 500m from pipelines	4. Buffer 500m pls + cables
5. Mineral extraction	5. N/C	5. Operative (Lavra)
6. Fishery Industrial	6. N/C	6. > 8h Operaion density
7. Maritime traffic	7. N/C	7. 500 m Cb + Sh (WA)
8. Tourism	8. N/C	8. Buffer 14 km (TB)
9. Offshore RE	9. Planned OWFs	9. >750 km^2

Note: Example of scenarios A1 and B1.
Source: The Author.

Table 4-22 shows the assessment of the OWE-activity matrix for the three coastal environmental units in Scenario B1 and refers to the competing assessment proposed by UNESCO (EHLER & DOUVERE, 2013, p. 59).

Table 4-22. OWE-Activity Matrix.

OWE-activity Matrix	OWE UNESCO	OW Areas Sc.B1 CEU Northwest	OW Areas Sc.B1 CEU Central	OW Areas Sc.B1 CEU East
Early planning OWFs (Opened permit process)	-1	-2	-2	-2
Commercial Fishing: Nets	-1	0	-1	-1
Commercial Fishing: Hooks/Fishing Line	-1	0	-1	-1

OWE-activity Matrix	OWE UNESCO	OW Areas Sc.B1 CEU Northwest	OW Areas Sc.B1 CEU Central	OW Areas Sc.B1 CEU East
Commercial Fishing: Traps/Lobster Pots	-1	0	-1	-1
Commercial Fishing: Harpoons/Spears	-1	0	-1	-1
Commercial Fishing: Trawls/Dredges	-1	0	-1	-1
Commercial Fishing: Seine Nets	-1	0	0	0
Commercial Fishing: Beach Seine	-1	0	-1	-1
Commercial Fishing: Seine	3	0	-1	-1
Fish Farms/Mariculture	-1	0	3	3
Commercial Fishing: Hooks/Fishing Line	-1	99	99	99
Recreational Fishing: Traps/Lobster Pots	-1	99	99	99
Recreational Fishing: Shell fishing	No Reference	99	99	99
Artisanal Fishing (Brazil):	-1	99	99	99
Recreation: Sailing	-1	99	99	99
Recreation: Boats	-1	99	99	99
Recreation: Personal Watercraft	-1	99	99	99
Recreation: Diving	-1	0	2	0
Recreation: Wildlife Watching	No Reference	99	99	99
Recreation: Water Sports**	No Reference	99	99	99
Recreation: Beach Tourism**	-1	2	-1	0
Maritime Transport	-1	0	0	0
Dock and Port Operations	2	0	0	0
Dock and Port Dredging	-1	0	0	0
Dredged Material Disposal	-1	0	99	99
Offshore Airports	-1	0	99	99
Offshore Industrial Plants	-1	0	0	0
Offshore LNG Terminals	-1	0	0	0
Offshore Oil and Gas Exploration	-1	0	0	0
Offshore Oil and Gas Production	2	0	0	0
Cables, Pipelines, Gas Lines, Transmission Lines	-1	0	-1	0
Sand and Gravel Extraction	-1	0	0	0
Offshore Renewable Energy: Wave Farms	-1	0	0	0
Offshore Renewable Energy: Tidal Energy	-1	0	0	0
Offshore Renewable Energy: Currents	-1	0	0	0
Seawater Desalination Plants	-1	0	0	0
Carbon Capture Plants	-1	0	0	0
Military Operations	-1	0	0	0
Strictly Protected Marine Reserves	-1	99	99	99
Multi-Use Marine Parks	2	0	0	0
Scientific Research	-1	0	0	0

Note: Multi-use competition between OWE and anthropic other activities. Conflict (-3) in red; Likely compatible (2) in yellow; Compatible (3) in green; Future conflict (-2); No apparent interaction (0) in grey, and no available public data (99) in black. Conflict or compatibility depend

on spatial overlaying (competition for space) or competition for resources. Temporal and seasonal competition also may exist.
Source: The Author based on EHLER & DOUVERE (2013. p. 59).

Figure 4-36 shows the mapping of competing sea use and compares the variation in non-conflicting areas (in light blue) when different assumptions on competing marine uses are applied. In the Base scenario 2023 (reference scenario with OWFs until 2023), all conceptual OWF projects were defined as future conflict activities. This can lead, for example, to a reduction in the remaining non-conflicting areas if a concession is required for the area in an independent leasing scheme (decentralized) or to an underestimation of the capacity potential in a planned leasing scheme (centralized).

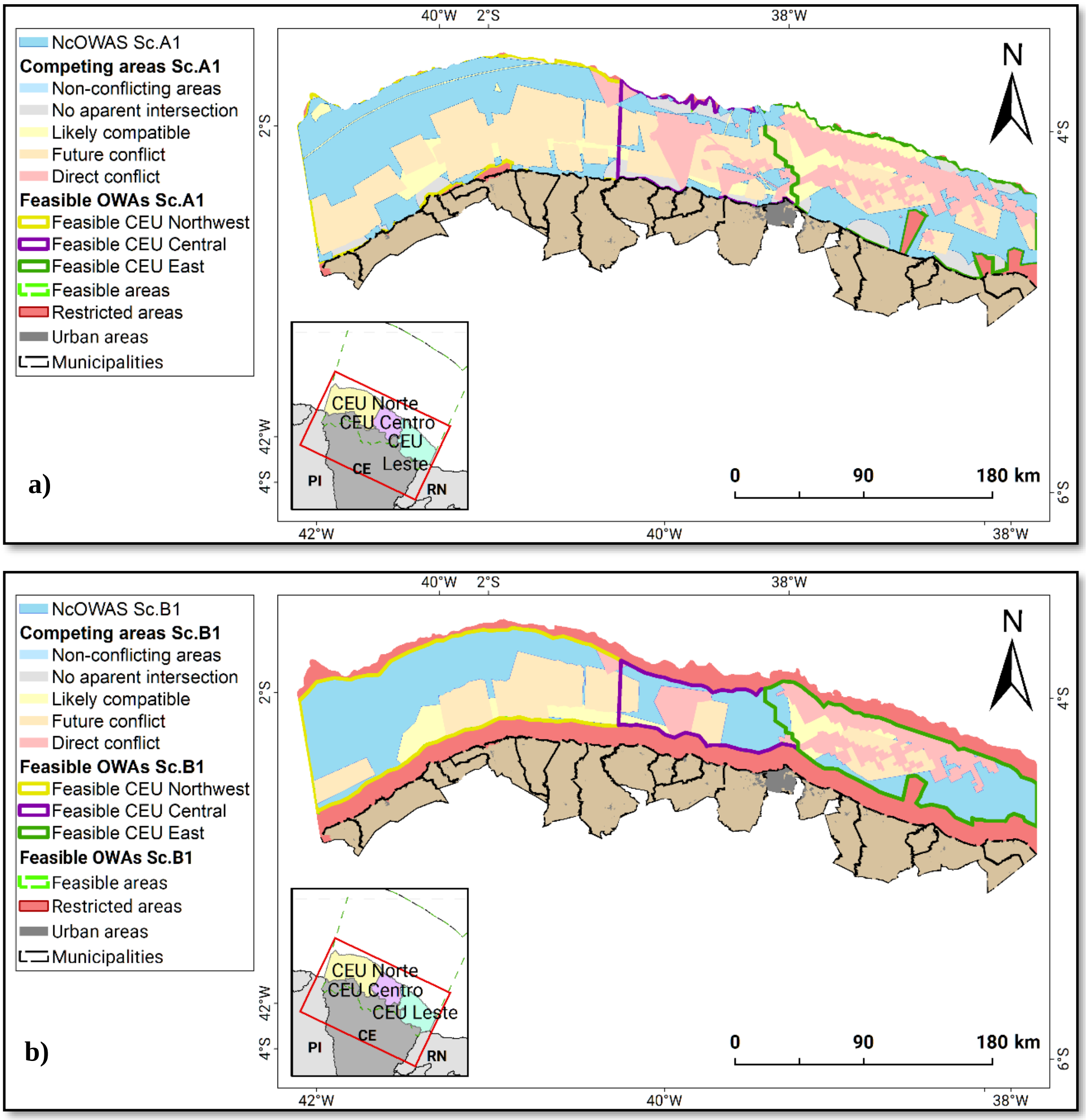


Figure 4-36. Sea-use competition mapping in in the coastal zone of the Ceará.
Note: Non-conflicting Offshore Wind Areas are shown in light blue.
a) Scenario A1. vs. b) Scenario B1
Source: The Author.

Table 4-23 summarizes extension and share of the resulting Non-Conflicting Offshore Wind Areas (NcOWAs, in blue) in the coastal zone and within the FeOWAs for the selected scenarios.

Table 4-23. Total areas of Non-conflicting Areas by Planning Scenario.

Scenario	NcOWA (in coastal zone) [km^2]	Share of total Coastal Zone area [%]	NcOWA (in FeOWA) [km^2]	Share of total FeOWA area [%]
Base Scenario 2023 (A1)	14,482	24.9	13,893	34.7
Sustainable Optimization (B1)	21,185	26.1	14,521	36.2
Total coastal zone areas	40,079	100	40,079	100

Note: Non-conflicting Offshore Wind Area (NcOWA)s; FeOWA: Feasible Offshore Wind Area; Scenarios are not complementary, difference between total coastal zone area and NcOWA represents other competition types and restricted areas.
Source: The Author.

4.5.4 Sustainable Offshore Wind Areas

Sustainable Offshore Wind Areas suggest areas with low environmental complexity or low-cost potential for the development of an offshore wind farm. These areas are defined by geospatial fuzzy optimization modeling that integrates strategic spatial variables related to environmental and cost drivers and follows risk profiles (see 4.1.2.3). The Spatial Environmental Suitability Index (SESI) represents the integration of ecological drivers related to environmental complexity, while the Spatial Cost Potential Index (SCPI) reflects variations that influence the LCOE.

These indices are compared with each other to identify areas where both indices show high performance and suggest areas with higher sustainability (trade-off between environmental and economic dimensions) to the decision maker as feasible and non-conflicting areas.

The Spatial Environmental Sustainability Index (SESI) and the Spatial Cost Potential Index (SCPI) were modeled using the ArcGIS tools fuzzy membership and fuzzy overlay for the selected scenarios (see input mapping in Appendix A), taking into account the assigned risk profile for each scenario (parameter gamma). For practical illustration, the optimization mapping for scenario B1 is presented in this section.

After optimization modeling, indices were interpreted and divided into three categories, transforming the spatial suitability indices into spatial suitability indicators showing high, medium and low suitability categories (see Figure 4-37).

the SCPI index was divided into three categories, using the same Quantile classification method. Areas with blue represents High low-cost suitability (i.e. low cost for deployment), green for medium low-cost suitability and light yellow for low-cost suitability to deploy offshore wind farm construction. The coastal zone of Ceará is characterized by a shallow bathymetry that extends from the coastline to a distance of 50 km and has a very light slope distance. The variation of the SCPI is determined by the distribution of the sedimentary material (FRANCISCONI *et al.*, 1974), depending on the classification of the material, which tends to carry physical structures. A high SCPI is concentrated along the contiguous zone (between 12 and 24 nm) of the CEU Northwest and East with a medium SCPI along the Territorial Sea; in the CEU Central, the high SCPI is concentrated in the municipalities of Trairi and Paraipaba, between 12 and 24 nm (contiguous zone), and the medium SCPI in the remaining area. Low SCPI was characteristic of deeper areas (> 50 m.u.sl.).

On the other hand, the SESI index was divided into three categories using the Quantile classification method. Areas with dark green color stand for high environmental suitability, green for medium suitability and light green for low suitability for the construction of offshore wind farms. This index shows that suitability also increases as distance from biological and ecosystem resources increases as well, according to an Ecosystem-based approach. In the coastal zone of Ceará, the areas with high ecological suitability were concentrated in the CEU Northwest, 42 km from the municipality of Itarema. In CEU Central and East, environmental suitability remained low between the coastline and 50 m water depth (55 km from the coast), where coral reefs and manatee mapping predominate, according to available data from the National Action Plans (solid polygons of relatively low quality (ICMBio, 2019).

Finally, the optimization mapping was zoomed to the local scale (CEU scale), since at the scale of the coastal zone of Ceará (a regional scale), the index variations were not shown when and integrated mapping with the non-conflicting OWAs (NcOWAs) and feasible OWAs (FeOWAs) was performed. Figure 4-38 shows variations of the optimization mapping of the SCPI for scenarios within non-conflicting OWAs and Figure 4-39 shows variations of the optimization mapping of the SESI for scenarios within non-conflicting OWAs.

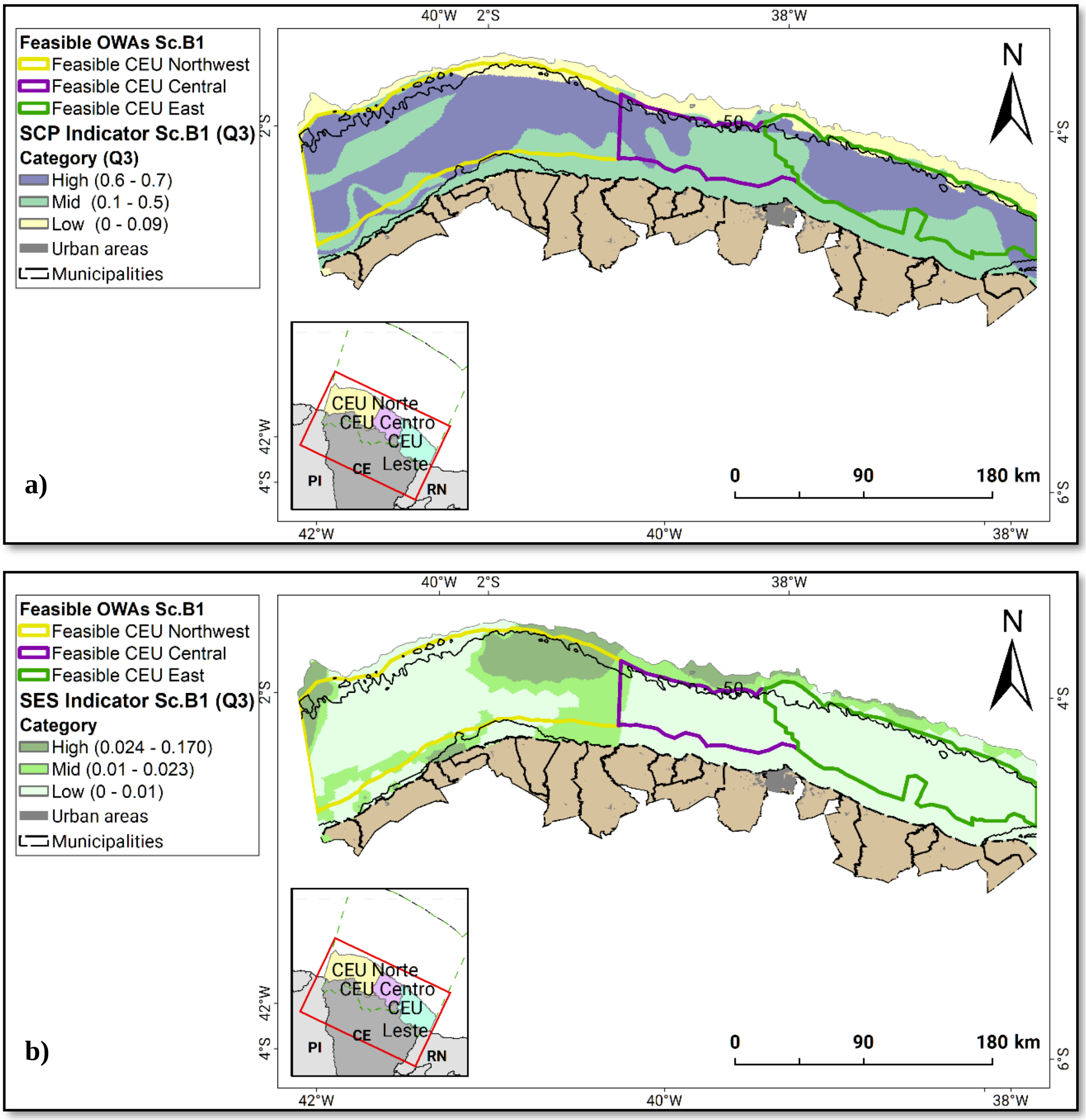


Figure 4-37. Optimization mapping for Scenario B1 in the Coastal Zone of Ceará. Note: a) SCPI map; b) SESI map.

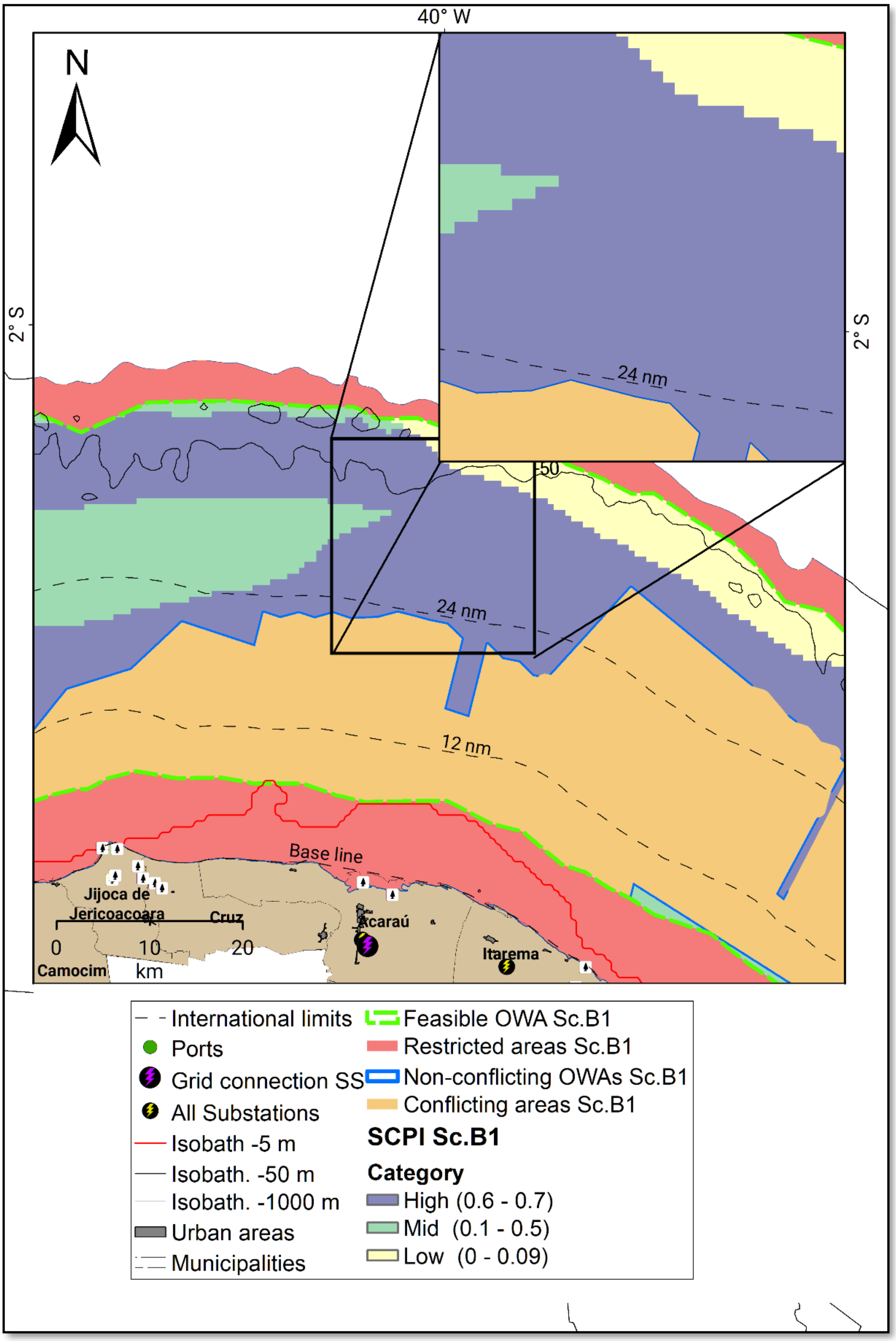


Figure 4-38. Spatial Cost Potential Index (SCPI) within Non-conflicting Areas - Scenario B1, CEU Central.
Source: The Author.

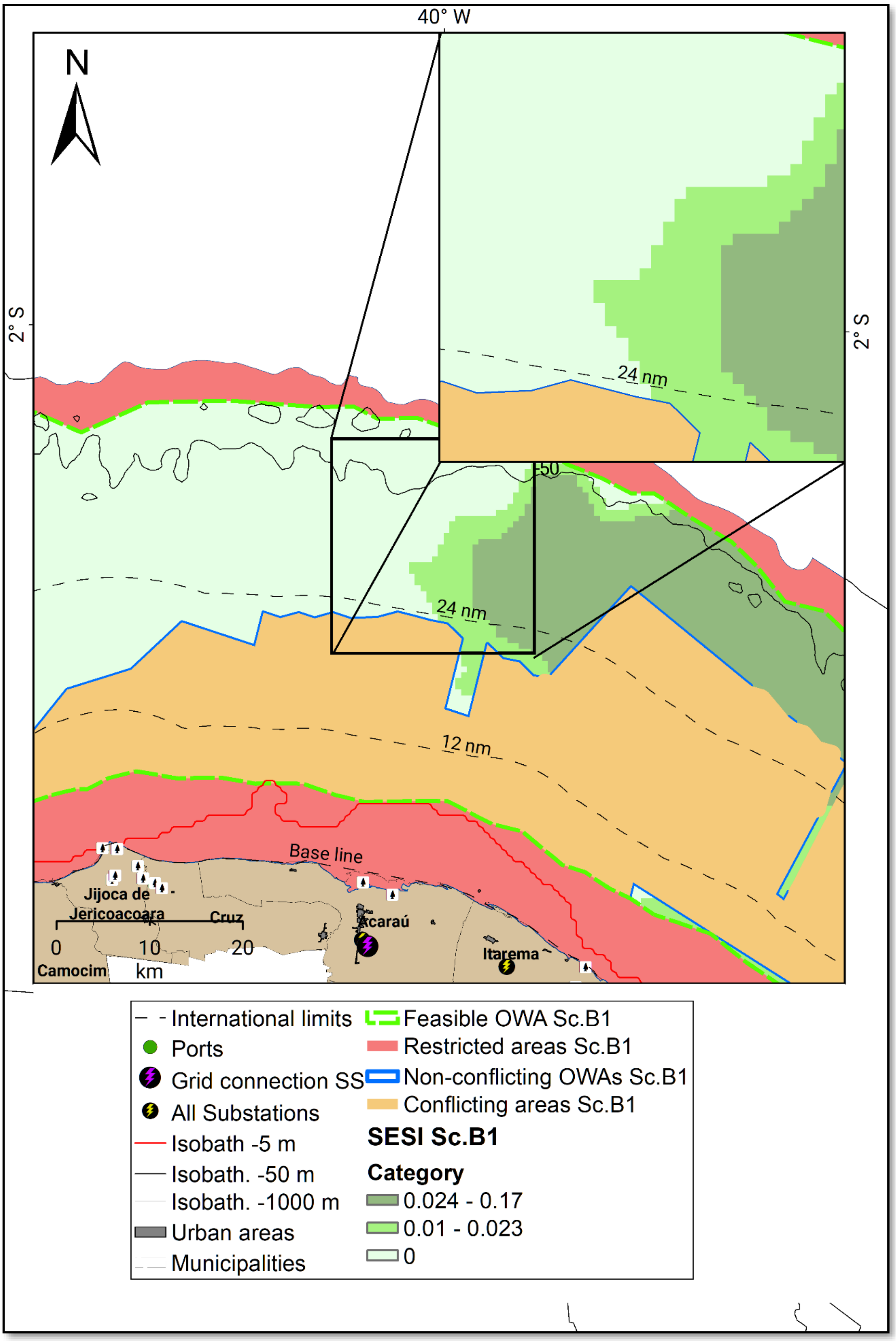


Figure 4-39. Spatial Environmental Suitability Index (SESI) within Non-conflicting Areas – Scenario B1, CEU Central.
Source: The Author.

Optimized sustainability indices only suggest more suitable areas to prioritize the siting of offshore wind farms or specific turbines. Therefore, the definition of sustainable offshore wind areas focused on prioritizing offshore wind turbines with higher integration rates between SESI and SCPI (i.e. SESI divided by SCPI or SCPI divided by SESI). This integration aims to identify trade-offs between environmental and economic factors instead of only considering cost drivers to model strategic guidelines in local scale.

Technological modeling is then required to site offshore wind turbines, which supports the analysis at the local scale (pre-micro-siting). Technological analysis also makes it possible to estimate the number of turbines to be sited in a given area with greater accuracy, then estimating capacity potential based on an assumed power density. Once the offshore wind turbines have been placed, the resulting information (pixel-by-pixel values) on environmental complexity and cost drivers is integrated. The optimization index values (SESI and SCPI) were extracted and visualized for each turbine. This analysis is explained in more detail in the following subsection (4.5.4.1).

4.5.4.1 Technological analysis for offshore wind areas in the state of Ceará

The technological analysis consisted of modeling the total number of turbines, their area of influence and preliminary localization in the area in question, in order to estimate the capacity potential (MW or GW) and power density (MW/km^2). In the turbine localization modeling – offshore wind turbine siting – the turbine rotor diameter (RD) and separation factor (SF) are calculated based on square layout configuration (see subsection 4.1.2.4). The input parameters (RD and SF) followed the assumptions for each planning scenario (see Appendix G).

The first step of the technological analysis was to analyze the turbine characteristics of different alternatives of offshore wind turbines and to select suitable alternative models for technological modeling.

The selection of the most suitable wind turbine is not a trivial task. The turbine model and its performance (represented by the power curve) are the main drivers for power generation, while other technological characteristics such as the turbine rotor diameter and the distance factor must be considered to optimize the layout of the wind farm and energy production. In the strategic planning stage, only siting analysis is required. The optimization of the wind farm layout – the micro-siting – is carried out in further stages, using the results of the siting as strategic input information. The better the strategic planning study (siting), the better the information for the micro-site siting activities.

Figure 4-40 shows the generic power curves of the theoretical offshore turbine models developed by NREL and considered in the technological analysis.

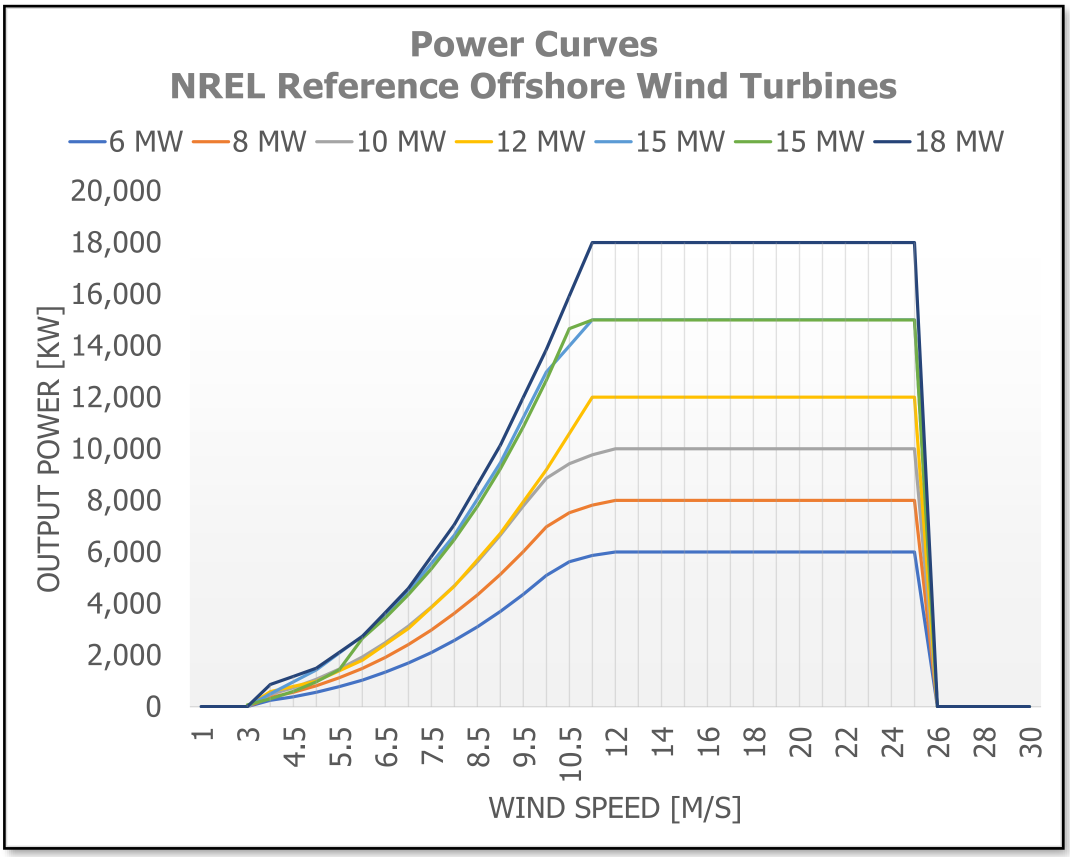


Figure 4-40. Power curves of reference offshore wind turbines.
Source: The Author based on NREL (2023).

The rotor diameter is the most important parameter in the development stage, as it influences the siting process – the design of the OWF (see 4.1.2.4). Table 4-24 lists the most important technical characteristics of the various offshore wind turbine models (including commercial and theoretical models). For example, the MHI Vestas – V164-10.0 offshore wind turbine has an attractive PR/RD ratio of 610 MW/m, compared to the Heliade-X 12-MW of 545 MW/m. This comparison therefore indicates that the MHI Vestas – V164-10.0 can generate more energy in the same area, allowing a higher capacity density of each turbine's radius of influence.

Table 4-24. Technical parameters of the Offshore Wind Turbines.

Turbine Model	Rated Power [MW]	Turbine Rotor Diameter [m]	OWF Square grid side length [m]	20H distance [m]	RP/RD ratio [x10000 MW/m]
WEG - AGW-110	2	110	880	2,200	182
SG - SWT-7.0-154	6	155	1,240	3,100	387
SG - SG 8.0-167 DD	8	167	1,336	3,340	479
MHI Vestas - V164-10.0 MW	10	164	1,312	3,280	610
GE - Heliade-X	12	220	1,760	4,400	545
NREL - WTG-15.0-246	15	240	1,920	4,800	625

Source: The author based on technical specifications of offshore wind turbines and separation factor of 8 times the Rotor Diameter.

IOANNOU *et al.*, (2018) concluded that larger offshore wind turbines lead to an inverse exponential relationship with CAPEX, OPEX and LCOE. Moreover, most wind farms in the conceptual offshore wind pipeline in Brazil have defined 15 MW turbines as the technological choice. Considering technological characteristics and the current market status, offshore wind turbines with a nominal capacity of 10 MW, 12 MW and 15 MW were selected for technological modeling. Initially, selection does not consider power density of each turbine model, instead, market trends and available technical data drove the selection of these models.

The localization of the turbines was calculated for the selected turbine models using the OW turbine grid tool with the following input parameters:

a) 10-MW, Rotor diameter (RD) = 164 m.
b) 12-MW, Rotor diameter (RD) = 220 m.
c) 15-MW, Rotor diameter (RD) = 240 m.
d) Separation Factor (SF) of 8 times of rotor diameter (RD) – for all technologies.

After technological modeling of turbine sites, more precise key figures for strategic planning can be estimated based on large amount of data. For instance, it was possible to model 64,224 turbines in the coastal zone of Ceará, gathering 10 MW, 12 MW and 15 MW turbine models, including two 10 MW models with 164 m and 190 m of rotor diameters, respectively. Each model turbine has a different total number of turbines installable in the same coastal zone area.

The resulting spatial data, including all technologies, was extracted into a consolidated database, to follow a data-driven decision-making approach for integrating the modeled data into each offshore wind turbine feature. The OWT database was tightly linked to the VIZ-SPOWER-BR(see Appendix E), which provides dynamic strategic information to support the decision-making process. This OWT database consolidates the fundamental information for accurate micro-siting, optimization of energy production and transmission, and estimation of LCOE or economic potential.

Geoanalytics focused on extracting and visualizing metrics to support three areas of strategic planning: Space, Energy and Supply Chain Planning. These metrics were consolidated into: a) total areas and their spatial distribution; b) energy density and capacity potential; and c) turbines and technical characteristics.

The technological analysis was prioritized in the non-conflict OWAs, where the risks associated with restricted areas (cumulative socio-environmental and economic constraints) and sea-use conflicts are lower according to the Ecosystem-based approach of MSP. For example, technological modeling in the entire offshore coastal zone of the state of Ceará would result in a technical potential – with no restrictions – of 232 GW with 10 MW turbines (23,169), 155 GW with 12 MW turbines (12,915) or 163 GW with 15 MW turbines (10,863). However, Table 425 summarizes the total number of turbines and the capacity potential in the Non-conflicting Offshore Wind Areas in Scenario A1 and B. As observed in this table, the total number of turbines decreases sharply with increasing capacity. Nevertheless, the highest capacity potential was 84.2 GW in Scenario B1 with 10 MW turbines and the lowest was 53.7 GW with 12 MW turbines in Scenario A. The capacity potential with 15 MW turbines showed a better performance in both scenarios in terms of power density (4.1 MW/km^2) compared to 12 MW turbines (3.9 MW/km^2). 10 MW technology showed higher metrics for capacity potential, power density and a significantly higher number of turbines with 8,064 and 8,423 units in Scenario A1 and Scenario B1 respectively.

Table 4-25. Total number of wind turbines in Non-Conflicting OWAs.

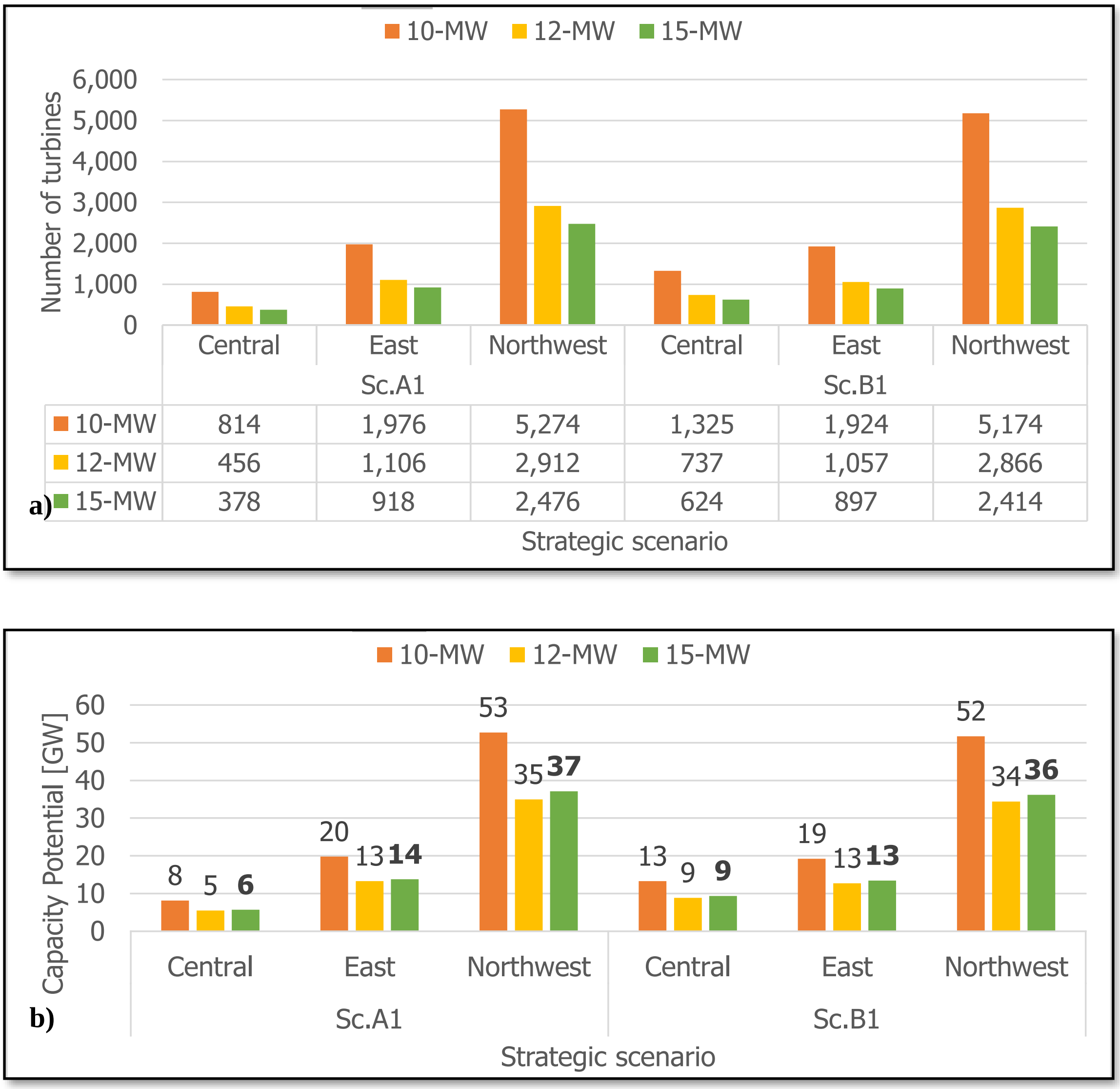
	OWA type	Area [km^2]	10-MW turbines	Capacity Potential [GW]	12-MW turbines	Capacity Potential [GW]	15-MW turbines	Capacity Potential [GW]
Offshore Coastal zone	-	55,729	23,169	232	12,915	155	10,839	163
Sc.A1	NcOWA	13,893	8,064	80,6	4,474	53,7	3,772	56,5
Sc.B1	NcOWA	14,521	8,423	84,2	4,660	55,9	3,935	59,0

Note: Coastal Environmental Unit (CEU); Offshore Wind Area (OWA).
Source: The Author.

Figure 4-41 summarizes the number of turbines per CEU (a) and the total capacity potential in the NcOWAs by CEU (b). As can be seen in this figure, the number of turbines tends to decrease exponentially as the rated power increases (a), but in terms of capacity potential (b), 10 MW turbines had a slight advantage with 15 MW turbines (green bars) compared to the 12 MW turbines (yellow) with higher power density, *i.e.*, 12 MW required more space, *i.e.*, 12 MW required more area to achieve the same capacity potential. the 10 MW turbines almost doubled the total number of turbines and capacity potential compared to the 12 MW and 15 MW technologies. However, the selection of 10 MW turbines needs to be analyzed, as a larger number of turbines means higher complexity in terms of installation, operation, costs and intervention in the biophysical space.

Therefore, 15 MW turbines should be chosen for larger installed capacities (*e.g.*, in CEU Northwest). For lower installed capacity and less space (*e.g.*, in CEU Centro), the difference between the turbines may be less significant. Turbine technology selection must be based on additional criteria, such as potential for low cost or environmental complexity.

For practical reasons, the 15 MW wind turbine technology was selected for the following analyses. As mentioned above, the choice of larger turbines with higher rated power leads to economies of scale, and a smaller number of turbines means less direct impact on the environment.



	Sc.A1 Central	Sc.A1 East	Sc.A1 Northwest	Sc.B1 Central	Sc.B1 East	Sc.B1 Northwest
🟧 10-MW	814	1,976	5,274	1,325	1,924	5,174
🟨 12-MW	456	1,106	2,912	737	1,057	2,866
🟩 15-MW	378	918	2,476	624	897	2,414

Figure 4-41. Offshore wind capacity potential in the Non-conflicting OWAs (NcOMWAs).
Note: a) Number of Turbines; b) Capacity potential [GW]
Source: The Author.

Estimating total capacity potential based on the total number of turbines improves accuracy in estimating costs, energy production, emissions reductions, and especially in estimating supply chain and logistics demand (*e.g.*, labor, marine and port logistics – loading/handling and storage). For further analysis of supply chain and logistics demand, the technology (dimensions) and number of turbines are crucial for estimating the required maritime transportation services and vessel operating hours. In addition, the dimensions of the vessels and their availability can be limited by the dimensions of the cargo, *i.e.*, the installation activities are not determined by the capacity of the wind farm but by the number and dimensions of the cargo.

Selection of turbine technology must be based on micro-siting assessments in further stages. Capacity potential analysis serve as indicative metrics at strategic planning stages.

Modeling and analysis of several technologies must be performed during strategic planning, developments, engineering and design and deployment stages.

Figure 4-42 shows an example of a technological modelling distribution considering 15 MW turbines in the Non-free offshore wind areas, zoomed in on an area close to the coast where the SCPI is high but the SESI is low.

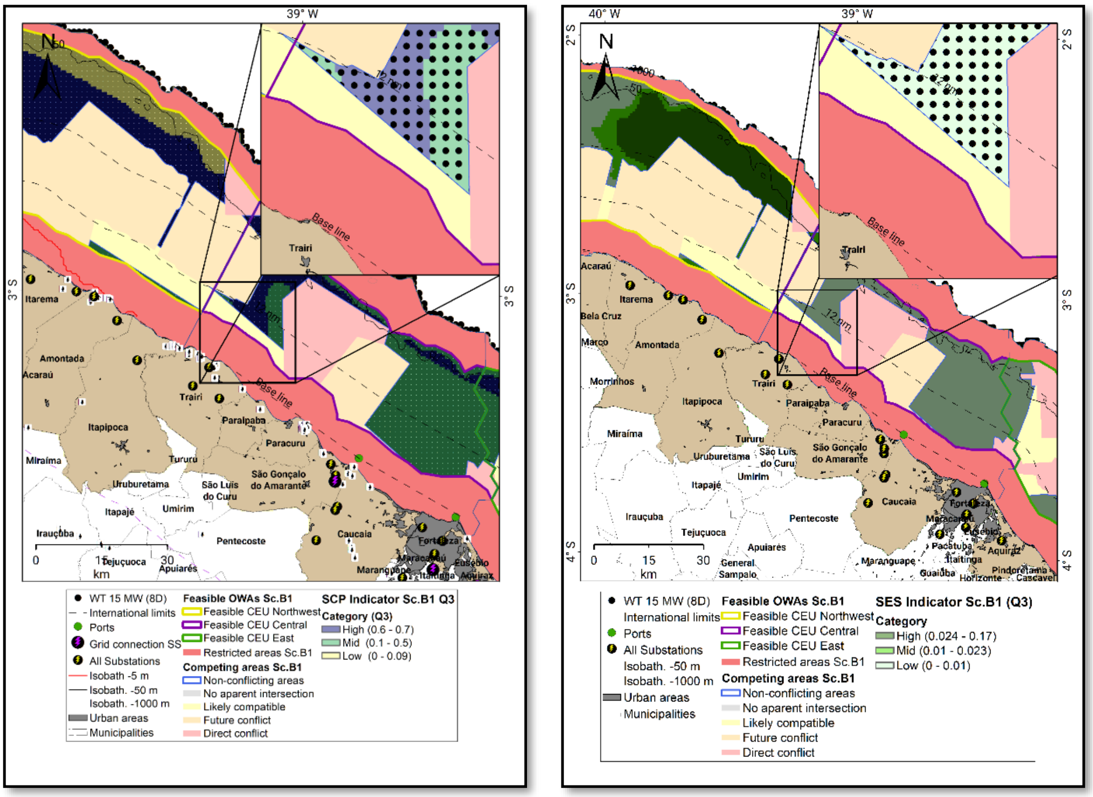


Figure 4-42. Technological modeling example: Scenario B1, 15-MW turbines, RD = 240 m; SF = 8. Note: Square layout; Spatial Cost Potential Index (SCPI); Rotor Diameter (RD); Separation factor (SF).
Source: The Author.

As mentioned in the previous section, an integrated analysis of SCPI and SESI provides additional results that can lead to better siting of wind farms or better localization of specific turbines; in addition, this information provides insights into additional environmental or economic complexity; this indicator should not be understood as limiting, but can point to complexities (*e.g.*, data gaps) that can be overcome with specific strategy design. Therefore, Figure 4-43 shows the Integrated Sustainability Indicator (SCPI normalized by SESI) in the same range as Figure 4-42, indicating low integrated sustainability for the same turbines.

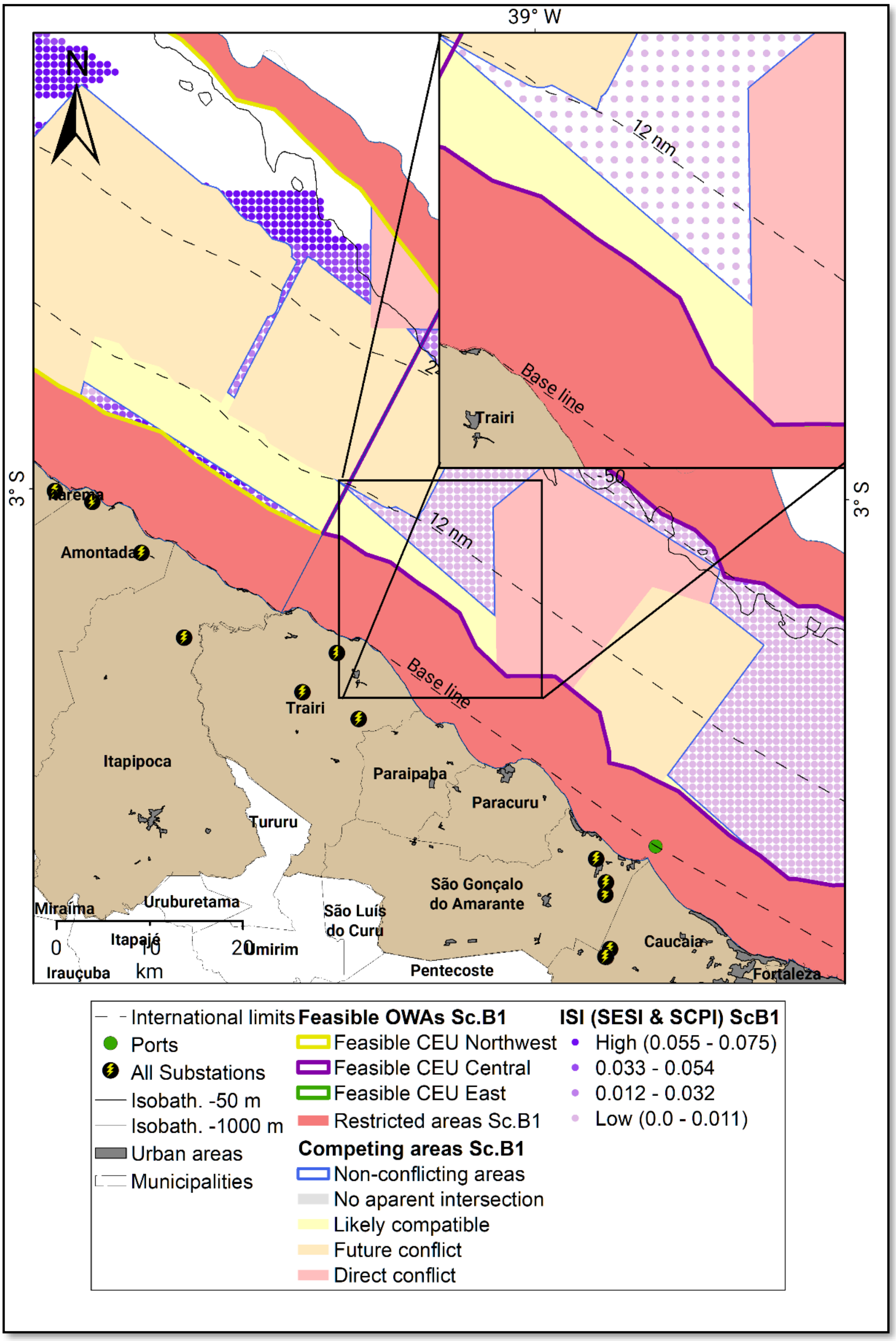


Figure 4-43. Integrated Sustainability Index based on SESI and SCPI. Source The Author.

The whole process of geospatial modeling has produced an enormous amount of data and integrated information. To summarize the key findings, Table 4-26 summarizes the overall results of the different types of offshore wind areas and their respective metrics. The resulting power densities were power density 5.8 (10-MW), 3.9 (12-MW) and 4.1 (15-MW).

Table 4-26. Results of geospatial modeling for definition of the Offshore Wind Areas.

Scenario	CEU	OWA type	Area [km^2]	Share of FeOWA [%]	Share of CZ [%]	Share of EEZ [%]	10-MW	Capacity potential [GW]	12-MW	Capacity potential [GW]	15-MW	Capacity potential [GW]
CE EEZ	Ceará EEZ	EEZ	215,978	-	-	100%	-	647,933*	-	647,933*	-	647,933*
CE CZ	Ceará CZ	CZ	55,729	-	100%	26%	23,169	232	12,915	155	10,839	163
CE CZ Central	Central	offshore	7,367	-	13%	3%	4,264	43	2,380	29	1,991	30
CE CZ East	East	offshore	12,960	-	23%	6%	7,489	75	4,169	50	3,498	52
CE CZ Northwest	Northwest	offshore	19,752	-	35%	9%	11,416	114	6,366	76	5,350	80
Sc.A1	Central	FeOWA	7,196	19%	13%	3%	4,177	42	2,324	28	1,948	29
Sc.A1	East	FeOWA	11,952	31%	21%	6%	6,925	69	3,848	46	3,233	48
Sc.A1	Northwest	FeOWA	19,162	50%	34%	9%	11,111	111	6,180	74	5,199	78
Sc.A1	Central	NcOWA	1,415	3.7%	2.5%	1%	814	8	456	5	378	6
Sc.A1	East	NcOWA	3,393	8.9%	6.1%	2%	1,976	20	1,106	13	918	14
Sc.A1	Northwest	NcOWA	9,085	23.7%	16.3%	4%	5,274	53	2,912	35	2,476	37
Sc.B1	Central	FeOWA	4,374	11%	8%	2%	2,543	25	1,410	17	1,190	18
Sc.B1	East	FeOWA	8,030	21%	14%	4%	4,655	47	2,594	31	2,173	33
Sc.B1	Northwest	FeOWA	14,955	39%	27%	7%	8,675	87	4,829	58	4,049	61
Sc.B1	Central	NcOWA	2,281	6.0%	4.1%	1%	1,325	13	737	9	624	9
Sc.B1	East	NcOWA	3,318	8.7%	6.0%	2%	1,924	19	1,057	13	897	13
Sc.B1	Northwest	NcOWA	8,922	23.3%	16.0%	4%	5,174	52	2,866	34	2,414	36

Note:)(*) Theoretical capacity potential calculated based on power density of 3 [MW/km^2]; Ceará (CE); Coastal Environmental Unit (CEU); Coastal Zone (CZ); Economic Exclusive Zone (EEZ); Feasible Offshore Wind Area (FeOWA); Non-conflicting Offshore Wind Area (NcOWA).

4.5.5 Goals and basic action roadmap for Ceará

Defining specific goals is one of the first steps in creating a clear roadmap. An integrated roadmapping approach (VISHNEVSKIY *et al.,* 2016) includes a forecast of clear target and technology characteristics to meet market needs, as well as a set of main tasks required to achieve these characteristics.

In this context, the sustainable optimization scenario (Scenario B1) in the non-conflict areas (NcOWAs), where the total capacity potential was estimated at 59,025 MW, was used as the basis for setting specific installation targets. The cumulative overall target for the state of Ceará was 11,805 MW of installed capacity by 2050, assuming 20% of the total capacity potential of the NcOWAs. This target corresponds to 12.3% of the 96 GW target in the ambitious scenario proposed by DNV & WBG (preliminary results) (2024).

This approach aimed to increase the integrated sustainability of offshore wind energy areas in the state of Ceará in the long term, using the proposed methodological framework. Geoanalytical techniques supported the compilation of an appropriate pipeline of OWF projects to consolidate an accurate selection process. Additionally, a validation of interference with other anthropic activities was performed and overlapping turbines were excluded. Ten Sustainable Offshore Wind Areas (SuOWA) were defined within the NcOWAs using geospatial assumptions and analytics techniques (see Appendix E), including different OWF scales, from demonstration to mega-scale variants. Table 4-27 lists a number of SuOWAs and the characteristics that were used to define the areas in order to reach the final target of 10.7 GW installed capacity.

Table 4-27. Geospatial assumption to limit the offshore wind project pipeline.

SuOWAs	Dist. to installation port [km]	Dist. To shore [nm]	Water depth [m]	15-MWTs	Installed capacity target [MW]
SuOWF-1	< 35	< 12 nm	< 20	4	60
SuOWF-2	< 36	< 12 nm	< 40	25	375
SuOWF-3	< 37	> 12 nm	< 40	43	645
SuOWF-4	35 - 70	< 12 nm	< 40	38	570
SuOWF-5	35 - 70	12 - 24 nm	< 60	199	2,985
SuOWF-6	100 - 200	< 12	< 20	210	3,150
SuOWF-7	70 - 100	< 12 nm	< 20	59	885
SuOWF-8	70 - 100	12 - 24 nm	< 40	12	180
SuOWF-9	100 - 200	12 - 24 nm	20 - 40	111	1,665
SuOWF-11*	< 70 km	> 24 nm	60 - 80	17	255
			Target	**718**	**10,770**

Note: number does not prioritize the (*) represents a suitable area for piloting floating offshore wind project.

Source: The Author based on Based on IOANNOU (2018a, 2018b, 2018c); BOSCH (2018); LAZER DOS REIS (2021).

Figure 4-44 shows the distribution of SuOWAs in the coastal zone of the state of Ceará. This first proposal aimed to achieve a sustainable target for offshore wind development rather than maximizing the installation of OWFs on the entire available area.

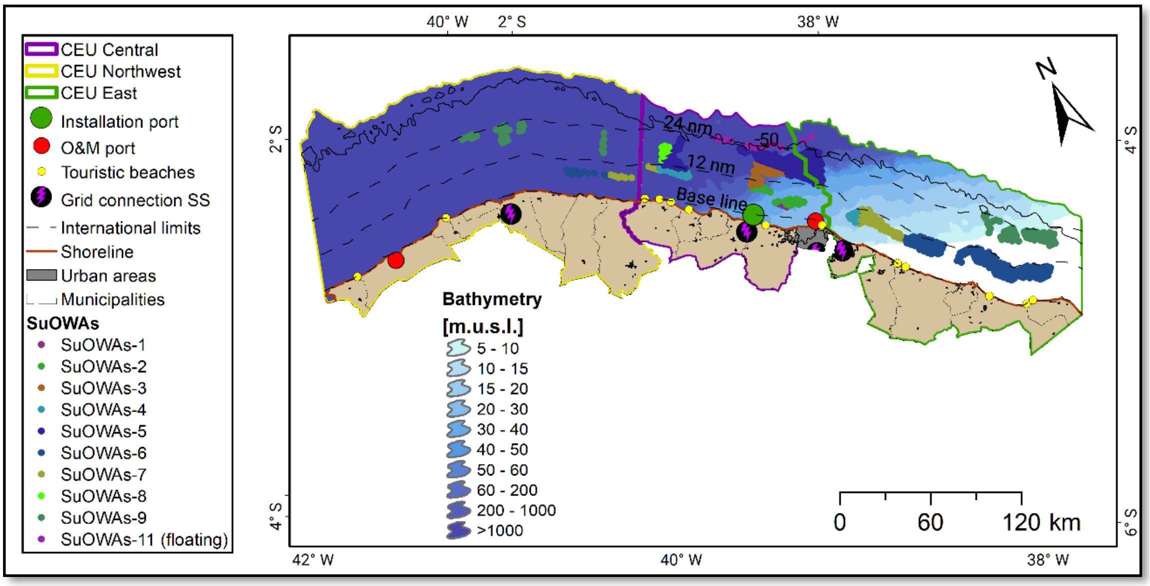


Figure 4-44. Offshore Wind projects pipeline (ONE COLOR) in the State of Ceará. Source: The Author.

As observed in this figure, the boundaries of the Coastal Environmental Units indicates the context and can determine the approach to strategic actions for offshore wind development in each unit. For example, actions in the Central CEU should focus on avoiding conflicts with other human activities, particularly maritime traffic and potential impacts on coral reefs or interference with Prioritized Areas for Conservation (APCBs). Actions in CEU East should address the environmental complexity associated with coral reefs and the extremely high priority for conservation; actions should be taken in this unit to reconcile offshore wind power with industrial fishing and protection of the marine environment. CEU Northwest has the lowest environmental complexity. However, industrial development is sparse and far from the installation port (with Porto do Pecém assumed to be the closest installation port), which could increase complexity and costs. Therefore, system readiness development strategies (installation ports, grid connection and supply chain) should be developed first to set the stage for the development of large-scale offshore wind projects.

Finally, the SuOWAs alternatives were prioritized using the integrated sustainability optimization analysis (SESI versus SCPI). Table 4-28 shows the SuOWAs prioritized by the integrated sustainability optimization analysis, where SuOWA-8 with 180 MW installed capacity, 12 turbines of 15 MW, an average wind speed of 8.2 m/s and an average bathymetry of 34.6 m.u.s.l. had the best score (0.311).

Areas SuOWA-1, SuOWA-2 and SOWA-3 had the worst scores (0.135). These areas are closest to the port. Nevertheless, as already mentioned, this region is the more complex area due to the density of human activities and the presumed complexity of the environment.

Table 4-28. Prioritization strategy for offshore wind development in the state of Ceará under Sustainable Optimization Scenario (Scenario B1).

SuOWAs	Area [km^2]	15-MW turbines	Installed Capacity [MW]	Mean Wind Speed at 150m [m/s]	Mean CF (IE1)	Potential AEP* [MWh]	Mean Bathymetry [m.u.s.l.]	Mean SESI ScB1	Mean SCPI ScB1	Mean ISOI ScB1	OWF scale
SuOWA-8	44.2	12	180	8.20	0.45	712,059	-34.59	0.000	0.622	0.311	Small commercial
SuOWA-9	409.2	111	1,665	8.51	0.48	7,072,824	-25.37	0.003	0.577	0.290	Full commercial
SuOWA-7	217.5	59	885	8.07	0.43	3,368,552	-14.99	0.001	0.554	0.278	Small commercial
SuOWA-4	140.1	38	570	8.15	0.44	2,213,693	-17.58	0.000	0.481	0.240	Small commercial
SuOWA-11	62.7	17	255	8.42	0.48	1,066,857	-67.09	0.000	0.454	0.227	Pilot
SuOWA-5	733.6	199	2,985	8.33	0.46	12,151,368	-34.13	0.000	0.300	0.150	Full commercial
SuOWA-6	774.1	210	3,150	8.42	0.47	12,919,200	-13.03	0.001	0.274	0.137	Large commercial
SuOWA-3	158.5	43	645	8.42	0.48	2,702,415	-30.35	0.000	0.270	0.135	Small commercial
SuOWA-2	92.2	25	375	8.39	0.48	1,569,113	-23.64	0.000	0.269	0.135	Small commercial
SuOWA-1	14.7	4	60	8.40	0.48	252,892	-18.70	0.000	0.269	0.135	Pilot
Total	2,646.8	718	10,770	8.36	0.47	44,028,973	-24.27	0.001	0.372	0.204	

Note: *Potential AEP is calculated as indicative values considering the Eq. 3-1 and spatial Capacity Factor provided by the Global Wind Atlas (2018); Sustainable Offshore Wind Area (SuOWA); Capacity Factor (CF); Annual Energy Production (AEP); Spatial Environmental Suitability Index (SESI); Spatial Cost Potential Index (SCPI); Integrated Sustainability Index (ISOI).

Source: The Author.

4.5.6 Sensitivity analysis of spatial and technological modeling

The sensitivity analysis analyzed the sensitivity of the modeling to different variables and parameters that affect the geoprocessing results. Subsequently, two sensitive input variables and parameters were tested for scenario B1, leaving the remaining inputs without variation.

Typically, multi-criteria assessment models and scenario planning approaches are more sensitive to certain assumptions. The complexity and the large number of variables are probably the causes of this phenomenon. In this regard, the sensitivity analysis focused on evaluating the sensitive parameters of the spatial modeling variables. Table 4-29 summarizes the selected sensitivity analysis.

Table 4-29. Selected sensitivity analyses.

Sensitivity analyses	Type	Criteria	Value
Constraint Mapping	Input spatial variable	Offshore average wind speed quality	5000x5000 (CEPEL,
Technological modeling	Technology selection	Turbine model	190 m

Source: The Author.

4.5.6.1 Constraint mapping – input of offshore wind resource data

For the sensitivity of the spatial input variables, the data from CEPEL (2017) for the mean wind speed (offshore wind resources) was used as input instead of the data from the Global Wind Atlas (2018). Figure 4-45 shows the offshore wind resources from the Global Wind Atlas (a) and CEPEL (b) in the study area. The variations in the input data were associated with higher values of maximum average wind speed. CEPEL data reached maximum values of more than 9.6 m/s in a large area from Barroquinha to Itapipoca (Northwest macro-region). In contrast, the data from Global Wind Atlas only reached maximum average wind speeds of between 9.0 and 9.5 m/s in the coastal area off the municipalities of Camocim and Barroquinha.

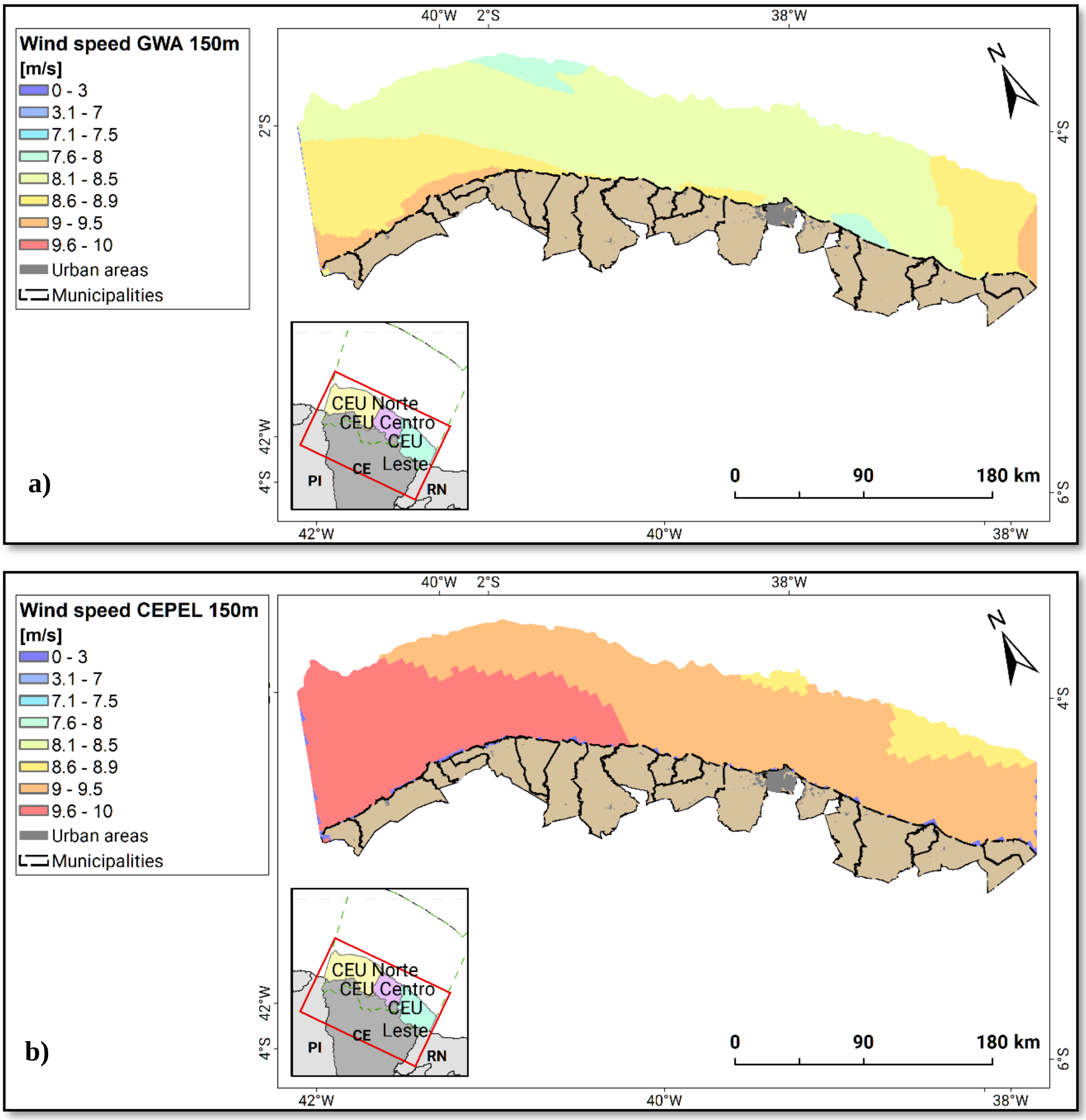


Figure 4-45. Offshore Wind Resource at 150 m height.
Note: a) Data from the Global Wind Atlas; b) Data from Cepel.
Source: CEPEL (2017); Global Wind Atlas (2019).

Nevertheless, the output modeling under the assumptions of Scenrio B1 was not sensitive to variations in the input data, as shown by Figure 4-46. The difference between Feasible OWAs was less than 2%, 27,359 km^2 versus 27,315 km^2 (Scenario B1 with CEPEL wind speed data).

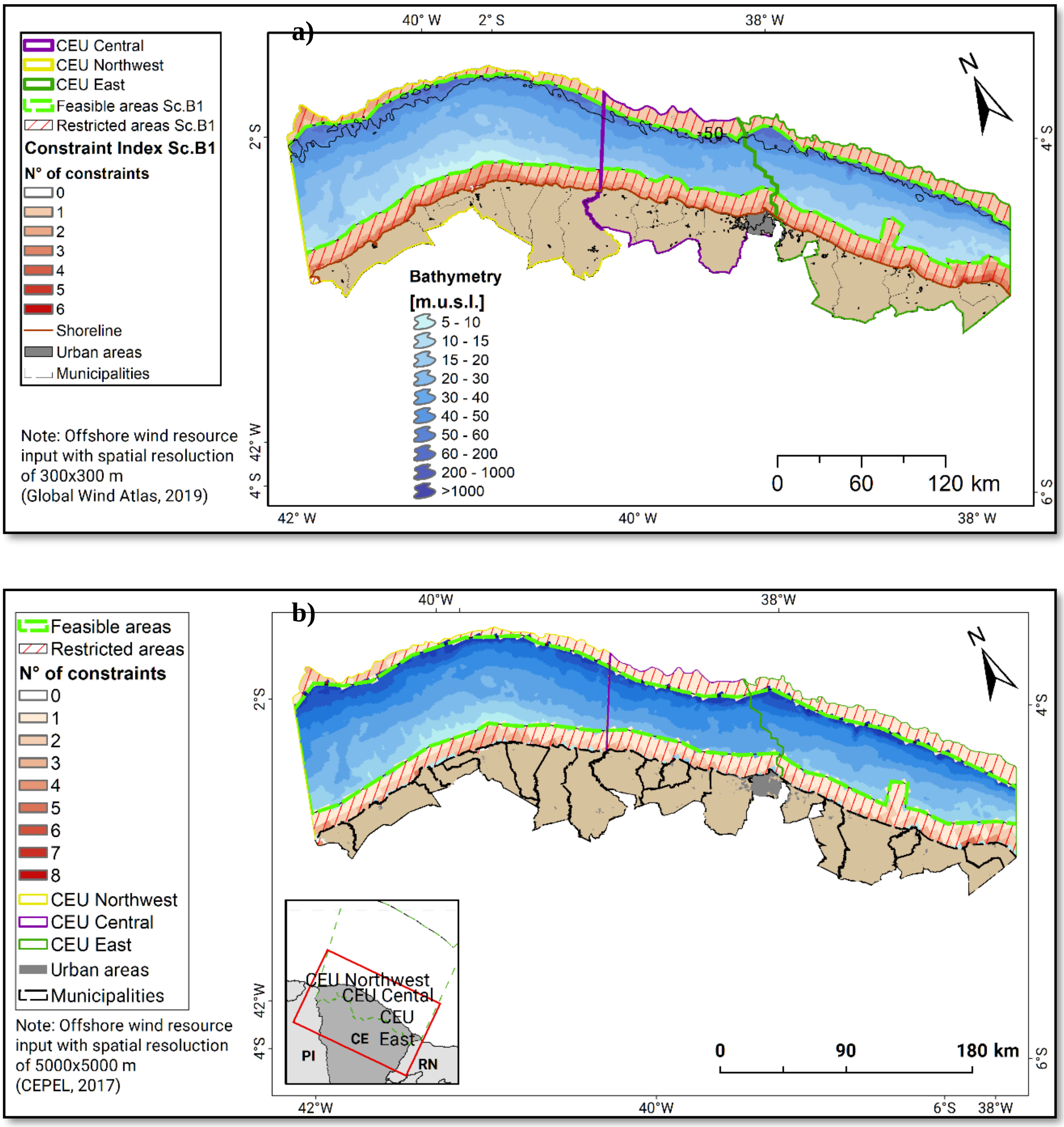


Figure 4-46. Feasible Offshore Wind Areas using different offshore wind resource data.
Note: a) FeOWAs using data from Global Wind Atlas (2019); b) FeOWAs using data from CEPEL (2017).
Source: The Author.

4.5.6.1 Technological modeling – rotor diameter 190m

Considering the technological development, the technical characteristics of offshore wind turbines have changed significantly in recent years and through manufactures. A technological analysis was performed, estimating the total installed capacity of CEU Central's proposed NcOWA with the 10 MW SeaTitan turbine, which has a 190 m rotor diameter, compared to the 10 MW MHI Vestas turbine with a 164 m rotor diameter. A separation factor of 8 times the rotor diameter was considered in both models. Table 4 30 shows the variations in the number of turbines and the total installed capacity.

Table 4-30. Variation of total installed capacity between 10-MW turbines in the NcOWA of CEU Central for Scenario B1.

Turbine model	RD [m]	N° of. Turbines	Installed capacity [MW]	Power density [MW/km^2]
MHI Vestas V164-10.0 MW	164	1,325	13,250	5.8
SeaTitan 10-MW	190	983	9,830	4.3

Source: The Author.

The results showed significant differences in installed capacity, with the total capacity potential of the SeaTitan turbine being 26% lower compared to the MHI Vestas in the same area. These estimates serve as insights into strategic stages to select technological alternatives to be evaluated in the micro-siting stage, as the technological characteristics influence the optimization of energy production and supply chain demand assessment for final decision making. Accurate selection of the most suitable technology reduces the time and resources required.

4.6 Analysis of the strategic planning scenarios for the state of Ceará

This section presents the main results of the comparison of the modelling of the different scenarios. The analyses focused on three main results: Total area, capacity potential and number of turbines suitable for different types of offshore wind areas in the marine areas of the state of Ceará.

The total marine area (EEZ boundary) of the state of Ceará was estimated at 215,978 km^2, with the total area of the offshore coastal zone (bounded by 1,000 m.u.s.l.) estimated at 40,079.3 km^2, 18% of the total area.

Taking into account the offshore area of the Coastal Environmental Units and 15 MW wind turbines, a total of 11,350 turbines could be installed in this area, assuming a standard offset between turbines of 8 rotor diameters in a square layout. This corresponds to a theoretical potential of 163 GW up to a height of 1,000 m.u.s.l.

After applying the constraint mapping analysis, the feasible area (FeOWA) in Scenario A1 decreased to 38,310 km^2, which corresponds to nearly the entire offshore coastal zone (17.7% of the marine zone). In Scenario B1, on the other hand, the feasible area (FeOWA) fell to 27,359 km^2 (13% of the marine area).

In turn, applying the analysis of competition for marine use, the non-conflict areas (NcOWA) of Scenario A1 became slightly smaller (13,893 km^2) than in Scenario B1 (14,521 km^2). There were fewer technical restrictions in Scenario A1 than in Scenario B1, but the current legal framework defines conflicts between offshore wind projects, which leads to a reduction in Non-free offshore wind areas. This deviation shows the importance of setting appropriate assumptions for competition. The regulatory framework must consider current and future competition trends between different and equivalent activities to avoid increasing conflicts.

The scenario planning approach makes it possible to vary the assumptions of the competition to reflect the likely outcomes in the real world. Simulating future conflicts during the strategic planning process for offshore wind development can support the development of strategies to avoid conflicts and potential compatibility between projects or activities.

Overall, the capacity potential in the NcOWAs in Scenario A1 and B1 showed interesting values for all CEUs, ranging from 5 GW (12 MW turbines) in the CEU Central to a maximum of 53 GW (10 MW turbines) in the CEU Northwest - both values in Scenario A1. Comparing the high values between the scenarios, the deviation was less than 1 GW in the Northwest and East CEUs (see Figure 4-41). However, when the area decreased, as in CEU Central, the difference in capacity potential was at least 62% higher in Scenario B1 considering all technologies.

The power density did not vary between the scenarios, as technological modeling maintains the same offset between the turbines. However, the power density was higher than the theoretical values. This could be due to the fact that technological modeling does not take into account the distance between the projects, so turbines must be avoided to prevent impacts on the energy production of the neighboring projects. The power density will decrease after defining the buffer zone between the projects according to the results of BOSCH (2018), an initial power density (3.14 MW/km^2) can decrease to 0.97 MW/km^2 if considering buffering of wake effects is taken into account.

When comparing the technologies evaluated, 10 MW turbines reached 5.8 MW/km^2 (10 MW turbine with 164 m rotor diameter), but dropped to 4.3 MW/km^2 when a 10 MW turbine with 190 m rotor diameter was modeled. This value remains higher than the power density of the 12 MW (3.9 MW/km^2) and 15 MW turbines modeled. the 12 MW turbines showed the lowest performance in terms of power density.

A target of 10.7 GW of installed capacity by 2050 set for the coastal zone of Ceará proved to be competitive compared to the preliminary results of the study on offshore wind development scenarios in the Brazilian EEZ (DNV, WBG, 2024), which defines three target scenarios by 2050: a) Base case with 16 GW, b) Intermediate with 32 GW and Ambitious with 96 GW. This shows that it is possible to set competitive and more realistic targets if a robust methodology (with an ecosystem-based approach) is applied. Contrary to the speculative trend of filling the entire available coastal space of states with offshore wind projects, offshore wind development must aim for regional and integrated development. Optimizing sea space allows efforts to focus on offshore wind deployment, supporting infrastructure and supply chain, based on clearer and more reliable strategies.

For example, prioritizing a pilot project such as SuOWA-1 or SuOWA-11 may be an appropriate strategy to test environmental, social and economic challenges and supply chain bottlenecks in an area where there are no conflicts or direct constraints. Furthermore, defining several sustainable OWAs available for different project sizes and increasing their sustainability has shown the versatility of the methodological framework for defining different non-monetary criteria within a competitive leasing process.

The possibility of including different technologies in the analysis, allows the modeling of alternative scenarios, which may include pilot projects or large-scale offshore wind projects. This feature aims to define strategies to reduce the high costs, but also to consider considering potential socio-environmental impacts and the possible participation and acceptance of society, as suggested by MÖLLER *et al.*, (2012).

Chapter 5 – Impact on Planning Policies and Developer Strategies

This chapter focuses on describing the implications of the methodological framework based on GIS technologies and analytics to support the strategic planning process for offshore wind energy (OWE) development from a policy or developer perspective beyond the case study. First, Section 5.1 highlights the originality of the methodological framework compared to previous studies in Brazil and internationally. Section 5.2 examines the impact of the implementation of the SPOWER-BR methodological framework on public policies for the expansion of OWE in Brazil and identifies policy gaps as an opportunity to strengthen the current regulatory framework. Finally, Section 5.2 discusses a strategic planning process that an offshore wind developer can use to improve the development phase and permitting process in order to develop strategies to overcome the regulatory framework requirements.

5.1 Originality of the methodological framework

The current methodological framework integrates multiple elements and complex analysis into a structured and robust geospatial analytical process that aims to improve the strategic planning process of offshore wind energy from the early stages (conceptualization) to the local scale analysis. This approach aims to improve the vertical integration between policies, plans, programs and projects.

The first challenge was to overcome the vast expanse of marine space and to understand the dynamics between the marine environment and human activities. The gap in strategic planning of marine space (Marine Spatial Planning or Strategic Environmental Assessment), which is common in developing and emerging countries, is a bottleneck for the planning and development of activities that utilize marine resources such as offshore wind energy.

Therefore, the integration of Marine Spatial Planning and Strategic Environmental Assessment concepts and procedures using spatial multi-criteria modeling techniques and geoanalytics into a semi-automated Decision Support System is still rare. In contrast to the findings of Schillings *et al.,* (2012), most tools and approaches for emerging countries cover a large extent of areas (*e.g.,* the Brazilian EEZ), with few variables, and none focus on detailed and integrated approaches that analyze local scales (when considering a continental country such as Brazil).

In Brazil, many studies have focused on estimating the offshore wind potential along the coast. The main studies have estimated the gross potential in different regions, such as PIRES *et al.*, (2020) in the southern region, DE ASSIS TAVARES *et al.*, (2020) and GOMES *et al.*, (2019) in the southeastern region or PIMENTA *et al.,* (2019), which include the temperature parameter to model the variation in air density, with the aim of estimating the wind resource in the entire Brazilian EEZ with greater accuracy. However, most of them lack strategies for reducing the scales of the analysis in an integrated and sustainable approach.

The proposed methodology integrates more than 35 spatial criteria in strategic decision making, focusing on the offshore wind industry. The semi-automation of the process does not affect the time spent during the assessments (SIMÕES *et al.,* 2023). The current framework guarantees the baseline geodatabase specifically targeting OWE, which is an additional innovation compared to previous studies. Furthermore, the strategic criteria and spatial planning procedure were selected considering an ecosystem-based approach to identify a sustainable installed capacity that can be installed in the future, as proposed by CASTRO-SANTOS *et al.,* (2019), contributing to ambitious national installation targets for this energy source.

As SIMÕES *et al.,* (2023) stated, the compilation of an interactive tool that increases replicability is an innovation. This is the case of the GIS-SPOWER-BR Toolbox within the state of the art in decision support systems focused on offshore wind development in the Southern Hemisphere. Most of the studies developed in Brazil such as DE ASSIS TAVARES *et al.*, (2020); DE AZEVEDO *et al.*, (2020); DOS REIS *et al.,* (2021); VINHOZA & SCHAEFFER (2021b); VINHOZA, SCHAEFFER, *et al.,* (2022) have estimated the energy potential based on the analysis of a technology and scenarios with few variables. On the other hand, studies such as NOGUEIRA *et al.,* (2023) have discussed the regional behavior of the electricity system considering the integration of offshore wind energy into the energy distribution subsystems, focusing only on the energy planning point of view. Consequently, their results show an outlook on a static situation.

In the international context, GIS-based decision support systems exist in several developed countries. These systems have been developed to improve the performance of strategic planning of offshore wind energy. These studies include BEITER, *et al.*, 2016 in the USA; OU *et al.*, 2018 in China; SCHILLINGS, et al (2012) in the North Sea; or SIMÕES *et al.*, (2023) and CASTRO-SANTOS et al (2019) in Portugal.

These approaches are not directly applicable to the Brazilian or Latin American context due to the geographical region in which they are implemented. In this respect, the GIS-SPOWER-BR methodological framework is the first integrated GIS-based decision support system for offshore wind energy development in an innovation market of an emerging economy in the Southern Hemisphere. According to TOLMASQUIM *et al.,* (2022), the development of local technologies, including computational tools, is an important prerequisite for the development of the offshore wind energy industry supply chain.

The main difference of the proposed framework is that it can integrate a large set of spatial input variables through the application of constraint mapping, analyze sea-use competition, and model detailed environmental and cost drivers within a cross-technology and robust scenario planning approach. The advantage of using the GIS-SPOWER-BR framework is that several previous studies can be replicated using the GIS-SPOWER-BR framework to complement them within an integrated sustainable modeling framework. Results from other studies such as MAGRIS *et al.,* (2021) on spatial data on marine biodiversity, LEMOS *et al.,* (2023) on ecological niche modeling of seabirds or DOS REIS *et al.,* (2021) on the LCOE of offshore wind energy can be used as spatial input variables for modeling further scenarios.

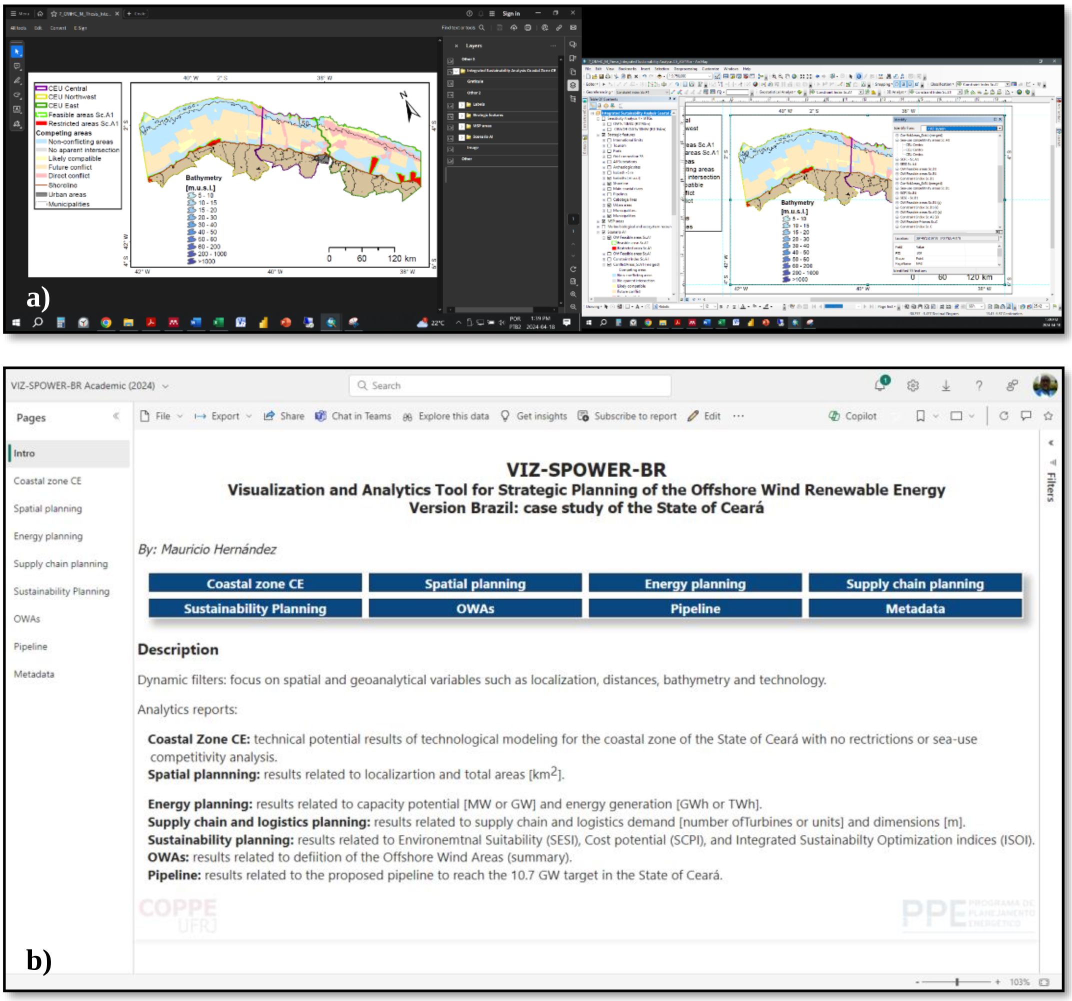
In addition, the outputs of the framework enable the consultation of different materials by different stakeholders. Figure 5-1a shows maps in PDF format (left), which can support social cartography in consulting local communities; the MXD format (right) can support specialized consultants and analysts. Both formats allow consultation of layers, overlay areas and strategic features. Figure 5-1b show the VIZ-SPOWER-BR, a dynamic analytics dashboard that consolidates results into a business intelligence platform to support executives and managers in strategic planning of offshore wind energy development.

In this context, the first application of the proposed methodology is to support the definition of offshore wind areas as part of a robust approach based on sustainable development and ecosystems. In addition, the results can support policy makers in prioritizing strategies and measures to be implemented in the short, medium and long term. These strategies may vary depending on the regional geographical context, as suggested by the mapping of key drivers and competition for marine use.

The GIS-SPOWER-BR Toolbox can be integrated or progressively linked to other WebGIS tools such as IBAMA's PAMGIA WebGIS, ANEEL WebGIS, ONS WebGIS, EPE WebGIS, Offshore Wind Data Panel and BiodivEPE. Even more important is the link with the PUG-Offshore (Portaria Interministerial MME/MMA 03-2023), which has been proposed as the official platform for managing the process of offshore wind projects.

Consequently, the GIS-SPOWER methodology, tools and results can be integrated into data-driven decision making to support the definition of offshore wind areas, installation targets, competitive leasing processes or the evaluation of independent concession bids (public sector). Private project developers can identify potential projects or evaluate current conceptual projects to prioritize them according to their particular strategic interests.

A multidisciplinary group of strategic stakeholders can exploit the potential of the GIS-SPOWER-BR framework. Figure 5-2 lists the strategic stakeholders that should participate during the strategic planning process with the support of the GIS-SPOWER methodological framework. It is emphasized that local communities can be involved in the strategic planning process since the conception of the offshore wind projects. Involving local communities in the strategic planning scenarios and parameters – which is reflected in the social cartography of constraints and land use competition – is a suitable strategy to improve the strategic planning process and increase the sustainability of offshore wind projects.



VIZ-SPOWER-BR
Visualization and Analytics Tool for Strategic Planning of the Offshore Wind Renewable Energy
Version Brazil: case study of the State of Ceará

By: Mauricio Hernández

Description

Dynamic filters: focus on spatial and geoanalytical variables such as localization, distances, bathymetry and technology.

Analytics reports:

Coastal Zone CE: technical potential results of technological modeling for the coastal zone of the State of Ceará with no rectrictions or sea-use competitivity analysis.
Spatial plannning: results related to localizartion and total areas [km^2].

Energy planning: results related to capacity potential [MW or GW] and energy generation [GWh or TWh].
Supply chain and logistics planning: results related to supply chain and logistics demand [number ofTurbines or units] and dimensions [m].
Sustainability planning: results related to Environemtnal Suitability (SESI), Cost potential (SCPI), and Integrated Sustainabilty Optimization indices (ISOI).
OWAs: results related to defiition of the Offshore Wind Areas (summary).
Pipeline: results related to the proposed pipeline to reach the 10.7 GW target in the State of Ceará.

Figure 5-1. GIS-SPOWER-BR as an interactive Decision Support System for the development of Offshore Wind Energy in Brazil.
Note: a) GIS multi-layer mapping (*.pdf format, left and *.mxd format, right); b) VIZ-SPOWER-BR analytics dashboard.
Source: The Author.

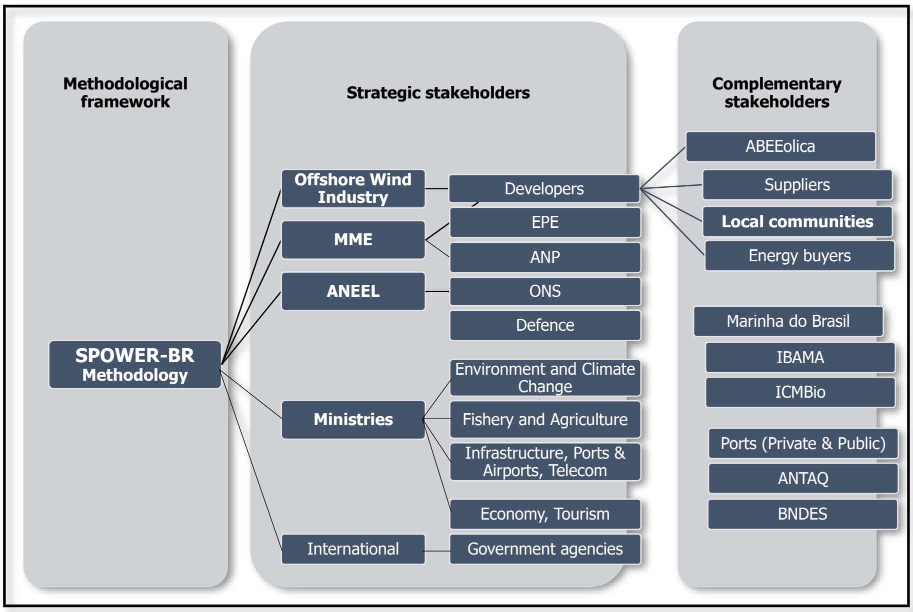


Figure 5-2. Impact on strategic stakeholders.
Note: Suppliers must involve as many suppliers as possible at the various levels of the supply chain (see Figure 2-24).

In the following sections, the impact of implementing the GIS-SPOWER-BR methodological framework on policy design, strategy and roadmapping is explained in more detail.

5.2 Impact on policy making – Public sector

This section identifies the potential implications for the policy-making process in relation to the strategic planning and development of the offshore wind energy sector, focusing on the Brazilian regulatory framework. It addresses the main gaps in the current regulatory framework and strategic planning process that have resulted from the implementation of the GIS-SPOWER-BR framework.

The current roadmap for offshore wind (version 1 and 2) (EPE, 2020b; EPE, 2022) indicates an installed capacity of 700 GW for the Brazilian coast below 50 m.u.s.l. However, no clear targets or development goals are defined in this study. When estimating the capacity potential, only protected areas, wind resources and bathymetry are taken into account as technical and environmental constraints.

The latest update of the Offshore Wind Roadmap (EPE, 2020b) emphasizes the importance of considering the analysis of conflicts in marine space to improve the planning process of this technology. The Global Wind Energy Council – GWEC (ZHAO *et al.*, 2022) also emphasizes the importance of developing marine spatial planning studies to support decision-making and auctioning of offshore wind energy in developing countries. However, the Marine Spatial Planning studies will not be published until 2026. The roadmap document does not include an analysis of competition for ocean use to estimate the capacity potential of offshore wind energy in the Brazilian EEZ or to set approximate development targets.

On the other hand, the preliminary results of the study Scenarios for Offshore Wind Development in Brazil (DNV, WBG, 2024) define three development scenarios: Base case (16 GW), Intermediate (32 GW) and Ambitious (96 GW). However, the background supporting the estimation of these targets is not clearly explained. Although the ten-year plan for the expansion of energy supply (MME, EPE, 2022) envisages an installed capacity of 16 GW by 2025, assuming a 20% reduction in CAPEX, the distribution in the marine space remains uncertain.

The GIS-SPOWER-BR framework has been tested in a real context to validate scenarios and model real assumptions for offshore wind development based on internationally known assumptions for target and strategy setting. Therefore, this framework can contribute to the Brazilian offshore wind roadmapping and support the strategic process of EPE, ANEEL and the MME. These tasks include the estimation of capacity potential, the definition of targets and the location of installations in the marine space. This process can also be carried out per region or state, depending on the level of detail of the desired analysis. The GIS-SPOWER-BR framework is able to scale down the analyses and strengthen the current process, while being compatible with the development of marine spatial planning or strategic environmental impact assessment.

With regard to the current specific legal framework, three instruments focus on the regulation of offshore wind energy in Brazil. These are Decree No. 10.946-2022 (PR, 2022), Portaria Normativa GM/MME No. 52-2022 (MME, GM, 2022) and Portaria Interministerial MME/MMA No. 3-2022.

The GIS-SPOWER-BR is compatible with the current regulatory framework, since the variables and criteria (restrictions and multi-use or marine space) included in the regulatory framework consider the spatial information required in the Previous Interference Disclosure (DIP) (Decree No. 10,946, Art. 10). Subsequently, the process of issuing the DIPs can be automated using the GIS-SPOWER-BR Toolbox. In addition, the application of the entire framework for the definition of offshore wind areas (in Portuguese Offshore Wind Prismas), including the construction of robust scenarios, can improve the planning concession system through the modeling of offshore wind areas, incorporating the disclosure of public consultation (Decree No. 10.946, Art. 12 - 13).

The application of the GIS-SPOWER-BR framework may enhance the independent concession system, as the results of geospatial modeling include details of the georeferenced area (Decree No. 10.946, Art. 14 - 16). In addition, the information provided by turbine future ensures greater robustness and transparency of the process. In addition, the results can provide input data for determining the energy potential of the required offshore wind area (Decree No. 10.946, Art. 18).

The procedures defined in Portaria Normativa No. 52-2022 for the calculation of royalties and penalties in the independent and planned concession systems can now be supported by the use of results from the modeling of offshore wind areas by the GIS-SPOWER-BR framework. The results are of particular use for Article 11, which requires the delimitation of a maximum area to be granted, and Article 13, which establishes the criteria of preliminary viability including proximity to other activities and minimum distance from the coast (see detailed criteria in Portaria Normativa No. 52-2022, Art. 13).

GIS-SPOWER-BR and VIZ-SPOWER-BR have a high potential to be integrated into the services of the unique portal for offshore wind energy management (Portuguese PUG-Offshore), providing developers with strategic insights into offshore wind areas and consolidating the geo-referenced information submitted by developers, following an organized approach and facilitating management and transparency (Portaria Interministerial MME/MMA No. 3-2022, Art. 1).

In relation to the project laws dealing with the regulation of offshore energy production (PL 5932-2023, PL 547-2021, 484-2017), PL 5.932-2023 consolidates the content of the previous project laws. The benefits of implementing the GIS-SPOWER-BR framework to support the strategic planning process for offshore wind energy development could include:

- Considering the international boundaries of the marine domain: territorial waters, contiguous zone and exclusive economic zone (Art. 3).
- Implementation of the strategic planning process, taking into account the principle of sustainable development (Art. 4, I) and the possibility of exploring different and new technologies to reduce greenhouse gas emissions (Art. 4, IV).
- Possibility of supporting permanent supply (independent concession scheme) and planned supply (planned concession scheme) in the short, medium and long term (Art. 5).
- Definition of offshore wind areas to avoid potential conflicts with other human activities (Art. 6).
- Support the definition of offshore wind areas through marine spatial planning and environmental authorization for these areas (Art. 6, No. 9).
- Guidance and standardization of studies supporting the expression of interest for a permanent offer (Art. 7).
- Guidance in the definition of requirements and non-monetary criteria to be met by developers (Art. 8).
- Support the integration of environmental studies, programs, plans and policies that influence the definition of offshore wind areas (Art. 9, No. 1).
- Provide details about the offshore wind area, findings to determine the assessment criteria and weighting factors, and requirements to promote the national industry (Art. 9, No. 3).

- Support the assessment phase (pre-development and development) and studies to determine the viability of the project (Art. 11, No. 1, I, III, IV; No. 2, No. 3).
- Guidelines on the establishment of measures to protect natural resources, maritime safety and the environment 9Art. 12).
- Optimization of the area occupation rate in R\$/km^{2} (Ar. 13, II).

Finally, the pre-processing and validation of the data for the study area in the case study identified spatial data gaps relating to the following:

a) Local data on offshore wind resource data or meteorological stations supporting micro-siting and detailed estimates of energy production.
b) Large gaps in empirical and raw data on endangered species, endangered species distribution and habitats for offshore wind activities.
c) Detailed data on strategic features such as port readiness levels; data related to available margins for future transmission and grid connection.
d) Consolidated database supporting integrated offshore wind assessment and planning.

In short, Figure 5-2 summarizes the strategic planning, permitting and approval processes that the GIS-SPOWER-BR can strengthen.

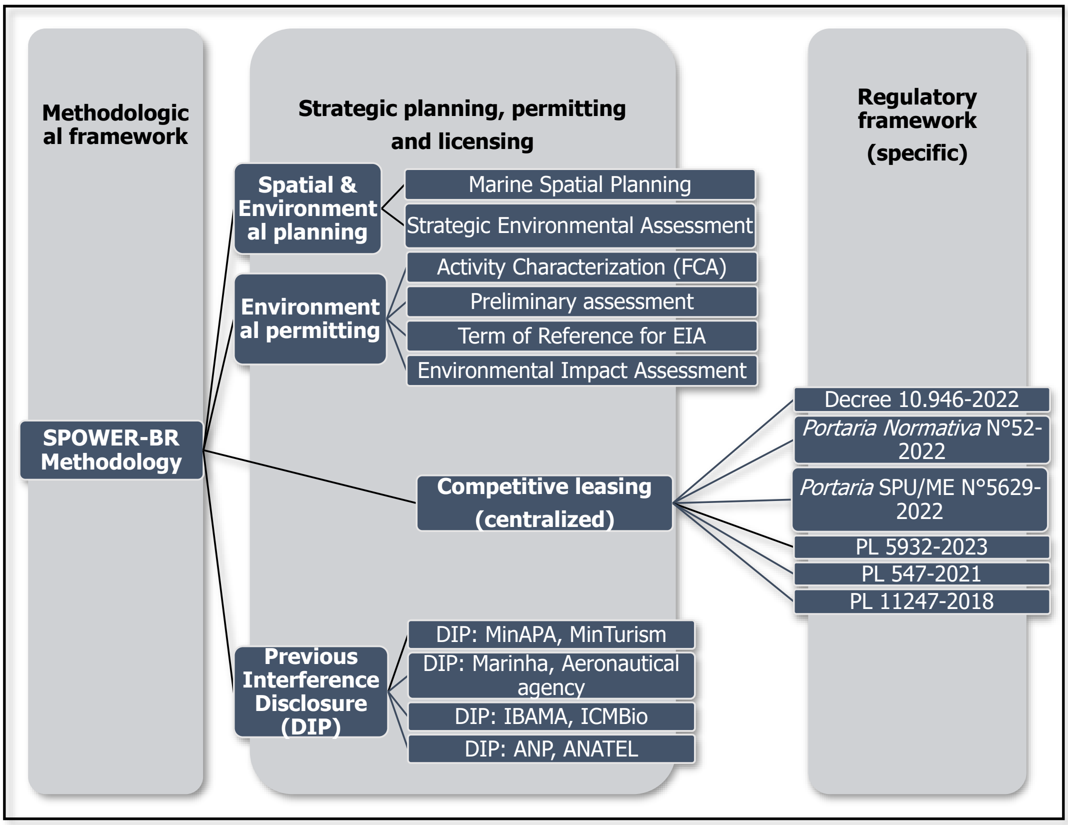


Figure 5-3. Impact on institutional pre-development processes: strategic and environmental planning, Competitive leasing (centralized), Environmental Licensing a permitting, leasing and auctioning.

5.3 Impacts on development strategies – Private sector

Gaps in targeting offshore wind energy have led to disorganized planning of offshore wind energy in Brazil.

As a result, conceptual projects for offshore wind farms have reached a potential installed capacity of 234 GW. The expansion of current projects does not reflect a realistic vision of offshore wind energy, as the number of projects can lead to conflicts with other marine activities. The number of overlapping areas will lead to sea-use conflicts among projects, requiring more complex solutions.

Private developers may enhance their decision making for the development of an offshore wind farm by considering feasible, non-conflicting and sustainable offshore wind areas. Pre-development and development activities (GONZÁLEZ *et al.*, 2020) that can be supported by the GIS-SPOWER-BR framework include:

- Adding a large amount of data (primary or secondary) from other environmental impact statements or strategic studies (*e.g.*, marine spatial planning or strategic environmental assessment).
- Supporting preliminary studies to submit to the Brazilian Institute of Environment and Renewable Natural Resources – IBAMA (*e.g.*, the FCA) by analyzing different site and technology alternatives with detailed results on required area and turbine technology (IBAMA, 2020).
- Improving the definition of the offshore wind farm area to request the Previous Interference Disclosure (DIP) from the public agencies involved.
- Integrating detailed data from environmental, geophysical and geotechnical studies.
- Incorporating the results of public consultation in the strategy (siting) and project development stages (EIA).
- Compliance with the requirements of the current and future legal framework in Brazil within the framework of the principle of sustainable development.

Results showed that the offshore wind suitability areas overlap with some of the current projects, validating the site selection using information from more than 35 spatial variables from official public sources. Marine use maps and non-free offshore wind areas are used to guide the strategy for compatibility and negotiation with other stakeholders. Feasible offshore wind areas show that parts of several projects overlap and provide insight into the absolute constraints on rearranging the wind farm layout. Finally, the turbine modeling approach provides accurate information to estimate the supply chain and logistics needs, which are essential for a better estimate of the wind farm deployment costs (LCOE). The methodological framework and the GIS-SPOWER-BR Toolbox have become a robust instrument for the assessment of current and future offshore wind projects.

In short, Figure 5-4 indicates the compatibility that private developers can ensure with the strategic planning, permitting and approval processes by supporting the strategic process with the GIS-SPOWER-BR framework.

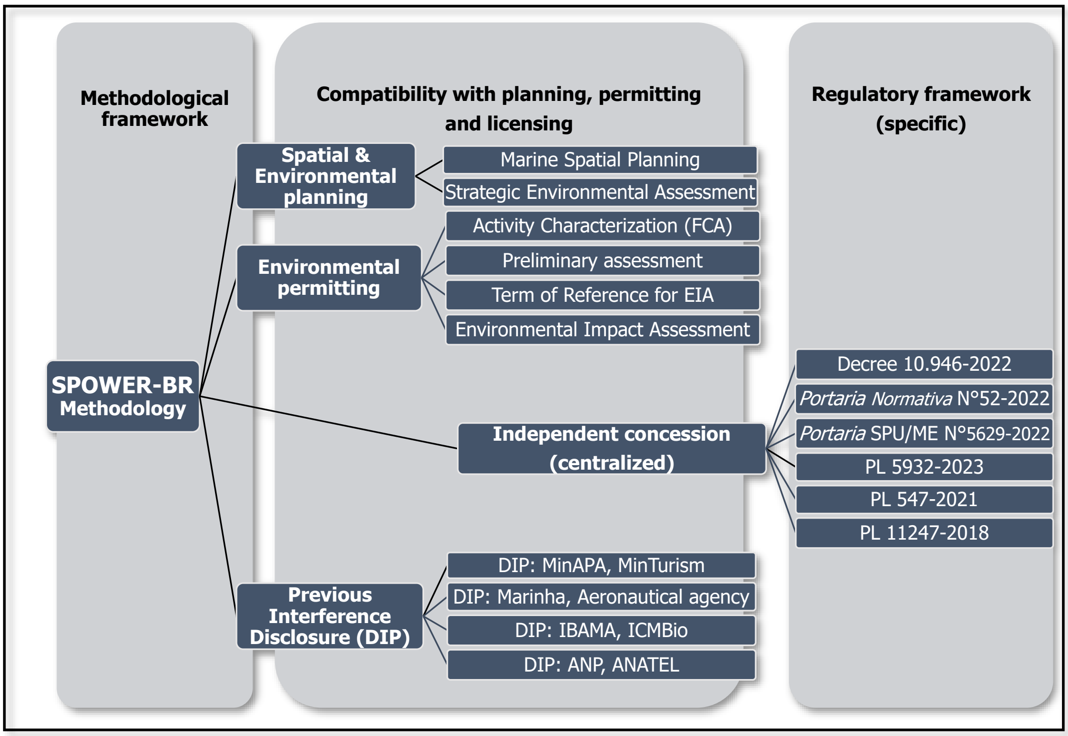


Figure 5-4. Impact on private pre-development processes.
Note: New business development, independent bidding (decentralized), environmental licenses and permits, leasing and auctioning.

Chapter 6 – Conclusions and recommendations

This chapter contains the conclusions and recommendations arising from the research process, findings and analysis presented in this thesis. The thesis has described the formulation, methodology and findings dedicated to exploring and improving the offshore wind strategic planning process.

Through the review of international experiences and state of the art technology, as well as the integration of concepts and procedures of methodological tools dealing with the strategic planning of the multisectoral and power generation sector, this research has consolidated a robust GIS-based methodological framework called GIS-SPOWER-BR framework, which aims to improve the vertical integration between planning and deployment stages of the offshore wind industry.

This framework comprises the methodological procedure, the basic geodatabase, the GIS-SPOWER-BR Toolbox and the VIZ-SPOWER-BR analytics dashboard. These components combine a cross-sectoral and holistic approach that aims to increase the sustainability of offshore wind development. These elements can reduce uncertainty during the decision-making process of concessioning offshore wind areas – in centralized or decentralized systems – by integrating more than 35 variables that influence the strategic planning process into a structured approach.

The methodology was developed to deal with the strategic information that answers questions such as: How much area is technically feasible? Where are the offshore wind areas located? Which areas are available for offshore wind farm development? Where are the best locations for implementing an OWF? How far from the coast is ideal for siting an OWF? What are the most sustainable areas for the development of an offshore wind farm? How many turbines can be installed in a given area? How much energy can be generated?

The GIS-SPOWER-BR framework was validated through a successful application to the case study of the state of Ceará in the Brazilian Northeast region. Results proved that it is possible to implement a robust methodology that addresses complex interactions at different scales.

In the short term, this proposal represents a reference framework to improve the strategic planning process, capable of periodically defining new offshore wind areas and consolidating a solid project pipeline. In the medium term, the results of this process can provide useful information to prevent conflicts in marine exploitation, support the environmental impact assessment process to avoid potential negative impacts on the environment, society and the economy, and provide guidelines for estimating supply chain and logistics needs to strategically support the development of the offshore wind industry.

Insights into feasibility, availability and complexity are important information for public and private decision-makers who set priorities and implement development strategies. Thus, the GIS-SPOWER-BR methodological framework can provide a robust tool for the assessment of current and future offshore wind projects.

Specific conclusions

Based on the offshore wind energy literature and international experience, this thesis has developed a robust analytical framework that takes into account the key technological drivers that influence strategic planning and decision-making. In addition, the proposed framework incorporates flexibility, including different offshore wind turbine technologies, and constraints for different foundation technologies.

This methodological proposal can support the Marine Spatial Planning Process, focused on allocating offshore wind areas. It can also support Strategic Environmental Assessment studies by providing and storing information on environmental and cost factors required for the evaluation of different technological alternatives, thus enabling a cyclical flow of information. Finally, the methodology provides the procedure and basic information for the process of micro-siting, boundary definition and preliminary turbine location. This information can be used to support the environmental impact assessment process.

In terms of data collection, the compilation of the geodatabase has confirmed that spatial environmental and social data is a critical gap in the planning and operational process. Furthermore, data collection, pre-processing and integration are time-consuming tasks that need to be prioritized when developing the Marine Spatial Planning and Strategic Environmental Assessment studies in Brazil or in other developing countries in Latin America. For example, it was found that the state of Ceará does not have accurate data on coastal species or ecosystems. This could jeopardize the sustainability of offshore wind development, as there is no strategic environmental assessment or robust environmental impact assessment for each project.

With the help of ArcGIS 10.6 software and Power BI, it was possible to integrate the geospatial analyses into the strategic planning process. The GIS-POWER-BR framework was able to progressively integrate the environmental, social and economic spatial variables to assess feasible and non-conflicting areas for OWE development. This integration was possible with publicly available data in Brazil. Moreover, geoanalytics techniques enabled the definition of development targets and areas and the prioritization of a portfolio of sustainable offshore wind areas through a second-best analysis assessment.

The application of the proposed SPOWER-BR methodological framework for strategic planning and sustainability of offshore wind energy has shown that vertical integration between the strategic and operational stages of the Offshore Wind Industry is possible. The definition of clear objectives and a project pipeline for the state of Ceará is replicable under different strategic planning scenarios and takes less time than a manual and unstructured process.

Finally, the methodological framework has proven to be able to consider the current regulatory framework – Decree 10.946 and *Portaria Normativa* No. 52-2022 – proposed for the development of marine renewable energy in Brazil by 2023. In addition, the robustness and flexibility in terms of computational support and parameterization allow the implementation of future legal frameworks such as PL 5.932-2023. Therefore, developers can also adapt their projects to the current and future legal framework.

Recommendations

The development of strategic scenarios compatible with future sectoral and national visions is a crucial process for the successful and sustainable development of the offshore wind industry in Brazil or in other emerging markets in the long term. This process requires the establishment of a dedicated offshore wind task force to lead the strategic planning process and integrate the visions of the different stakeholders into a common offshore wind development goal with clear short, medium and long-term objectives.

This task force should involve strategic stakeholders, including local communities and academia. A holistic task force is crucial to prevent future project failures or permit rejections due to environmental or social acceptance problems caused by weak community management processes.

The Brazilian federal government – supported by the National Energy Policy Council – should guide the definition of concrete goals and targets based on its vision for offshore wind development. Supported by an offshore wind task force, the federal agencies – ANEEL and EPE – could consolidate a portfolio of offshore wind areas to continuously feed a pipeline of areas to be offered to the market in the short, medium and long term. This portfolio would ensure sustainability in temporal, environmental, social and economic terms.

Current public spatial information systems and platforms now need to be integrated to support Marine Spatial Planning, Strategic Environmental Assessments, leasing and Environmental Impact Assessment studies. This includes cross-sector collaboration between public agencies and communities related to offshore wind development and marine activities. Through this collaboration, data would be made available using a common symbolization language (common cartography, symbolization and data architecture patterns). Given the spatial data collected as part of the current research, active research of endangered and vulnerable species in the northeast region must be prioritized at least to the contiguous zone (24 nm or 44 km from the coastline).

The definition of regional targets and roadmaps is strongly recommended due to the diversity of Brazil's offshore wind resources. These targets and roadmaps should be harmonized to be consistent with the federal government's objectives.

The process of environmental impact assessment of projects in the early stages of planning should be preceded by the implementation of a strategic site assessment strategy. Environmental sensitivity mapping can suggest areas that should be avoided by offshore wind farm projects. Environmental sensitivity mapping would go beyond the Previous Interference Disclosure that must be issued by Brazilian Institute of Environment and Renewable Natural Resources – IBAMA and the Chico Mendes Institute for Conservation of Biodiversity – ICMBio.

Regarding the gaps in environmental data in the three offshore wind hotspots along the Brazilian coast, the priorities for data collection for the development of a strategic environmental assessment of the offshore wind industry should be first in the Northeast region, second in the South region and third in the Southeast region. This prioritization is based on the experience of the offshore industry: the gaps in data on the distribution of biological resources are larger in the Northeast region, where no empirical primary data for threatened species have been found (LEMOS, HERNÁNDEZ, *et al.*, 2023).

It is strongly recommended to promote and finance pilot projects for offshore wind farms – preferably on a pilot scale – where several technologies are tested under different local conditions. The pilot projects should be tested in the three offshore wind hotspots. These projects will provide real data to test the maturity of the supply chain and logistics (including ports and grid infrastructure). The regulatory and environmental permitting framework can explicitly support these initiatives, while the local supply chain and market strengthen their workforce and infrastructure, and grid expansion takes place to achieve sufficient transmission capacity in the offshore wind hotspots.

Finally, all of these guidelines bring together actions that require an integrated research and development program focused on offshore wind development to support and fund projects that enable current knowledge gaps to be filled.

Research challenges

This research faced several challenges that could become bottlenecks for the actual development of offshore wind energy or new technologies for large-scale electricity generation in the future. Some of the challenges identified were:

- Funding for fieldwork and testing of the methodological framework and computational tools.
- Data collection (availability and quality), especially in relation to maritime data, spatialized data linked to metocean data (monitoring stations), geotechnical data, supply chain, logistics, available interconnection spans, employment.

- Search for skilled manpower from strategic stakeholders.
- Institutional articulation of sector representatives for the design of integrated planning scenarios.
- Integration of public participation and involvement of local communities due to lack of resources for consultation and surveying.

Relevance of this research

The relevance of this research is based on the technological development of computational tools to support the decision-making process in planning the use of renewable energy resources within a sustainability approach. The registration of the GIS-SPOWER-BR Toolbox as a computer program at the Brazilian National Institute of Industrial Property (HERNANDEZ C. *et al.*, 2022a) shows the potential of developing local technologies that meet the specific context of innovation markets in emerging or developing countries.

Significance of this research

The importance of this research stems from its potential to strengthen the development of offshore wind energy in a wide range of applications in the Brazilian and Latin American markets. Extending the analysis to the entire Brazilian coast could support the definition and prioritization of sustainable offshore wind energy projects by each state to achieve national goals. In addition, the results can identify strategies to estimate demand and supply chain challenges. Other studies can focus on the spatial suitability of ports and grid connection points. In addition, the implementation of a robust and semi-automated GIS-based framework can reduce uncertainties and assessment time. This improves decision support as numerous spatial variables can be taken into account, making the process more efficient and less bureaucratic.

Limitations

The main limitations of the methodological framework and tools are related to the strategic approach, which takes into account a large number of assumptions. Changes in the assumed values for almost all parameters lead to different results suggesting different solutions. The results are indicative to support strategic decisions on localization and feasibility assessment rather than providing detailed designs.

The results of the current methodological proposal bring more robustness to the planning process and the linking of strategic activities to operational stages, *e.g.*, linking the definition of the offshore wind areas program to the environmental impact assessment and the competitive leasing process for offshore wind energy within a common analysis framework.

Regarding the analysis of spatial costs and economic potential, the current tools does not calculate costs estimations automatically, spatial tools only integrates the cost drivers (spatial variables and parameters) that influence the assessment of economic potential. Results of the Spatial Cost Potential Index (SCPI) are only indicative due to the many indirect assumptions that would be necessary to formulate a specific economic model in emerging markets such as Brazil and other Latin American countries. For this reason, specific power generation and cost models have not been automated in the current version of the GIS-SPOWER-BR.

The current version of GIS-SPOWER-BR remains in Model Builder version 10.6 and needs to be updated to newer versions of ArcGIS platforms.

Further research

Further work may focus on developing a specific GIS-based economic and cost model for offshore wind energy development that represents the local market context in Brazil and other emerging markets. This includes modeling the local energy pricing market, local marine transportation and port logistics, taxation and incentives, workforce and training costs.

In addition, the automation of the economic model into a GIS-based tool would complement the applicability of the GIS-SPOWER-BR toolbox and the GIS-SPOWER-BR methodological framework.

Moreover, further application of the GIS-SPOWER-BR methodology could explore synergies to assess sustainable hydrogen production or compatibility with offshore oil and gas production for decarbonization of the industry.

The integration of GIS-SPOWER-BR and VIZ-SPOWER-BR into a single platform (the ESRI ArcGIS Pro or Enterprise platforms) would facilitate implementation of geoanalytics techniques and integrate dynamic dashboards for displaying geospatial data without the need for a hard link between ArcGIS and MS Power BI software.

In addition, a further study could explore generative artificial intelligence techniques and tools into the GIS-SPOWER-BR Toolbox to support the construction of strategic planning scenarios, generation of synthetic data to fill the identified gaps, or analyzing the output data.

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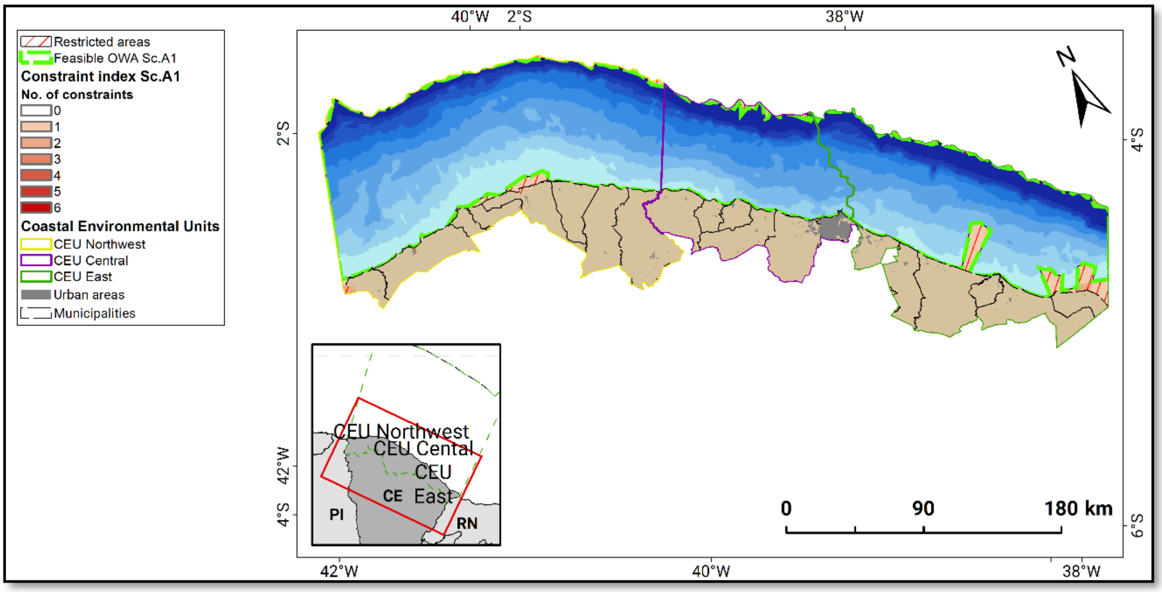
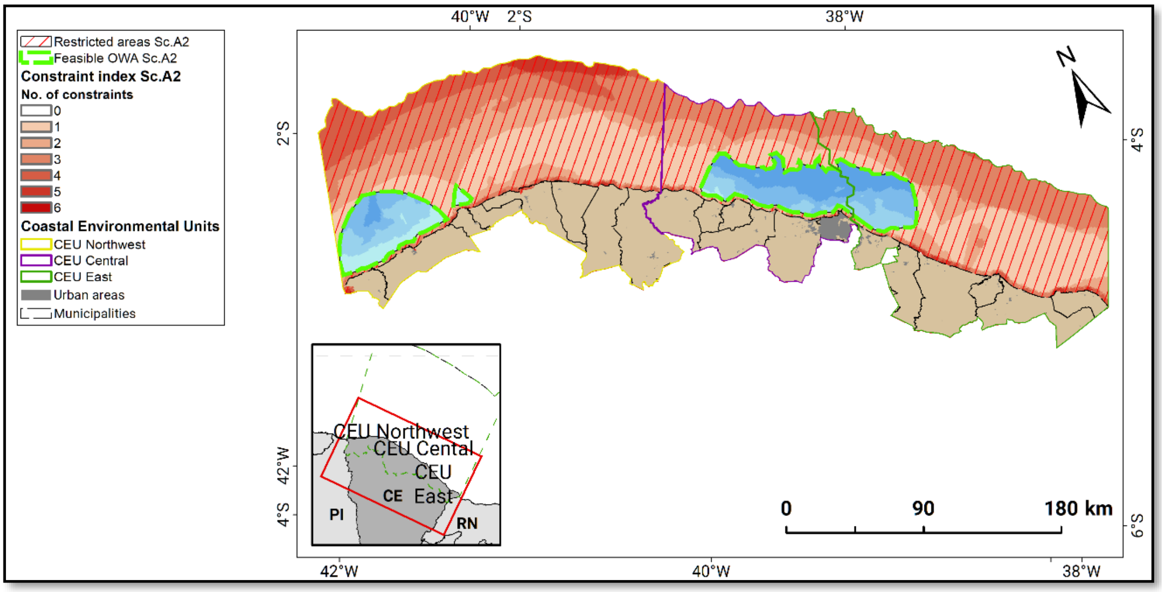
Appendices

Appendix A – Maps

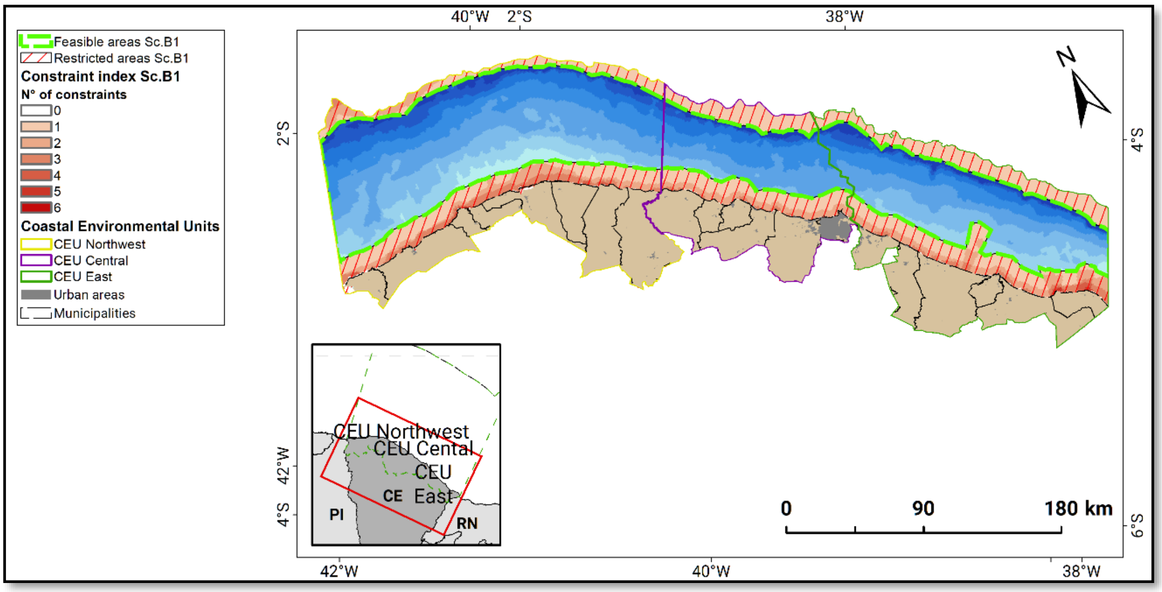
Constraint mapping



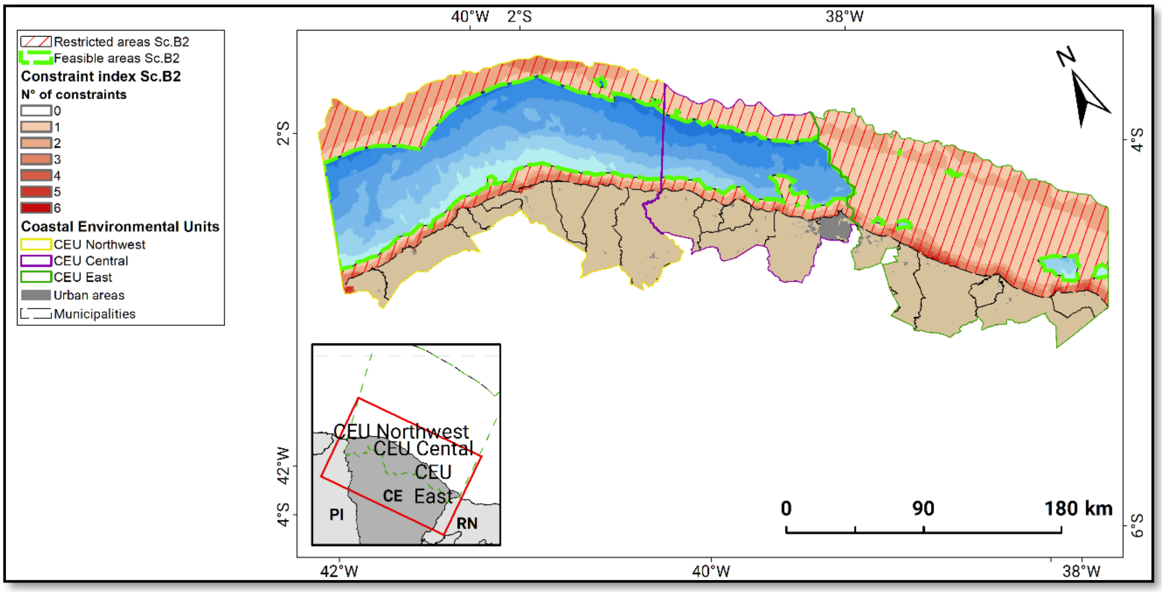
Map 1. Constraints mapping, Scenario A.1: Base Scenario 2023 for Coastal Coastal Zone of Ceará. Source: The Author.



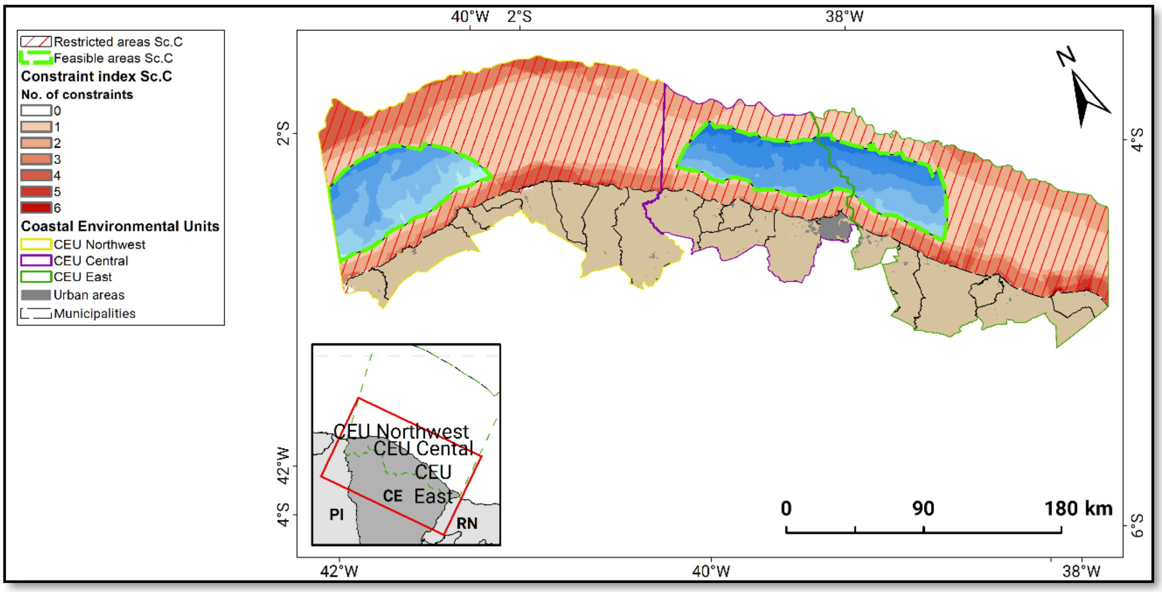
Map 2. Constraints mapping, Scenario A.2: Economic maximization for for Coastal Coastal Zone of Ceará.
Source: The Author.



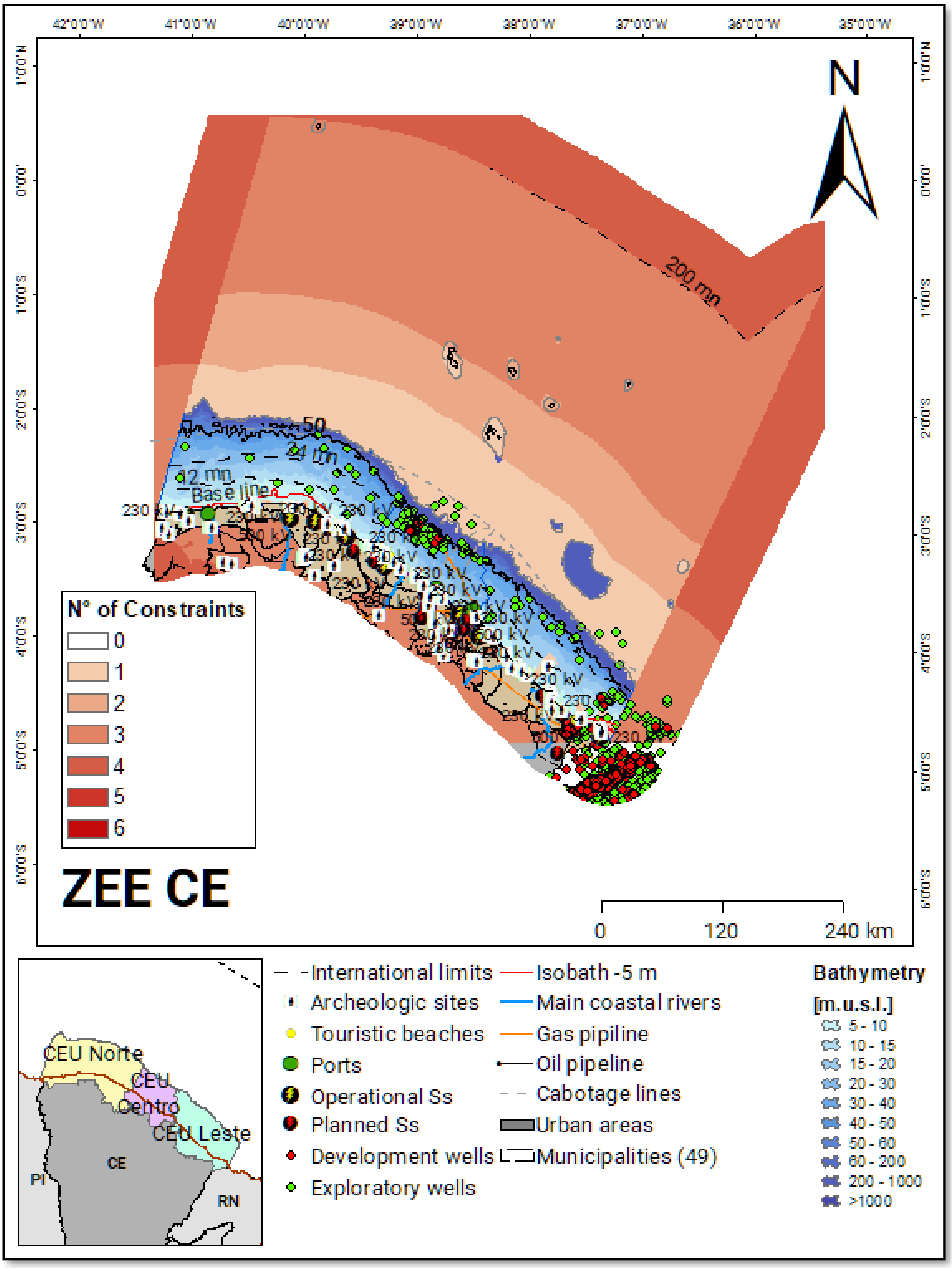
Map 3. Constraints mapping, Scenario B.1: Sustainable Optimization for Coastal Coastal Zone of Ceará. Source: The Author.



Map 4. Constraints mapping, Scenario B.2: Smart investor for Coastal Coastal Zone of Ceará. Source: The Author.

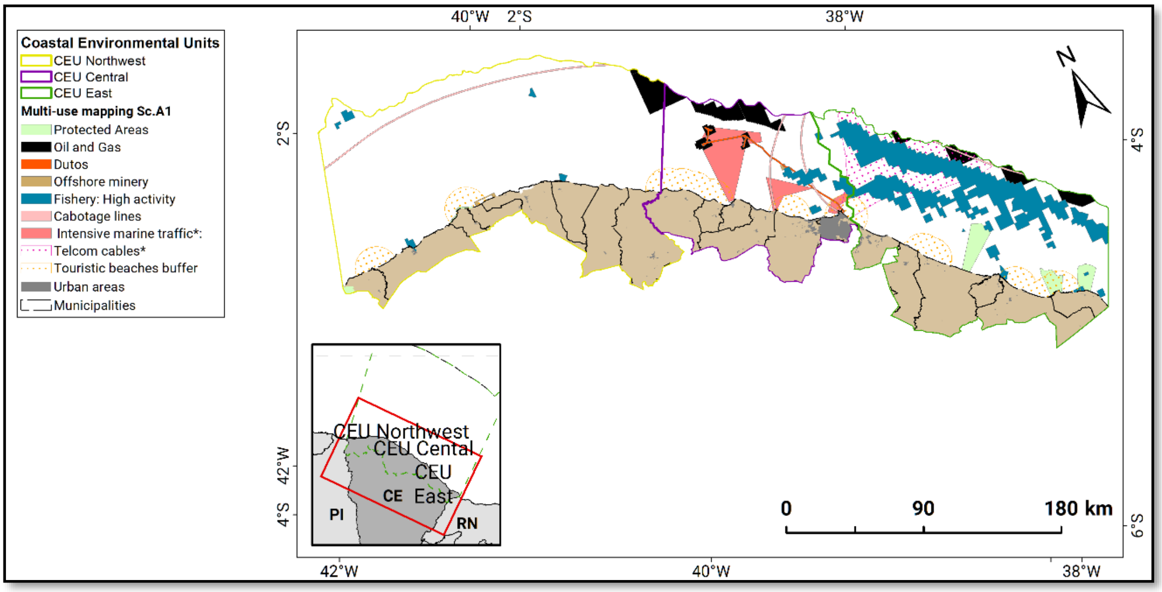


Map 5. Constraints mapping, Scenario C: Socio-environmental precaution for Coastal Coastal Zone of Ceará.
Source: The Author.

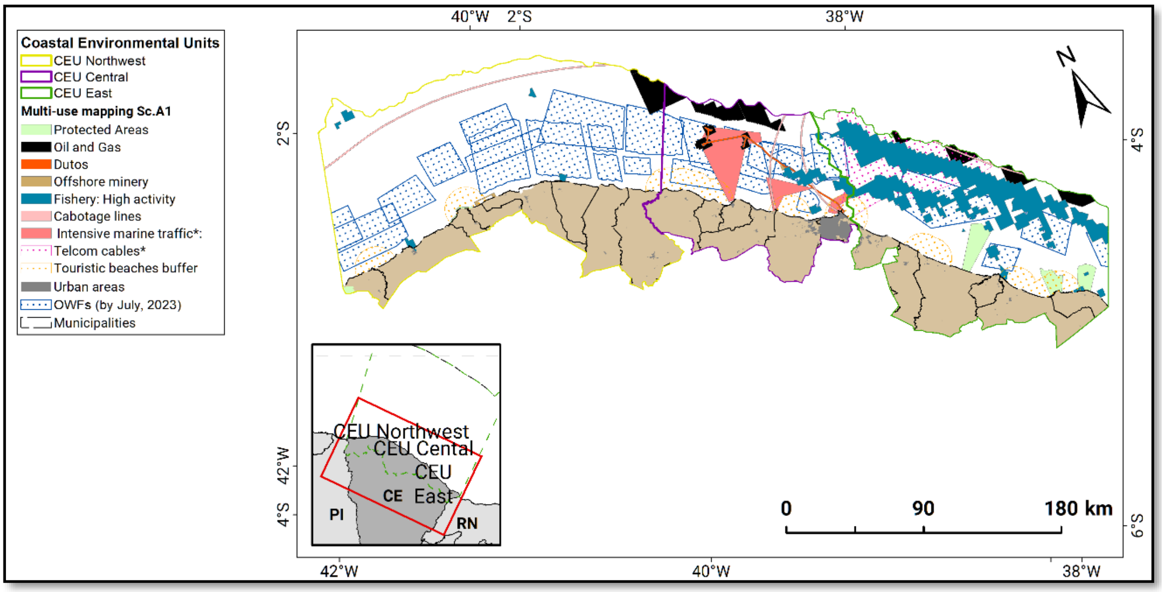


Map 6. Constraint mapping – Marine Spatial Planning Area of the State of Ceará.
Note: Geoprocessing area of 60km offset.
Source: The Author.

Multi-use mapping

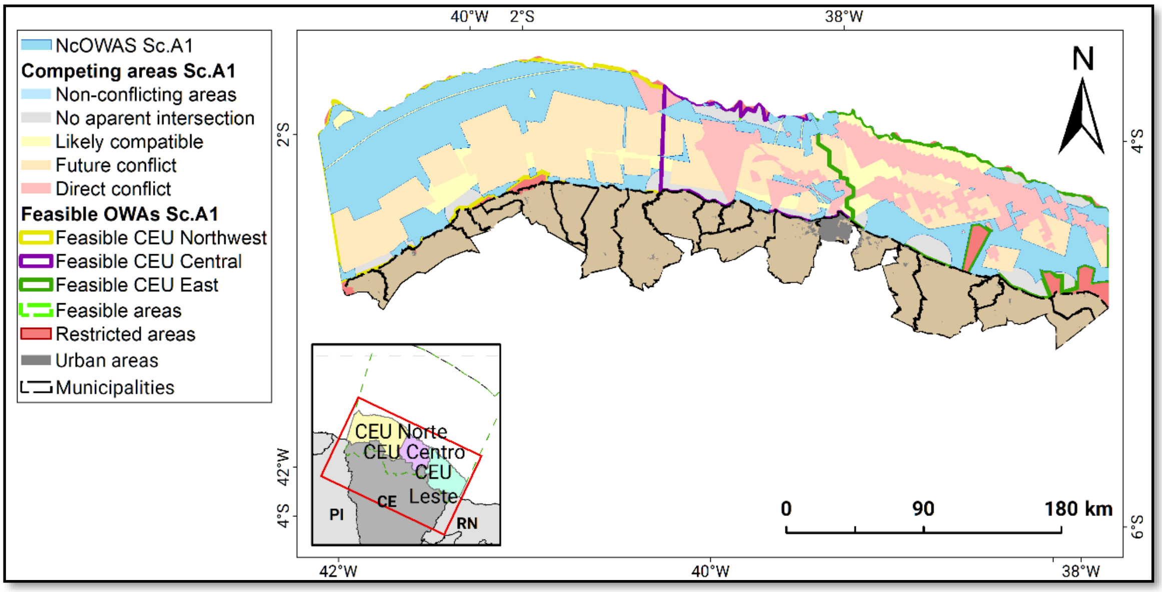


Map 7. Multi-use mapping, no Offshore wind frams in the Coastal Zone of Ceará.
Source: The Author.

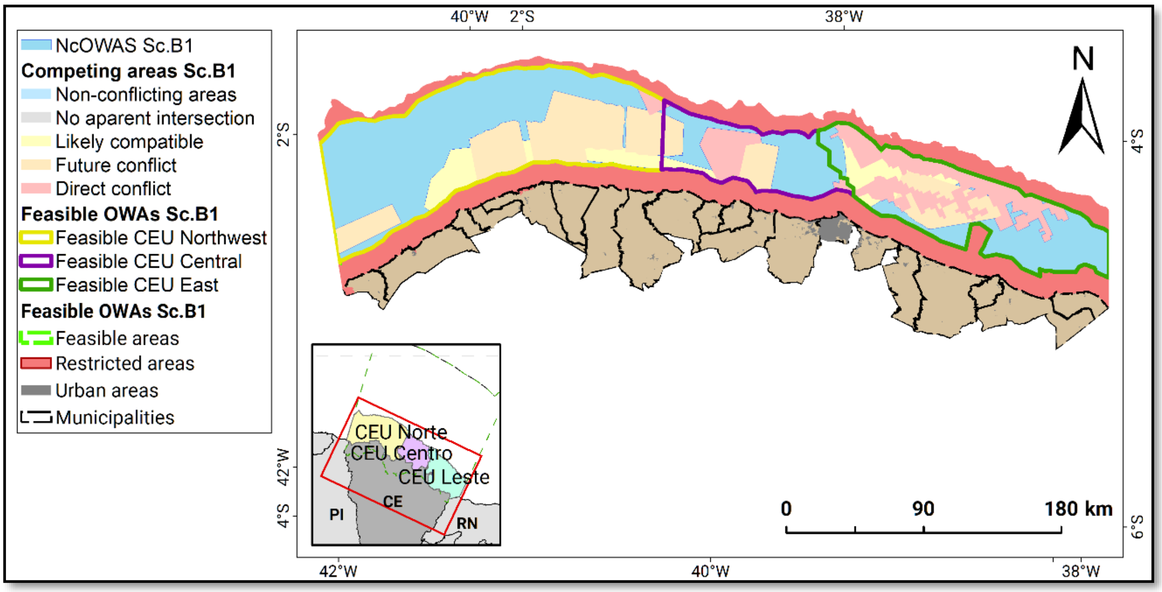


Map 8. Multi-use mapping, Offshore wind frams by 2023 in the Coastal Zone of Ceará.
Source: The Author.

Sea-use competition mapping

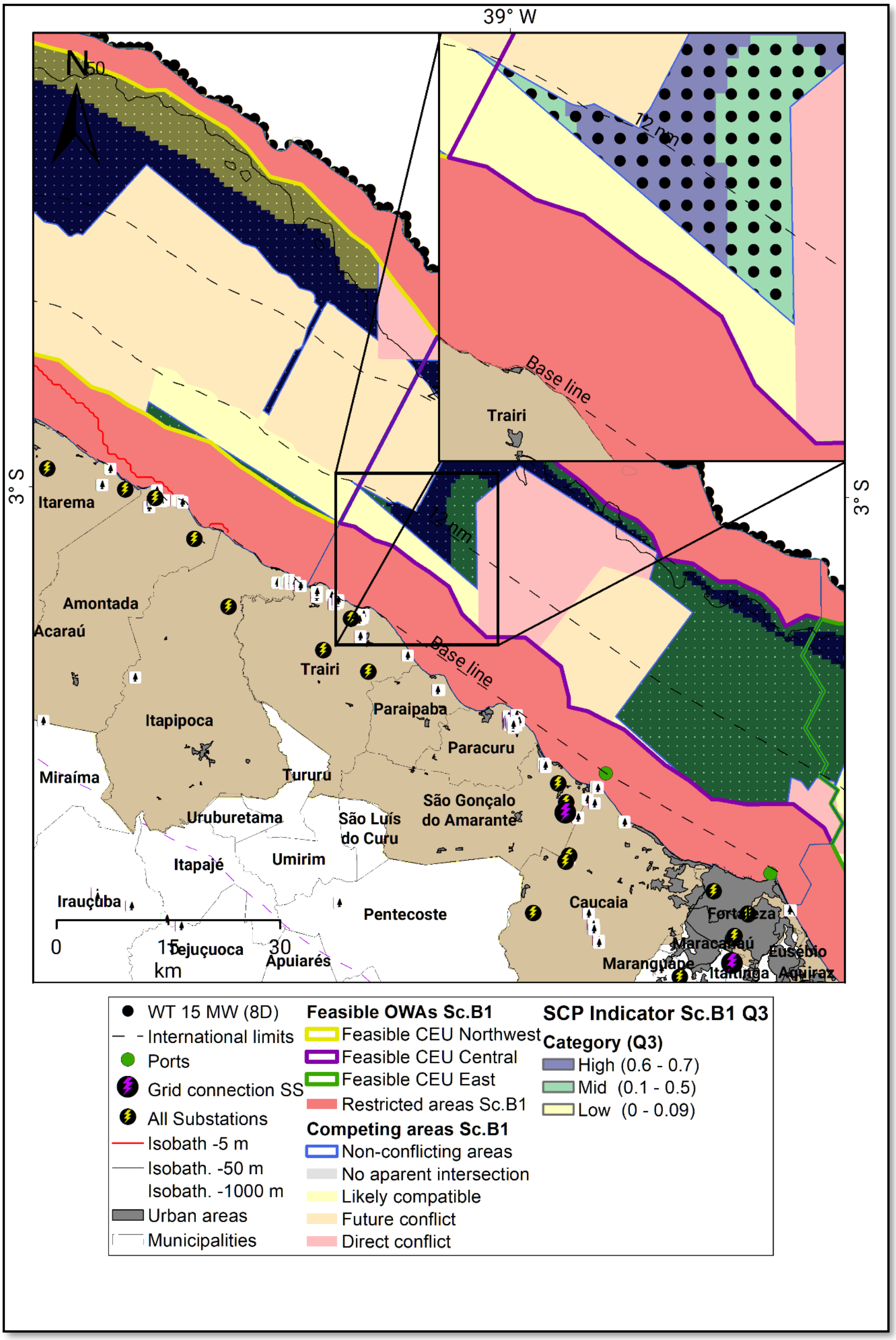


Map 9. Non-conflicting Offshore Wind Areas, Scenario A1.
Source: The Authors.

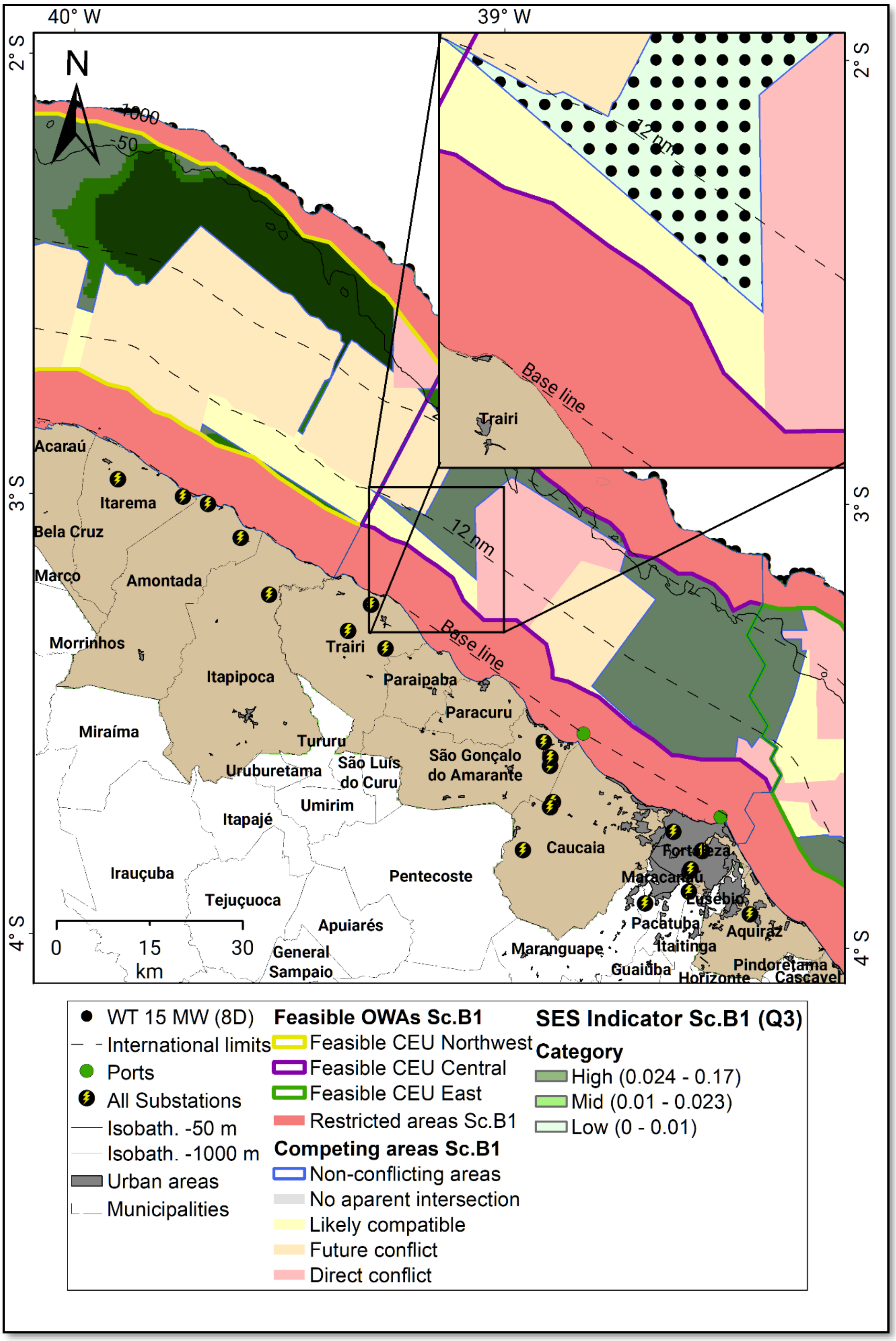


Map 10. Non-conflicting Offshore Wind Areas, Scenario B1.
Source: The Authors.

Sustainability mapping

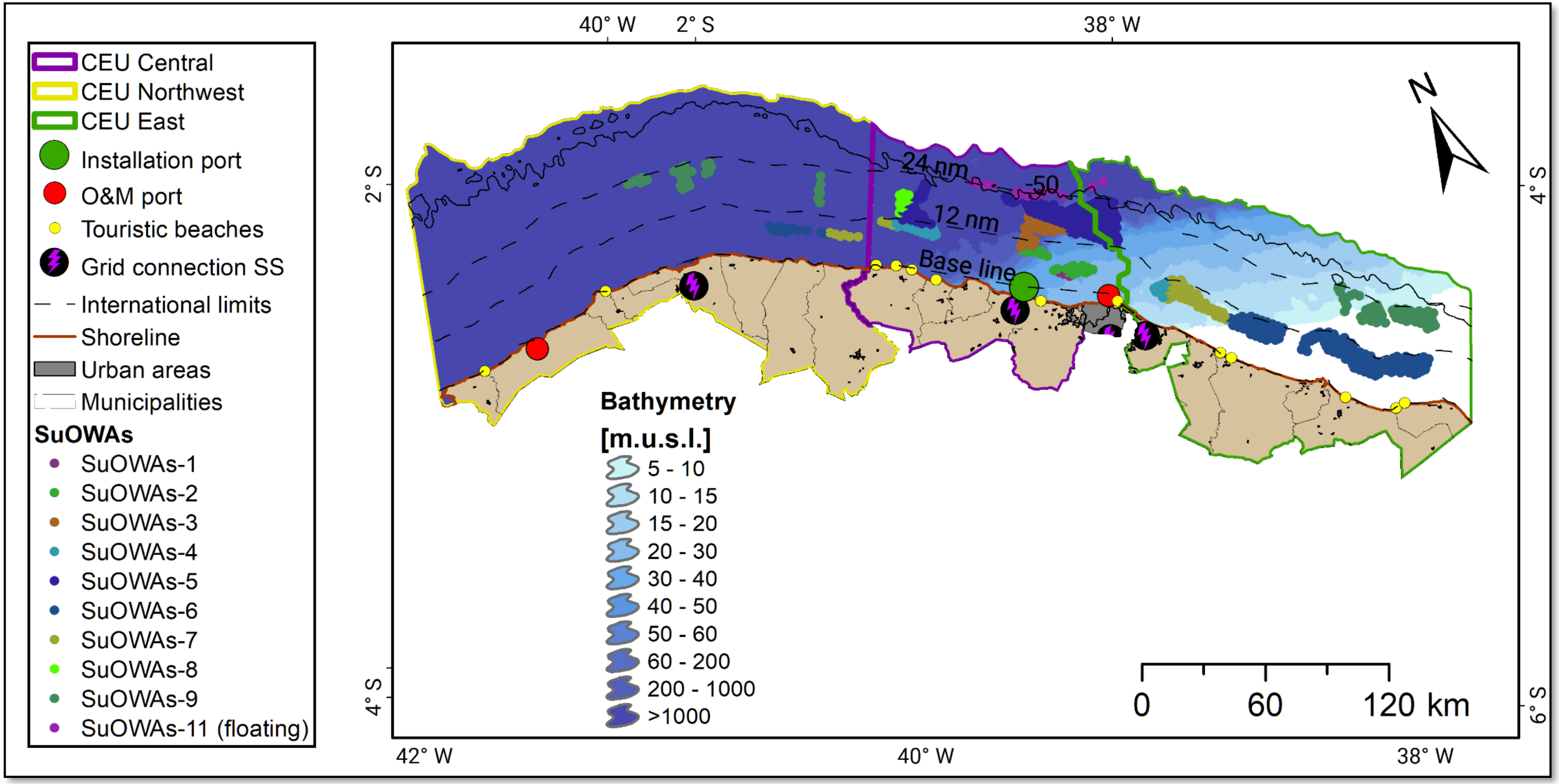


Map 11. Spatial Cost Potential Indicator (SCPI), Scenario B1.
Source: The Author.



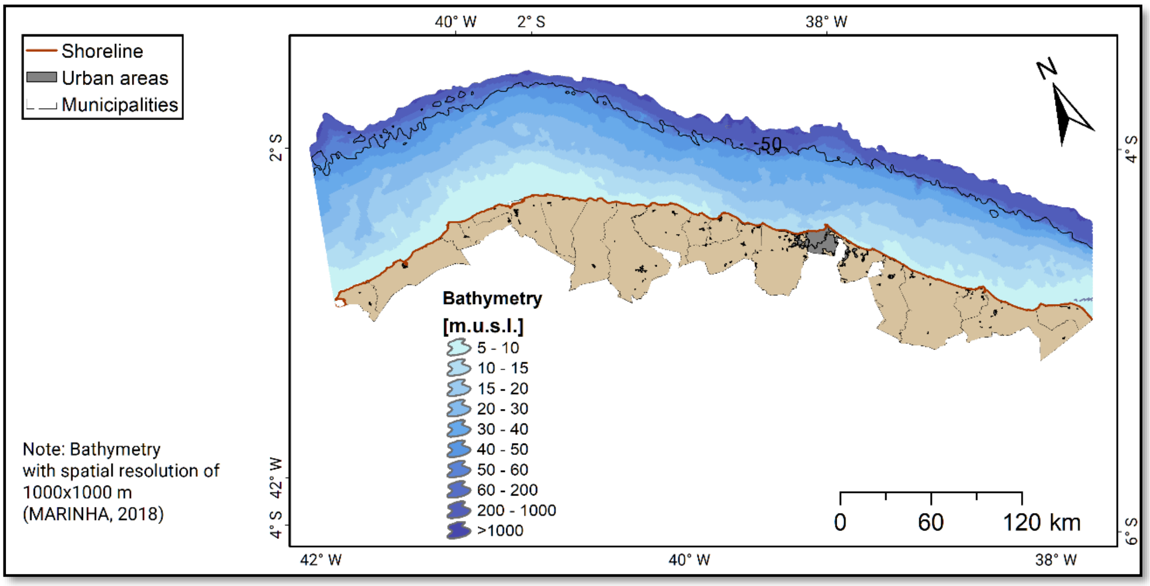
Map 12. Spatial Environmental Suitability Indicator, Scenario B1.
Source: The Author.

Sustainable Offshore Wind Areas Pipeline for expansion of offshore wind energy in the State of Ceará.

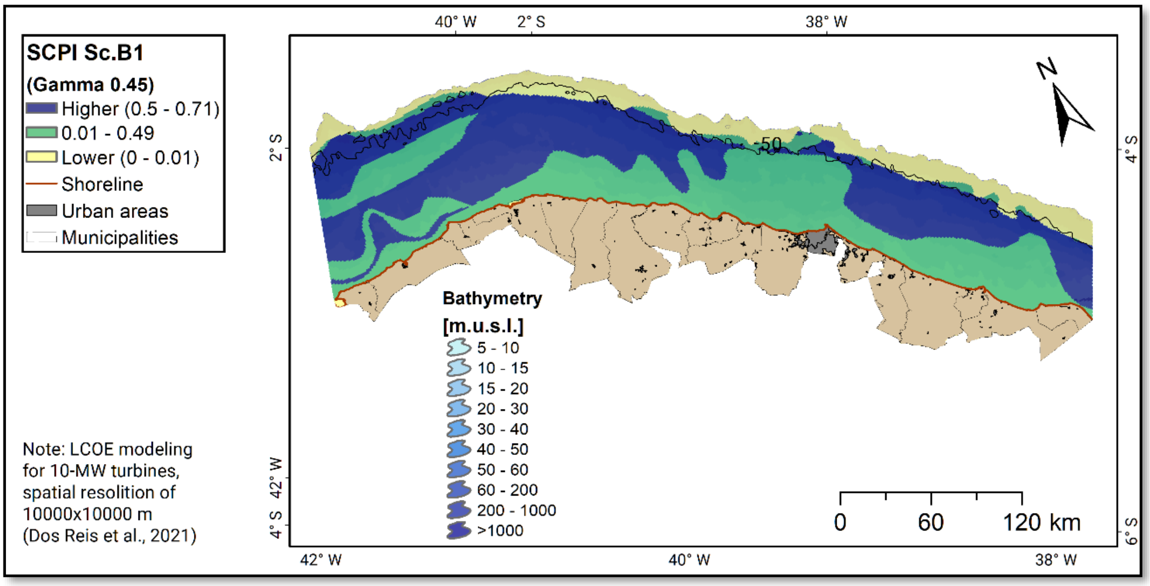


Map 13. Proposal for exanding the Offshore Wind Energy in the State of Ceará - Projects pipeline.
Note: resulst under Sustainability Optimization Scenario Vision (Scenario B1).
Source: The Author.

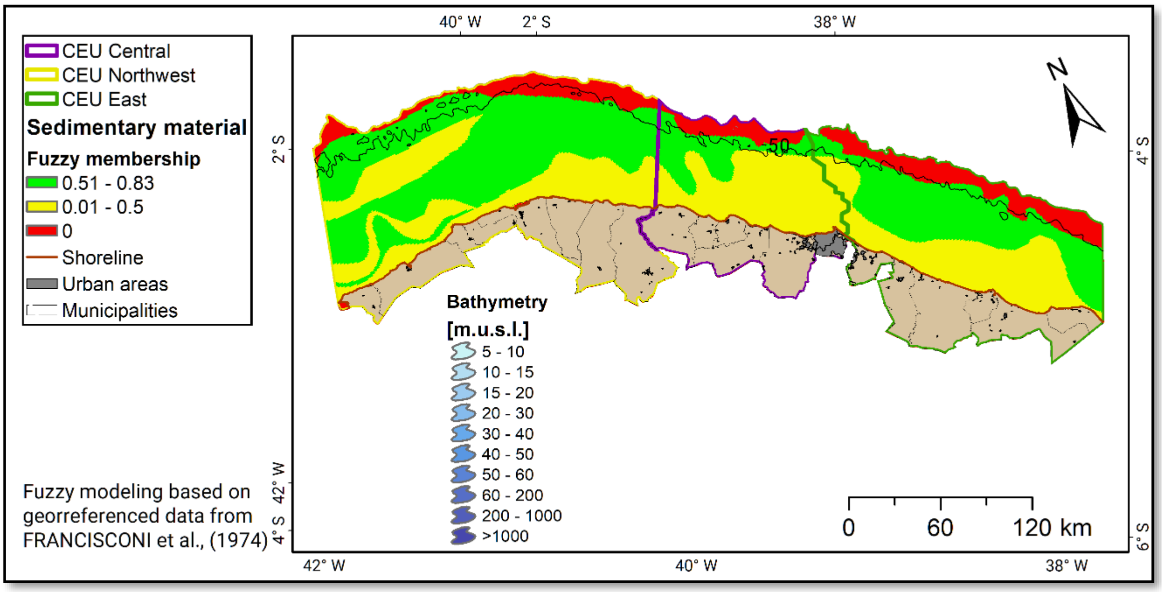
Examples of input spatial variables Mapping



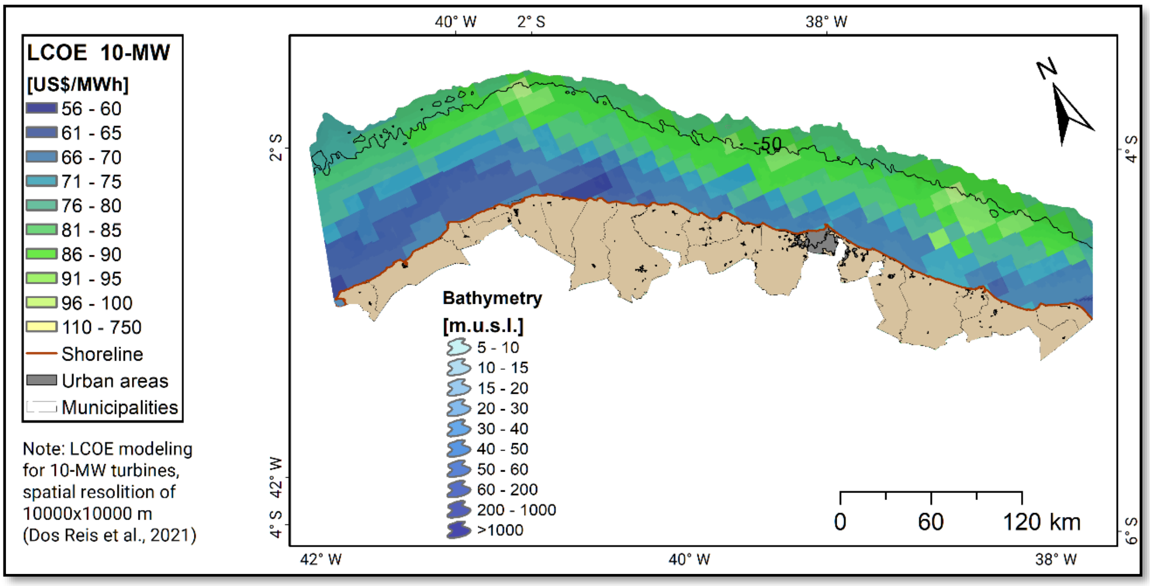
Map 14. Sedimentary material (Francisconi et al., 1974).
Source: The Author.



Map 15. Sedimentary material (Francisconi et al., 1974).
Source: The Author.



Map 16. Fuzzy membership of Sedimentary material, Scenario B1 (Gamma = 0.45) (Francisconi et al., 1974).
Source: The Author.



Map 17. LCOE based on 10-MW turbines modeling (Dos Resi et al., 2021).
Source: The Author.

Appendix B – Detailed activities of an offshore wind farm

Stage	Activity	Subactivity
Planning and development	Development and consenting services	Environmental impact assessment (pre-FEED)
	Environmental surveys	Environmental surveys: Benthic, fish and shellfish, sea mammals, ornithological, onshore; Social impact studies
	Resource and metocean assessment	Installation of structure
	Geological and hydrological surveys	Geophysical, geotechnical, and hydrographic surveys
	Engineering and consultancy	Front-end engineering and design (FEED) studies address
Installation and commissioning	Construction port	Workshops, Personnel facilities
	Offshore logistics	Marine coordination, weather forecasting
	Foundation installation	Transport, handling, installing
	Turbine installation	Installation and Commissioning
	Offshore substation	Substation installation
	Offshore cable installation	Cable installation (laying, burial, plough)
	Onshore substation installation	construction of the infrastructure and electrical equipment
	Onshore cable installation	Connection export cable (between offshore and onshore substations)
Operation and Maintenance	Operation	Training, onshore, and offshore logistics, health, and safety inspections
	Maintenance and service	Planned and maintenance and unplanned service
Decommissioning	Turbine decommissioning	Turbine removal and shipment to shore
	Foundation decommissioning	Foundation removal/cut-off
	Cable decommissioning	Cable removal and shipment
	Substation decommissioning	Substation removal/cut and shipment
	Decommissioning port	Equipment removal
	Reuse, recycling, or disposal	Extracting values, recycling, or disposal
	Environmental surveys	NA

Table B-1. List of detailed offshore wind farm activities.
Source: The Author based on BVG Associates (2019).

Appendix C – Computational Program Register of the GIS-SPOWER-BR Toolbox

REPÚBLICA FEDERATIVA DO BRASIL
MINISTÉRIO DA ECONOMIA
INSTITUTO NACIONAL DA PROPRIEDADE INDUSTRIAL
DIRETORIA DE PATENTES, PROGRAMAS DE COMPUTADOR E TOPOGRAFIAS DE CIRCUITOS INTEGRADOS

Certificado de Registro de Programa de Computador

Processo Nº: **BR512022001514-5**

O Instituto Nacional da Propriedade Industrial expede o presente certificado de registro de programa de computador, válido por 50 anos a partir de 1° de janeiro subsequente à data de 02/02/2022, em conformidade com o §2°, art. 2° da Lei 9.609, de 19 de Fevereiro de 1998.

Título: GIS-SPOWER-BR Toolbox: GIS-based method for Strategic Planning of the Offshore Wind Renewable Energy for BRazil

Data de publicação: 02/02/2022

Data de criação: 02/02/2022

Titular(es): UNIVERSIDADE FEDERAL DO RIO DE JANEIRO

Autor(es): OMAR MAURICIO HERNANDEZ CARRASCAL; ELIAB RICARTE; EMILIO LEBRE LA ROVERE

Linguagem: OUTROS

Campo de aplicação: EN-01; EN-02; EN-04; GC-08; MA-01; MA-02

Tipo de programa: AP-02; DS-04; SM-01; SO-02; TC-01

Algoritmo hash: SHA-512

Resumo digital hash:
088cb21c7e99a2a8fde86cdd7a724729ea5e04ee9285c6195a46d322a236c7217001109053a3a600aed7bd7377a76728
86d9968029644320fd2e46e3fee22960

Derivação autorizada: Sim, Título do programa Original: ArcGIS Desktop 10.6

Expedido em: 05/07/2022

Figure C-1. Computational Program Register of the GIS-SPOWER-BR Toolbox.
Source: INPI (2022).

Appendix D – GIS-SPOWER-BR Toolbox

This Appendix present the ***GIS**-based **S**trategic **P**lanning **M**odel for of **O**ffshore **W**ind **E**nergy in Brazil*, here called the GIS-SPOWER-BR Toolbox. Automating the previous GIS-based multicriteria analyses is the last step in assembling a Decision Support System into the GIS platform. An automated or semi-automated DSS assembled in GIS platforms, including a baseline geodatabase, simplifies the data collection and preprocessing of all necessary data. In addition, a robust and specialized DSS makes the strategic planning a less time-consuming process, considering the complex spatial multi-criteria methods (SIMÕES, COUTO, *et al.*, 2023), integrated for enhancing the decision-making about sustainable development of an offshore wind farm.

The GIS-SPOWER-BR[11] is registered under the Computational Program Registration Certificate N° BR512022001514-5, issued on July 5th, 2022 by the National Institution of Industrial Property of Brazil (INPI). Its first version was published on February, 22th 2022 (HERNANDEZ C. *et al.*, 2022).

The GIS-SPOWER-BR is the main difference with previous studies conducted in Brazil that used geoprocessing techniques for assessing OWE potential. The aim is to provide a first approach of a Decision support system that support strategic stakeholders' decision about sustainable siting and prioritization of areas or projects. This toolbox allows dynamic simulations, using technology, data accuracy, and strategic scenarios as input parameters. Figure D-1 present the conceptual structure of the GIS-SPOWER-BR. Data module become a structural component, being transversal to the geoprocessing modules. The baseline geodatabase must be updated periodically. Instead, the simulations can be when required, preferably when relevant input data be updated, when new milestones in regulatory framework be published or for resetting new offshore wind development goals and targets.

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[11] See Appendix E for more documentation

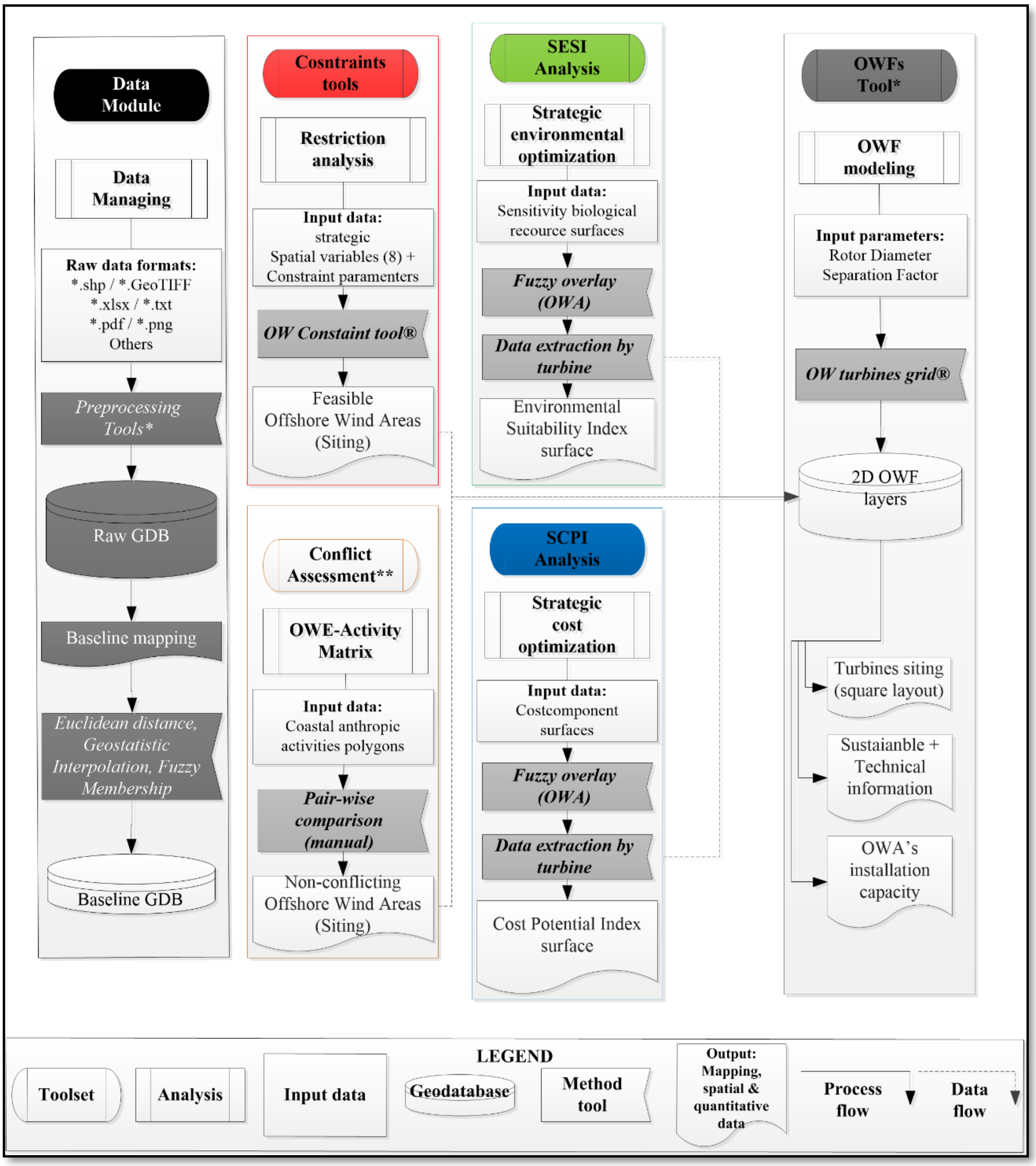


Figure D-1. Conceptual model of the GIS-SPOWER-BR.
Note: *: preprocessing tools include ArcGIS built-on and GIS-SPOWER-BR tools; **Manual assignment of conflict values.
Source: The Author.

Currently, the GIS-SPOWER-BR gathers four modules especially developed for the offshore wind energy industry. The GIS-based modules are: *Constraint tools*, *Offshore Wind Farms tools* (includes *Wake buffering tool*), and *Pre-processing tools*. Further steps in improving the GIS-SPOWER-BR Toolbox (decision support system) are developing additional tools that automate the Multi-use conflict assessment and LCOE estimation, providing geoanalytics to optimize decision-making. In the ArcCatalog user interface, the GIS-SPOWER-BR is composed by five toolsets (see Figure D-), as follows:

- Preprocessing tools
- Constraint tools
- Offshore Wind Farm tools
- Wake Buffering tools
- Sustainability Analysis tools[12]

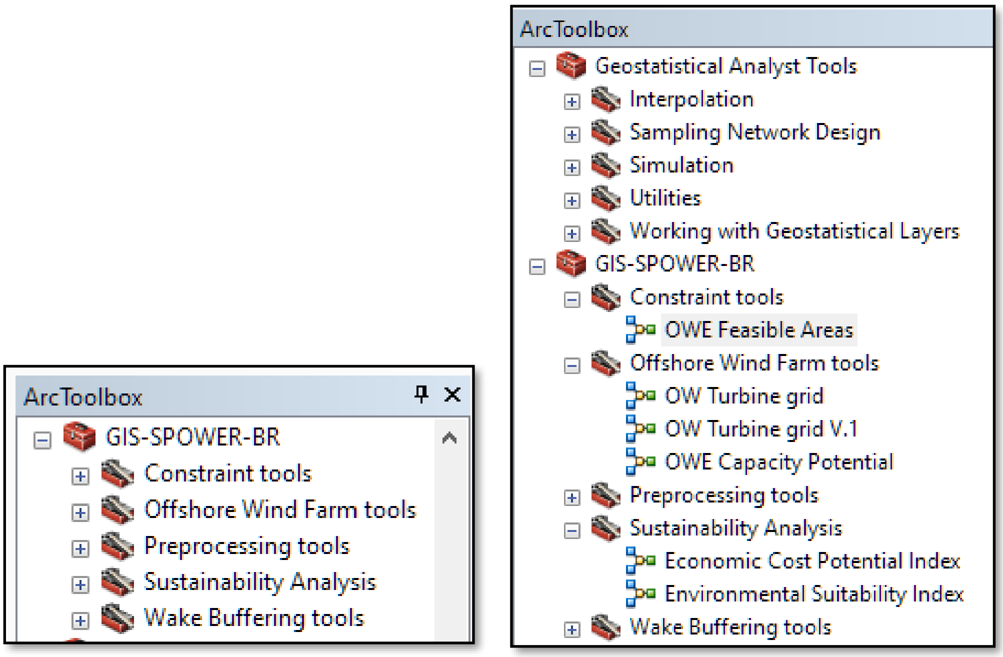


Figure D-2. GIS-SPOWER-BR Toolbox structure.
Source: The Author based on HERNANDEZ C. *et al.* (2022).

Following subsection present main tools, the necessary input data, parameters, and outputs.

Constraints tools: OWE Feasible Areas

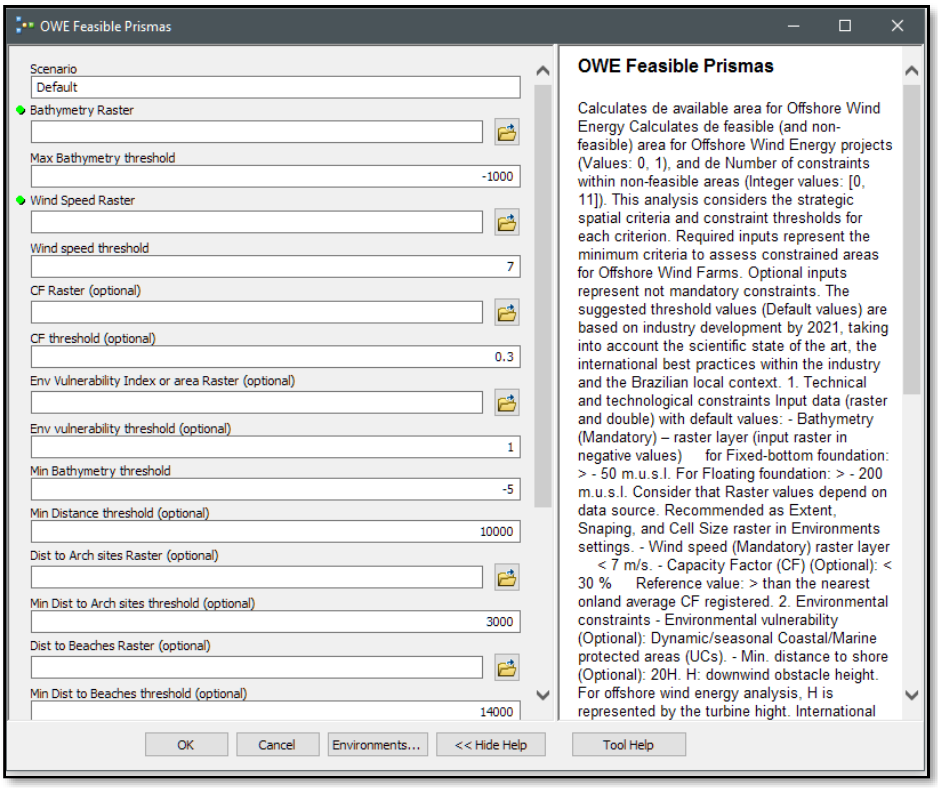
The *OWE Feasible Areas* tool aims to defines the feasible areas (boundaries) for offshore wind development and calculates their extension in km^2. This tool models direct absolute restrictions (constraint criteria) based on specific parameters (see Figure 4-3) of the selected strategic criteria, these parameters are the constraint thresholds defined for each criterion. In addition, it calculates the total number of constraints (Constraint Index raster) throughout the non-feasible areas (Integer values: [0, 11]). This calculation aims to identify lowest and highest constraint areas, in case on restriction issues along the restriction boundary or future expansion of the offshore wind areas.

---

[12] Tools for sustainability analysis are included in the ArcGIS built-on tools.

Figure D-3 shows the tool's user interface. The *OWE Feasible Areas* tool requires 12 parameters and 9 spatial data inputs (raster format). Setting parameter values must be aligned with the strategic scenarios, supported by technical analyses of each criterion (literature review, experts knowledge, Delphi surveys, or public consultation). This tool brings the possibility of materializing quantitate parametrization of the strategic scenarios. Tool's inputs are:

a) **Scenario (mandatory):** to identify the output data
b) **Bathymetry layer (mandatory) + parameters:** minimum and maximum water depth restriction
c) **Offshore wind resource layer (mandatory) + parameters:** minimum offshore wind speed restriction
d) **Offshore wind Capacity Factor layer (mandatory) + parameters:** minimum CF restriction
e) **Distance to shore + parameters (optional):** minimum and maximum distance restrictions
f) **Biological resources layer + parameters (optional):** 1 for defines biological resource areas layer or minimum suitability threshold for Species Richness/Ecologic Niche Modeling layers.
g) **Distance to beaches layer + parameters (optional):** minimum distances to beaches (especially touristic beaches).
h) **Distance to archeologic sites layer + parameters (optional):** minimum distance to archeologic sites
i) **Distance to substations layer + parameters (optional):** maximum distance to substations or grid connection point(s).
j) **Distance to ports layer + parameters (optional):** maximum distance to ports (it may vary due to Installaton or O&M ports assumptions in the input layer).



Scenario: Default
Bathymetry Raster:
Max Bathymetry threshold: -1000
Wind Speed Raster:
Wind speed threshold: 7
CF Raster (optional):
CF threshold (optional): 0.3
Env Vulnerability Index or area Raster (optional):
Env vulnerability threshold (optional): 1
Min Bathymetry threshold: -5
Min Distance threshold (optional): 10000
Dist to Arch sites Raster (optional):
Min Dist to Arch sites threshold (optional): 3000
Dist to Beaches Raster (optional):
Min Dist to Beaches threshold (optional): 14000

OWE Feasible Prismas

Calculates de available area for Offshore Wind Energy Calculates de feasible (and non-feasible) area for Offshore Wind Energy projects (Values: 0, 1), and de Number of constraints within non-feasible areas (Integer values: [0, 11]). This analysis considers the strategic spatial criteria and constraint thresholds for each criterion. Required inputs represent the minimum criteria to assess constrained areas for Offshore Wind Farms. Optional inputs represent not mandatory constraints. The suggested threshold values (Default values) are based on industry development by 2021, taking into account the scientific state of the art, the international best practices within the industry and the Brazilian local context. 1. Technical and technological constraints Input data (raster and double) with default values: - Bathymetry (Mandatory) – raster layer (input raster in negative values) for Fixed-bottom foundation: > - 50 m.u.s.l. For Floating foundation: > - 200 m.u.s.l. Consider that Raster values depend on data source. Recommended as Extent, Snaping, and Cell Size raster in Environments settings. - Wind speed (Mandatory) raster layer < 7 m/s. - Capacity Factor (CF) (Optional): < 30 % Reference value: > than the nearest onland average CF registered. 2. Environmental constraints - Environmental vulnerability (Optional): Dynamic/seasonal Coastal/Marine protected areas (UCs). - Min. distance to shore (Optional): 20H. H: downwind obstacle height. For offshore wind energy analysis, H is represented by the turbine hight. International

Figure D-3. OWE Feasible Areas tool.
Source: The Author based on HERNANDEZ C. *et al.*, (2022).

The suggested threshold values (set by default) were based on industry development by 2022, considering the scientific state of the art, the international best practices in the industry and the Brazilian offshore wind context.

Tool's outputs are polygon features (shapefile) that represent the offshore wind feasible areas, and exclusion areas. An intermediary output is the Constraint Index surface (raster) that represents the toral number of constraints at each pixel.

Offshore Wind Farm tools: *OW Turbine grid tool*

The *OW Turbines grid* tool calculates the number of turbines within a defined Offshore Wind Area (OWA). This allows to estimate total installed capacity potential for any area, based on the total number of turbines (see Subsection **Erro! Fonte de referência não encontrada.**). Considering a square layout of an OWF, this tool extracts technical data from selected raster of spatial variables or indicators (*e.g.*: bathymetry, mean wind speed, SESI, SCPI, etc.) into each turbine feature.

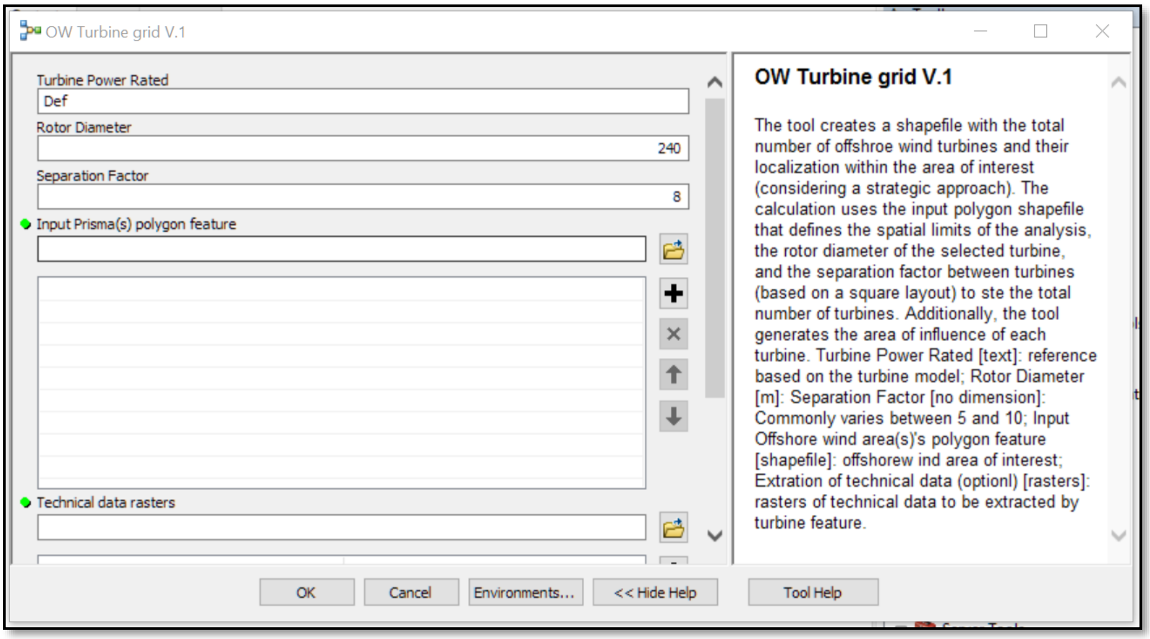
Erro! Fonte de referência não encontrada. shows the tool's user interface. The *OW Turbine grid tool* requires four parameters (numerical inputs of technical characteristics of desired offshore wind turbines), the offshore wind area polygon (mandatory input polygon in vector geometry) and optional technical surfaces (in raster format). The tool's inputs are:

a) **Turbine model (mandatory):** to identify the output data

b) **Rotor diameter parameter (mandatory):** rotor diameter based on turbine's model in meter [m].

c) **Separation factor:** desired separation factor to calculate distance between turbines (under square layout).

d) **Technical data rasters (optional):** surfaces (raster format) with technical data (values by pixel) to be extracted into each turbine (point shapefile).


OW Turbine grid V.1

Turbine Power Rated: Def

Rotor Diameter: 240

Separation Factor: 8

Input Prisma(s) polygon feature

Technical data rasters

OW Turbine grid V.1

The tool creates a shapefile with the total number of offshroe wind turbines and their localization within the area of interest (considering a strategic approach). The calculation uses the input polygon shapefile that defines the spatial limits of the analysis, the rotor diameter of the selected turbine, and the separation factor between turbines (based on a square layout) to ste the total number of turbines. Additionally, the tool generates the area of influence of each turbine. Turbine Power Rated [text]: reference based on the turbine model; Rotor Diameter [m]: Separation Factor [no dimension]: Commonly varies between 5 and 10; Input Offshore wind area(s)'s polygon feature [shapefile]: offshorew ind area of interest; Extration of technical data (optionl) [rasters]: rasters of technical data to be extracted by turbine feature.

Figure D-4. OW Turbine grid tool.
The Author based on HERNANDEZ C. *et al.* (2022).

Tool's outputs are point features (shapefile) that represent each turbine at the calculated localization. Each sited turbine is associated with its localization, rated power, and additional technical data. The extracted information (technical data) are used in the sustainability analyses and serve as input for estimations of the economic potential (LCOE) within a strategic approach (with no optimization or micro siting calculations).

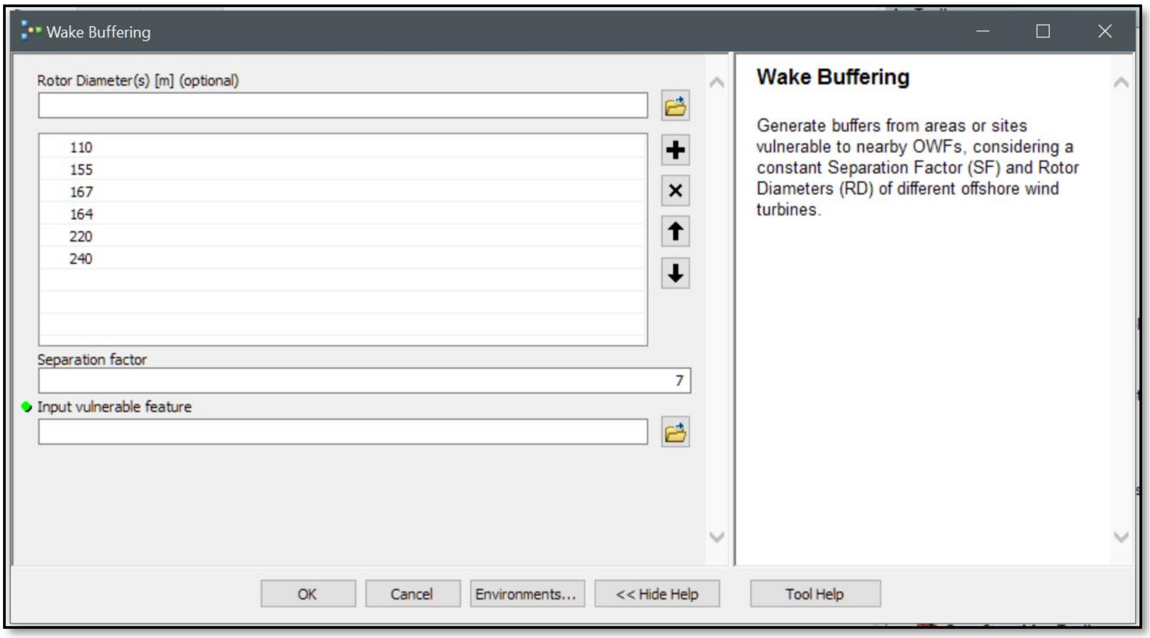
This tool was specially designed for supporting decision-making related with technological analysis of offshore wind turbines at strategic stage. Calculation of number of turbines, total installed capacity, or power density are indicative for optimization and micro siting stages. This analysis does not replace optimization analysis performed by specialized software (such as OpenWind, WindSIM, WaSP).

Wake buffering tools: Wake buffering tool

Wake buffering tool generates reference buffers around the selected area of interest (e.g.: offshore wind farm or specific wind turbine localization), considering different *Rotor Diameters* of desired wind turbines using a constant *Separation factor*. Reference buffers support conflict analysis with other human activities, but specially, with other wind farms. The wake effect can affect neighbor wind farms and their energy yield.

Erro! Fonte de referência não encontrada. shows tool's user interface. The *OW Turbine grid tool* requires two parameters (numerical inputs of technical characteristics of desired offshore wind turbines), and one vector polygon or point feature. The tool's inputs are:

a) **Rotor diameter parameter (mandatory):** rotor diameter of desired offshore wind turbines [m].
b) **Separation factor:** desired separation factor to calculate distance between turbines (under square layout).
c) **Input vulnerable feature:** input areas or sites (shapefile) that may be vulnerable to nerby offshore wind farms.



Wake Buffering

Rotor Diameter(s) [m] (optional)

110
155
167
164
220
240

Separation factor: 7

Input vulnerable feature

Wake Buffering

Generate buffers from areas or sites vulnerable to nearby OWFs, considering a constant Separation Factor (SF) and Rotor Diameters (RD) of different offshore wind turbines.

Figure D-5. Wake buffering tool.
Source: The Author based on HERNANDEZ C. *et al.* (2022).

Tool's outputs are polygon features (shapefile) that represent the possible influence (distance) of the wake effect generated by nearby turbines or offshore wind farms. This output can support constraint analysis or competitive analysis between offshore wind farms and other activities, especially other wind farms interested in neighbor areas.

Fuzzy multi-criteria analysis

The Fuzzy multi-criteria analysis is performed by two spatial tools: *Fuzzy Membership tool* and *Fuzzy Overlay tool*. These tools apply the Ordered Weighted Analysis (OWA) principles (YAGER, 1988) to perform the spatial multi-criteria modeling – integration of several criteria into a fuzzy suitability index. ESRI implemented both tools into the ArcToolbox that gathers all build-on geoprocessing tools, included in the ArcGIS suite software.

Fuzzy Membership tool performs the order weighting or "reordering" procedure of the Ordered Weighted Analysis (OWA). Complementarily, the *Fuzzy Overlay tool* performs the importance weighting procedure of the OWA. This tool uses the fuzzy operators based on risk profiles to integrate the different criteria, based on pixel-to-pixel assessment (spatial modeling).

Fuzzy membership tool[13]

Fuzzy Membership tool assigns the order weighting pixel-by-pixel. It identifies the maximum value (the first order weight) and the minimum value (the last order weight) of the input surface raster (spatial variable) as reference of membership. Then, it uses the fuzzy membership functions to assign the order weight to each pixel. The tool's inputs are:

a) **Input raster:** it is the input raster of the spatial variable (normalized values area required).
b) **Membership type (fuzzy membership functions)**[14] **parameter:** it indicates the strength of the membership (order weighting) of the input surface, based on the specified fuzzy function (ordering algorithm). The selection of membership type depends on the spatial dispersion of the input values, regarding the higher values means higher membership (suitability) or vice versa.
c) **Mean multiplier or Midpoint parameter:** it sets the mean or midpoint of the fuzzy function to match with the mean or midpoint of the input values.
d) **Spread or Standard deviation multiplier parameter:** it determines how rapidly the fuzzy membership values decrease from 1 to 0.

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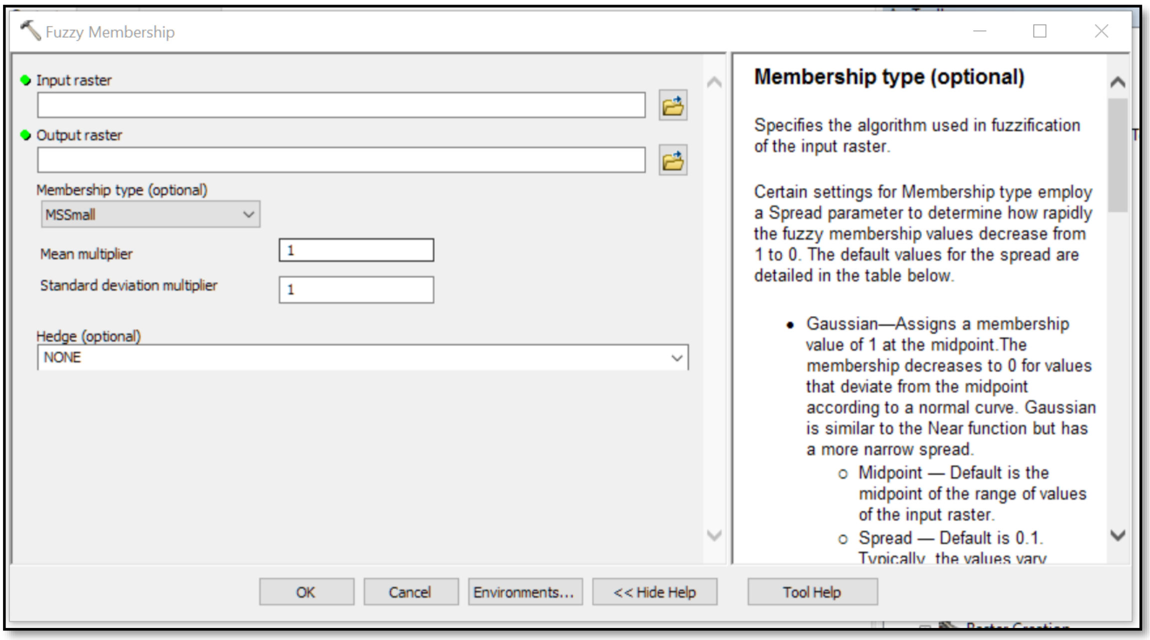
[13] Tool included into the ArcGIS suite software.

[14] Consult ArcGIS *Fuzzy Membership tool* documentation for more setting details.



Input raster

Output raster

Membership type (optional): MSSmall

Mean multiplier: 1

Standard deviation multiplier: 1

Hedge (optional): NONE

Membership type (optional)

Specifies the algorithm used in fuzzification of the input raster.

Certain settings for Membership type employ a Spread parameter to determine how rapidly the fuzzy membership values decrease from 1 to 0. The default values for the spread are detailed in the table below.

- Gaussian—Assigns a membership value of 1 at the midpoint.The membership decreases to 0 for values that deviate from the midpoint according to a normal curve. Gaussian is similar to the Near function but has a more narrow spread.
  - Midpoint — Default is the midpoint of the range of values of the input raster.
  - Spread — Default is 0.1. Typically, the values vary

Figure D-6. Fuzzy Membership tool.
Source: ArcGIS 10.6 software.

Tool's outputs are normalized surfaces with values between 0 and 1 (normalized spatial indicators in raster format) of each strategic criteria included in the Spatial Environmental Suitability Index or in the Spatial Cost Potential Index (see Subsection 4.1.2.3). These results are inputs of the *Fuzzy overlay tool* that performs the importance weighting procedure – a multi-criteria integration procedure.

Fuzzy overlay tool[15]

Current approach uses *Fuzzy overlay tool* to integrate the input criteria (normalized rasters) of sustainability indices: the SESI and SCPI indices. This tool incorporates the risk-taking nature, from the Ordered Weighted Analysis (OWA), into the Overlay method parameter. Here, Fuzzy Gamma is the selected Overlay method because it associates multiple input criteria, rather than OR operator or AND operator which simply return the value of a single membership set (ESRI, 2018). Gamma a numerical input is required to assign the fuzzy membership weighting (risk-taking profile). Figure D-7 shows how the value of parameter Gamma represents the risk-taking profile for the integration of criteria. When Gamma value is equal to the midpoint between AND and OR operators – Gamma ~0,45 – the tradeoff between criteria is complete; in this case the result of the fuzzy integration is equal to a WLC of equal weights for all criteria (DROBNE & LISEC, 2009, GORSEVSKI *et al.*, 2012, HERNANDEZ C., 2016). Section 0 details implementation of OWA into the spatial analysis.

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[15] Idem

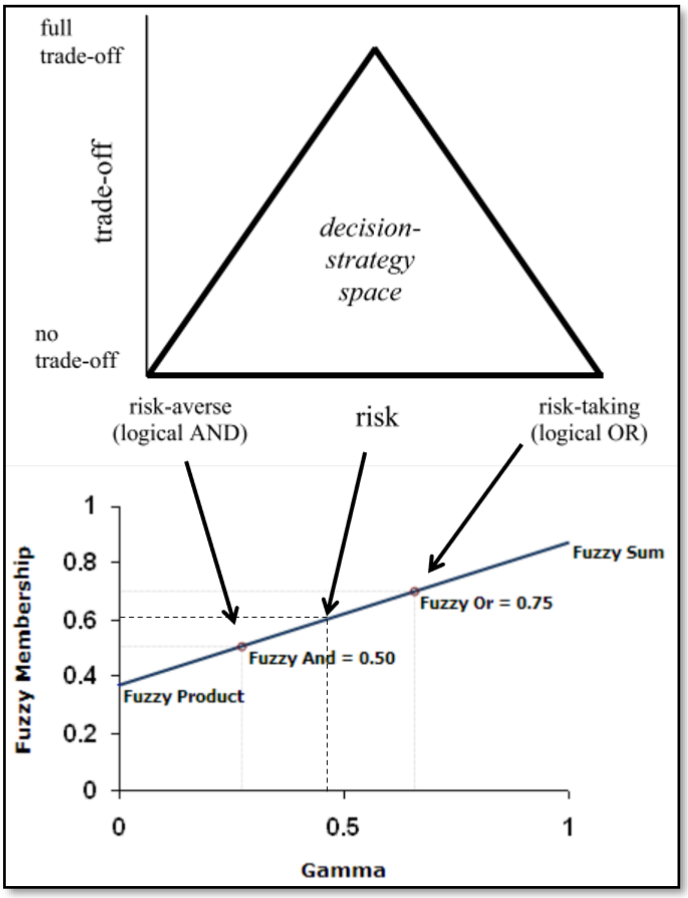
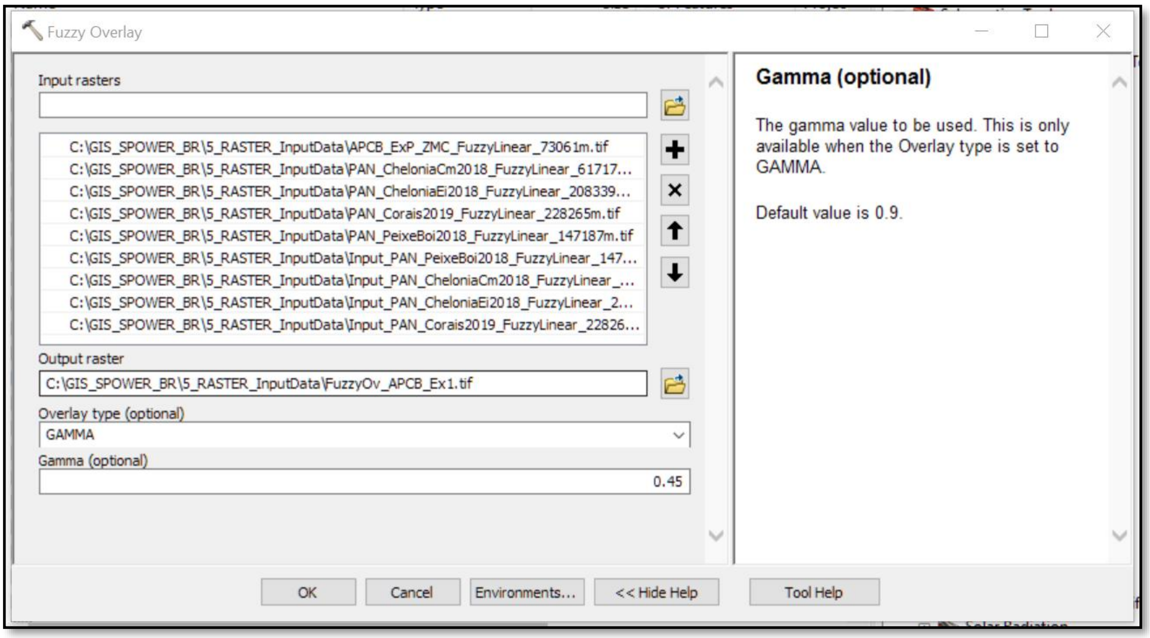


Figure D-7. Relationship between risk-taking profiles and Fuzzy membership, based on Gamma values. Note: Risk-averse (logical AND) = Fuzzy AND (Gamma = 0.50); Risk-taking (logical OR) = Fuzzy Or (Gamma = 0.75); Risk (neutral) ~ Fuzzy neutral (Gamma = 0.45) or equivalent to a Weighted Linera Combination (WLC) with maximum trade-off between criteria.
Source: The author based on DROBNE & LISEC (2009); GORSEVSKI *et al.* (2012); HERNANDEZ C., (2016); ESRI (2018).

The tool's inputs are:

a) **Input rasters:** these are the normalized input rasters of the spatial variables (spatial indicators).

b) **Gamma value parameter:** it is the value of the Fuzzy Gamma overlay method that represents the risk-taking profile for integrating input criteria.



Input rasters

C:\GIS_SPOWER_BR\5_RASTER_InputData\APCB_ExP_ZMC_FuzzyLinear_73061m.tif
C:\GIS_SPOWER_BR\5_RASTER_InputData\PAN_CheloniaCm2018_FuzzyLinear_61717...
C:\GIS_SPOWER_BR\5_RASTER_InputData\PAN_CheloniaEi2018_FuzzyLinear_208339...
C:\GIS_SPOWER_BR\5_RASTER_InputData\PAN_Corais2019_FuzzyLinear_228265m.tif
C:\GIS_SPOWER_BR\5_RASTER_InputData\PAN_PeixeBoi2018_FuzzyLinear_147187m.tif
C:\GIS_SPOWER_BR\5_RASTER_InputData\Input_PAN_PeixeBoi2018_FuzzyLinear_147...
C:\GIS_SPOWER_BR\5_RASTER_InputData\Input_PAN_CheloniaCm2018_FuzzyLinear_...
C:\GIS_SPOWER_BR\5_RASTER_InputData\Input_PAN_CheloniaEi2018_FuzzyLinear_2...
C:\GIS_SPOWER_BR\5_RASTER_InputData\Input_PAN_Corais2019_FuzzyLinear_22826...

Output raster: C:\GIS_SPOWER_BR\5_RASTER_InputData\FuzzyOv_APCB_Ex1.tif

Overlay type (optional): GAMMA

Gamma (optional): 0.45

Gamma (optional)

The gamma value to be used. This is only available when the Overlay type is set to GAMMA.

Default value is 0.9.

Figure D-8. Fuzzy overlay tool.
Source: ArcGIS 10.6 software.

Tool’s output is an integrated spatial suitability index with vales between 0 and 1. For current approach, the outputs are the Spatial Suitability Environmental Index and the Spatial Cost Potential Index.

Additional preprocessing and geoprocessing tools

Additional preprocessing tools were developed for helping in data clearance and formatting. Those were developed to fulfill specific necessities when preparing and complementing input data. These tools comprise:

a) *Adding data source information* tool
b) *Clean NoData* tool
c) *Species Richness Index* tool

Appendix E – VIZ-SPOWER-BR Geoanalytics dashboard

Geoprocessing modeling is an analysis that generates considerable amount of data. When geoprocessing drives a sustainability approach, the amount of data can increase drastically due to the integration of large number of criteria – layers – at regional or national scales.

On the other hand, the decision-making process is facing challenges for managing vast amounts of data, resulting from sustainability system analysis (STEINEBACH, GUHATHAKURTA, *et al.*, 2009).

Hence, analytics and geoanalytics – analytics that include geopositioning data – approaches are recommended to support the final decision-making process. An additional tool was assembled as a data-driven decision-making tool; A basic version of the Visualization dashboard tool, here called VIZ-SPOWER-BR. Ith considers the vast quantity of collected data (at least 80 layers with regional coverage) and modeling data (54 fiels with 64,224 features), generated throughout the whole GIS-based analysis. This tool is a dashboard based on analytics flowcharts, assembled in MS Power BI. The VIZ-SPOWER-BR aims of consolidating more information from the resulting data generated with the GIS-SPOWER-BR Toolbox: Offshore Wind Turbines Database and Offshore Wind Areas Database. A set of dynamic filtering dashboards present a vast amount of data in an interactive structure for decision-makers and policymakers. Figure E-1 shows the general view (static) of the VIZ-SPOWER-BR, Dashboard of the Coastal Zone modeling; the online version of the VIZ-SPOWER-BR is available in: VIZ-SPOWER-BR Data-driven tool for Integrated Strategic Planning of the Offshore Wind Development.

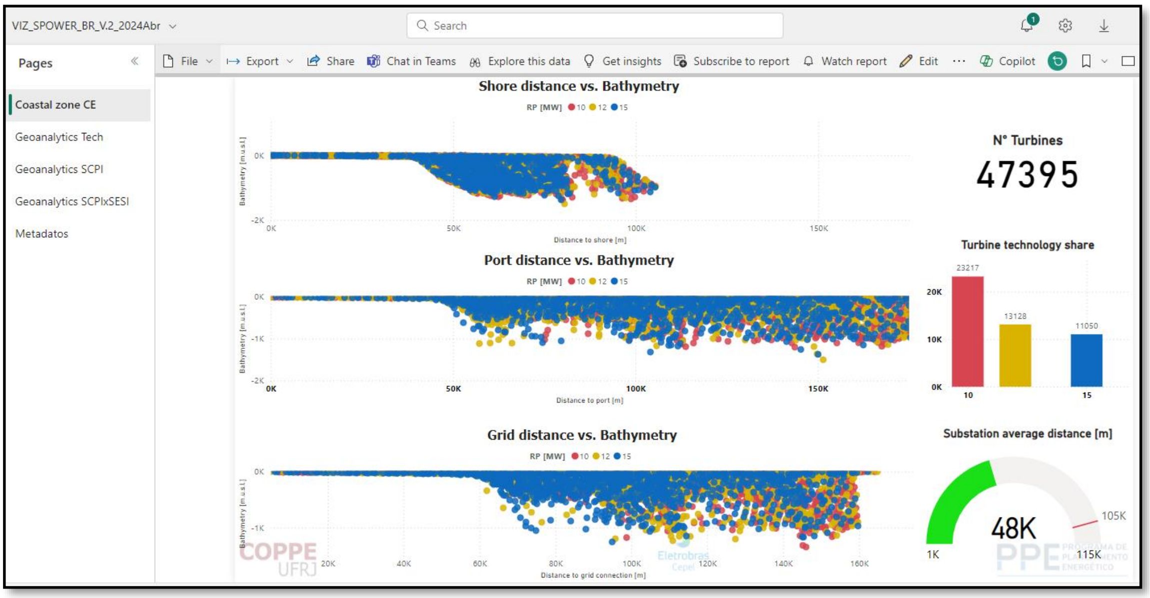
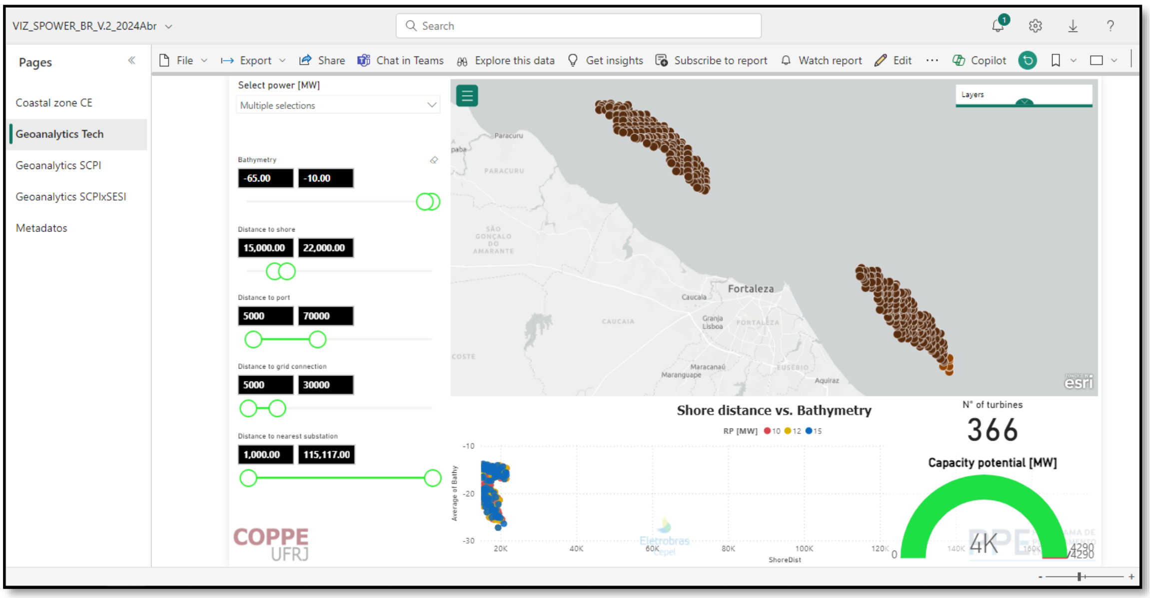


Figure E-1. VIZ-SPOWER-BR Data-driven tool: Summary of technology potential in the Ceara's Coastal Zone.



Select power [MW]: Multiple selections

Bathymetry: -65.00 / -10.00

Distance to shore: 15,000.00 / 22,000.00

Distance to port: 5000 / 70000

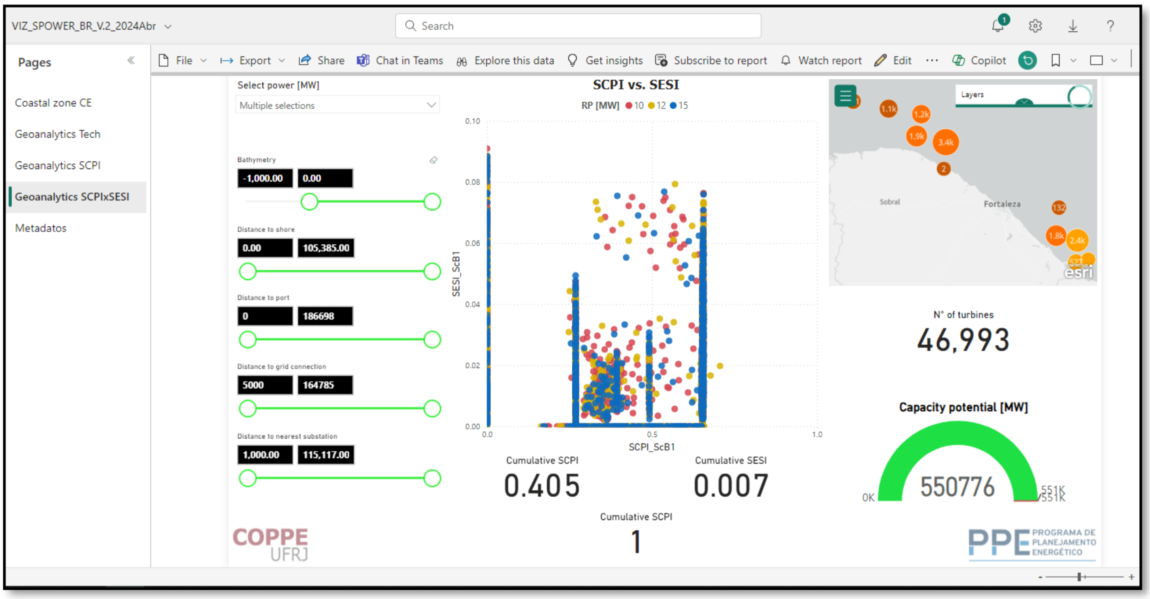
Distance to grid connection: 5000 / 30000

Distance to nearest substation: 1,000.00 / 115,117.00

N° of turbines: 366

Capacity potential [MW]: 4K (0 – 4290)

Figure E-2. VIZ-SPOWER-BR Data-driven tool: Geoanalytics of technical parameters.
Note: Figure shows an example of
Source: The Author.



Select power [MW]: Multiple selections

Bathymetry: -1,000.00 / 0.00

Distance to shore: 0.00 / 105,385.00

Distance to port: 0 / 186698

Distance to grid connection: 5000 / 164785

Distance to nearest substation: 1,000.00 / 115,117.00

Cumulative SCPI: 0.405

Cumulative SESI: 0.007

Cumulative SCPI: 1

N° of turbines: 46,993

Capacity potential [MW]: 550776 (0K – 551K)

Figure E-3. VIZ-SPOWER-BR analytics dashboard – Filtered by Scenario B1.
Note: Figure shows an example of
Source: The Author.

All data were generated through geoprocessing modeling which were hard-linked to the VIZ-SPOWER reports to be presented in a summarized and user-friendly interface. The strategic data is presented, showcasing the most important variables, totals, averages and trends, supporting agile and accurate decision-making. Table E-1. Shows the Geoanalytics codes used to limit SuOWAs pipeline:

Field Value	Dist. to Port [km]	Dist. to shore [nm]	Water depth [m]	15-MWTs	Installed target [MW]	Geoanalytics expression
1	< 35	< 12 nm	< 20	17	255	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "ShoreDist" < 22000 AND "InstPorDis" < 35000 AND "Bathy" > -20
2	< 36	< 12 nm	< 40	71	1,065	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "ShoreDist" < 22000 AND "InstPorDis" < 35000 AND "Bathy" > -40 AND "Bathy" < -20
3	< 37	> 12 nm	< 40	112	1,680	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "ShoreDist" > 22000 AND "InstPorDis" < 35000 AND "Bathy" > -40
4	35 - 70	< 12 nm	< 40	57	855	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "ShoreDist" < 22000 AND "InstPorDis" > 35000 AND "InstPorDis" < 70000 AND "Bathy" > -40
5	35 - 70	12 - 24 nm	< 60	229	3,435	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "ShoreDist" > 22000 AND "ShoreDist" < 44000 AND "InstPorDis" > 35000 AND "InstPorDis" < 70000 AND "Bathy" > -60
6	100 - 200	< 12	< 20	223	3,345	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "InstPorDis" > 100000 AND "InstPorDis" < 200000 AND "ShoreDist" < 22000 AND "Bathy" > -20
7	70 - 100	< 12 nm	< 20	57	855	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "InstPorDis" > 70000 AND "InstPorDis" < 100000 AND "ShoreDist" < 22000 AND "Bathy" > -20
8	70 - 100	12 - 24 nm	< 40	14	210	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "InstPorDis" > 70000 AND "InstPorDis" < 100000 AND "ShoreDist" > 22000 AND "ShoreDist" < 44000 AND "Bathy" > -20

Field Value	Dist. to Port [km]	Dist. to shore [nm]	Water depth [m]	15-MWTs	Installed target [MW]	Geoanalytics expression
10	100 - 200	12 - 24 nm	20 - 40	115	1,725	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "InstPorDis" > 100000 AND "InstPorDis" < 200000 AND "ShoreDist" > 22000 AND "ShoreDist" < 44000 AND "Bathy" < -20 AND "Bathy" > -40
11	< 70 km	> 24 nm	60 - 80	22	330	RP_MW = 15 AND "FeOWA_ScB1" = 1 AND "NcOWA_ScB1" = 1 AND "InstPorDis" < 70000 AND "ShoreDist" > 44000 AND "Bathy" < -60 AND "Bathy" > -80

Table E-1. Geoprocessing properties and codes for targeting the OWFs alternatives.
Source: The Author.

Appendix F – Detailed GIS-based tool’s equations

OW Feasible Areas Tool

The calculation is based on the general Equation 4-1.

$$\textbf{Constraint Index raster} = -\sum_{i=1}^{n} C_{i,j} \begin{cases} \textit{if Constraint Index} = \mathbf{0} \rightarrow \textit{Feasible area} \\ \textit{if Constraint Index} \leq -\mathbf{1} \rightarrow \textit{Exclusion area} \end{cases} \quad \textbf{Eq. 4-1}$$

The *Constraint Index raster* is the surface that indicates the number of constraints that the area of assessment has for offshore wind energy development (e.g., Constraint Index = 4 is an area with four cumulative constraints). Ci is a Boolean constraint raster (values 0 or 1) that represents the feasibility of offshore wind energy depending on constraint type i, varying from $i = 1$ to $n = 11$ (criteria). Then, let $spVi$ be a input spatial raster surface of continuous values, and let θ be the constraint threshold parameter for installing and offshore wind farm.

The Ci is calculated using the step function $H(x)_i$, that performs the conditional assessment for the spatial raster surface spV_i, at the pixel localization (x,y), then each pixel represents the continuous value of the spatial variable $spV_i(x,y)$ at the specific pixel location. Eq. 0-1 is defined as follows:

$$C_i = H(x)_i \begin{cases} 1 \; if \; x > \theta \rightarrow Constraint \\ 0 \; if \; x \leq \theta \rightarrow Feasible \end{cases} \quad \textbf{Eq. 0-1}$$

The conditional assessment for spatial raster surface (spatial variable) $spVi$ with the constraint threshold parameter θ can be written as:

$$C_i(\mathrm{x},\mathrm{y}) = H(spV_i(x,y) - \theta)_i \quad \textbf{Eq. 0-2}$$

Here, Ci is the output raster, where $C_i(x,y)$ is the Boolean constraint value (0 or 1), where $spV_i(x,y)$ represents the input value at pixel location (x,y) in the input raster spV_i. The conditional assessment evaluates whether each pixel’s value in spV_i, is greater than the constraint parameter θ or not, assigning 1 if true (constraint) and 0 otherwise (feasible). Thise representation assumes 2D spatial raster surfaces (spatial variables).

Appendix G – Strategic Planning Scenarios for Offshore Wind Energy Development

Element	Scenario A1	Scenario A2	Scenario B1	Scenario B2	C
Concept	Minimum constraints (current situation)	Higher profitability	Sustainability balance (environmental, social, economic)	Higher profitability under environmental constraints	Minimum environmental risk
Title	Base Scenario 20.23	Economic maximization	Sustainable Optimization	Smart investor	Socio-environmental precaution
Objective	Assess current trends and regulatory framework	Higher profitability	Achieving Sustainable Development	Economic and Environment tradeoff	Higher environmental and social protection
Decision-maker	Private/Public	Private	Public-Private	Private	Public environmental agency
Risk profile	High	High	Neutral	Neutral	Low
Timeframe	very short-term: 2028	Short-term: 2030	Target by 2050	Short term: 2035	very short-term: 2030
Geographical localization	Ceará, NE	Ceará, NE	Ceará, NE	Ceará, NE	Ceará, NE
Strategic restrictions:					
Bathymetry	> 1000 m.u.s.l.	> 30 m.u.s.l.	> 200 m.u.s.l.	> 50 m.u.s.l.	> 50 m.u.s.l.
Average wind speed	< 7 m/s	< 8 m/s	< 7 m/s	< 8 m/s	< 8 m/s
Capacity Factor	No constraint	< 36% (> coastal value)	< 30 %	< 40% (on Ceará's coast)	< 50%
Environmental vulnerability	UCs (All: State)	UCs (All: Federal)	UCs + UCs + Ex. High APCB/VHRI	UCs + Ex. High APCB	UCs + APCB + VHRI
Min. distance to shore	No constraint	3 km and < 5 m.u.s.l.	< 10 km	< 20H	22 km
Archeological sites	No constraint	< 3km	< 3 km	< 3 km	< 6 km
Touristic beaches buffer	No constraint	< 3 km	< 14 km	< 8 km	< 24 km
Max. Distance to shore	> 500 km	> 70 km	> 150 km	> 100 km	N/C
Max. Distance to ports	>500 km	> 50 km	> 300 km	> 200 km	N/C
Max. Distance to grid connection (SS)	> 150 km	> 50 km	> 100 km	> 80 km	N/C

Element	Scenario A1	Scenario A2	Scenario B1	Scenario B2	C
Strategic sea use conflicts with human activities and natural resources at coastal-marine zone: Protected areas Military areas Oil and Gas Infrastructure Mineral extraction Fishery Industrial Maritime traffic Tourism Offshore RE	Fed. & Ste. UCs (IP) All areas Block and production fields Buffer 500m from pipelines N/C N/C N/C N/C Planned OWFs	All UCs All areas Blocks and fields Buffer 500m from pipelines All "fases" N/C 500 m Cabotage Buffer 10 km (TB) N/C	All UCs All areas Block and production fields Buffer 500m pls + cables Operative (Lavra) > 8h Operaion density 500 m Cb + Sh (WA) Buffer 14 km (TB) >750 km^2	All UCs + APCB-Eh. All areas Block and production fields Buffer 500m pls + cables All "fases" (Regimes) > 8h Operaion density 500 m Cb + Sh (WA) Buffer 14 km (TB) > 1.000 km^2	All UCs, APCB, BioRes All areas Block and production fields Buffer 500m pls + cables All "fases" > 4h Operaion density 500 m Cb + Sh (WA) "Buffer 25 km (TB) >250 km^2
Offshore wind farm optimization assumptions	15 MW, 5*RD	21 MW, 5*RD	10-12 MW, 8*RD	15 MW, 7*RD	8 MW, 10*RD
Transmission and connection optimization assumptions	no optimization	Closest distance to Substation	Optimized to connection	Optimized distance to Substation	Optimized-High availability
Port infrastructure and logistics	Closest port	Closest port	Installation-O&M	Closest port	High System Readiness level
Potential solution alternatives	Total available area	Least cost-highest generation	High generation-Low cost-Low environmental risk	Optimal cost	Minimum area

Appendix H – Parametrization references

Development dimension	Factor/Criteria	Spatial variable/indicator	Parameter (Reference examples)
Technological	Wind resource	Mean wind speed at 150m	C: < 7 m/s (BEITER *et al.*, 2016; GUSATU *et al.*, 2020)
			S: > 7m/s (Beiter et al. 2016, GUSATU *et al.*, 2020)
Technical/technological	Wind resource	Wind direction [N/A]	NA
Technical/technological	Wind resource	Capacity factor [%]	C: < 30% < 36% (FELIPE, 2014)
			S: > 30% Ref. in the coast of Ceará > 36 % (FELIPE, 2014)
Technical/technological	Geomorphology	Bathymetry/Water depth [m.u.s.l.]	C floating: > 1000 m.u.s.l. (BEITER *et al.*, 2016) > 200 m.u.s.l. (MSP) > 500 m.u.s.l. C fix-bottom: > 50 m.u.s.l. (BHATTACHARYA, 2019; TATUM & HILL, 2023); IOANNOU *et al.*, 2018; BOSCH *et al.*, 2018).
			S: < 1000 m.u.s.l.
Technical/technological	Wave resource	100-year wave [m]	C: N/A
			S: < 100-year wave
Technical/technological	Geology	Sedimentary material/Slope [category]	C: N/A
			S: Material resistance/% (FRANCISCONI *et al.*, 1974; TATUM & HILL, 2023)
Environmental	Biological resources/Biodiversity	Strategic ecosystem areas [presence]	C: Absolute HERNANDEZ *et al.*, 2021; MAXWELL *et al.*, 2022; BAULAZ *et al.*, 2023)
Environmental	Biological resources/Biodiversity	Seasonal vulnerable areas/Conservation areas (UCs-Sustainable use, Prioritized areas for conservation, PANs, Critical habitats) [type]	C: if defined in robust local studies
			S: if defined in federal/regional studies HERNANDEZ *et al.*, 2021; MAXWELL *et al.*, 2022; BAULAZ *et al.*, 2023)
Environmental	Geomorphological resources	Min. Bathymetry [m.u.s.l.]	C: 5 m.u.s.l.
Social	Acceptance	Perception index [N/A]	N/A (out of scope) S: N/A
Social	Human resources	Presence of Universities/Technical institutes [presence]	NA (out of scope) (Authors)
Social	Landscape/ Seascape	Min. Shore distance [km]	C: < 22 km (12 nm) (SCHILLINGS *et al.*, 2012) < 10 km (MÖLLER *et al.*, 2012); (OU *et al.*, 2018); (GUSATU *et al.*, 2020) < 8 km (VINHOZA & SCHAEFFER, 2021a)

Development dimension	Factor/Criteria	Spatial variable/indicator	Parameter (Reference examples)
			S: > 8 or 10, 22 km (SULLIVAN *et al.*, 2013); SHILLINGS *et al.*, 2012)
Social	Heritage	Archeologic sites [presence]	C: buffer 3 km (based on analysis of SPYRIDONIDOU *et al.*, 2020)
			S: > 3 km (based on analysis of SPYRIDONIDOU *et al.*, 2020)
Economic	Max. distance to shore	Max. shore distance [km]	C: > 70 – 175 km (SCHILLINGS *et al.*, 2012) > 200 km (VINHOZA & SCHAEFFER, 2021a)
			S: > 10 km (OU *et al.*, 2018; IOANNOU *et al.*, 2018; BOSCH *et al.*, 2018.
Economic	Logistical/Support infrastructure	Port Distance [km]	C: > 80 km (SPYRIDONIDOU *et al.*, 2020) > 100 km (SPYRIDONIDOU *et al.*, 2020) > 500 km (VINHOZA & SCHAEFFER, 2021b); ; IOANNOU *et al.*, 2018; BOSCH *et al.*, 2018.
			S: < 80 - 100 km
Economic	Logistical/Support infrastructure	Grid connection distance HV (> 200 kV) [km]	C: > 20 km (KIM *et al.*, 2016) > 80 km (SPYRIDONIDOU *et al.*, 2020) > 100 km (SPYRIDONIDOU *et al.*, 2020) > 150 km (based on analysis of MÜLLER, 2019)
Multi-use	Protected Areas	Static vulnerable/Endangered areas (UCs-Integral Protection, official threatened/endangered areas, Key Biodiversity Areas, Extremely High Priority/Importance) [type]	C: Conflict areas Legally defined Conservation Units (Integral Protection category) (MMA, 2014; ICMBio, 2019; OU *et al.*, 2018)
			S: Low Conflict, Compatible/Non-conflict, non-overlapping
Multi-use	Military Areas	Restricted areas [presence]	C: absolute (GUSATU *et al.*, 2020; SPYRIDONIDOU *et al.*, 2020)
			S: (OU *et al.*, 2018)
Multi-use	Fishery activity (Industrial/Artisanal)	Industrial fishery intensity (apparent effort) [hours/km^2]	C: > 8 (Standard working-day hours)
			S: < 8 (Standard working-day hours)
Multi-use	O&G activity	Exploratory blocks, Production fields [presence]	C: absolute (potetial conflict) < 500 m from wells/platforms (Ricarte, 2007; RODRIGUEZ *et al.*, 2011; GUSATU *et al.*, 2020); Billing n° 50-2020 (DPC-Marinha

Development dimension	Factor/Criteria	Spatial variable/indicator	Parameter (Reference examples)
			do Brasil, 2020); NORMAM-17 5th Rev. (DHN, 2021)
			S: > 500 m from wells/platforms NORMAM-17 (DHN, 2021); OU *et al.*, 2018
Multi-use	Tourism activity	Seascape/Recreative sports	C: < 14 km (SULLIVAN *et al.*, 2013)
			S: > 14 km (SULLIVAN *et al.*, 2013)
Multi-use	Infrastructure	Pipelines, Cables [presence]	C: < 500 m (RICARTE, 2007; RODRIGUEZ *et al.*, 2011; GUSATU *et al.*, 2020; Decree n° 50-2020 DPC-MARINHA DO BRASIL, 2020; NORMAM-17 5th Rev., DHN, 2021; OU *et al.*, 2018).
Multi-use	Mineral resources	Mineral extraction areas [presence]	C: absolute
			S: special categories/status
Multi-use	Maritime traffic	Rout density / Cabotage lines [routs/km^2/year] (based on MarineTraffic.com online density maps)	W: > 114 [routs/0.31 km^2/year]
			S: < 114 [routs/0.31 km^2/year]
Multi-use	Offshore Renewable Energy	OWFs [presence]	C: Interest submited to MMA (Decree 10946-2022)
			S: Planned + > 500 m from structures (Billing n° 50-2020 DPC-MARINHA DO BRASIL, 2020; NORMAM-17 5th Rev. - DHN, 2021).

Table H-1. Multi-criteria parametrization values and references. Source: The Author based on cited literature.

Note: Constraint threshold (C), Suitability threshold (S), Warning threshold (W).

Appendix I – Matrix Activity-Activity format and instructions

This table[16] aims to collect assessments of Compatibility between activities focusing in Offshore Wind Energy (OWE).

Evaluator must analyze and assess the Activity-Activity Matrix, considering the new Offshore Wind Energy Generation activities as the assessed activity. Considering the Marine Spatial Planning framework published by the UNESCO Manuals (UNESCO-IOC European Commission, 2021; Ehler and Douvere, 2013), an OWE-Activities Matrix was configured (OWE-Act Analysis sheet).

Compatibility assessment between activities (OWE vs. Other marine activities) must be done based on the Compatibility-conflict matrix between human uses, following the instructions:

1. Fill the cell EVALUATOR (B7) with brief description of your knowledge about Offshore Wind Energy, Sea-use, and Land-use compatibility-conflict analysis.
[N: Previous knowledge about these topics are required.

2. Save the Excel file (*.xlsx) with the same name, followed by your name.

3. Cell will be colored automatically, depending on the number inserted: 0, 1, -2, -3, -99, etc.

Empty areas = 10 (blue)
Compatible = 3 (in green)
Likely compatible = 2 (in yellow)
No apparent interaction = 0 (in grey)
Future conflict = - 2 (in orange)
Conflict = -3 (in red)
Low quality (manual digitalization) = -88 (in pink)
No public data available = -99 (in black)

4. Assess columns D, E, F based on CEUs maps, considering only the areas within the Light Green boundary (Feasible areas).
[N: conflict or compatibility depends on spatial overlaying (competitiveness for space) or resources; in addition, temporal/seasonal competitiveness also may exist.

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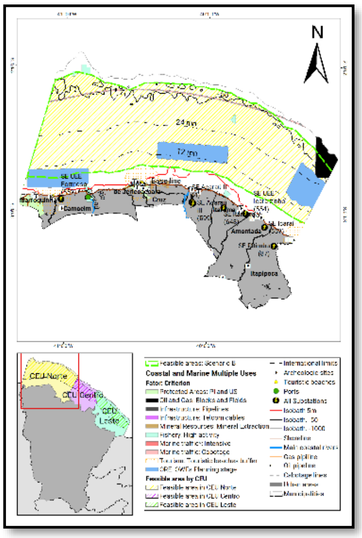
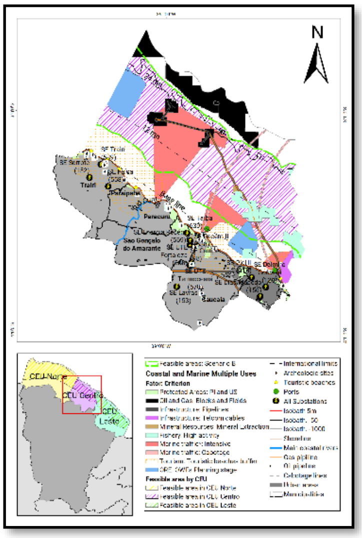
[16] Excel file name: Assessment_Table_Activity-Activity_Analysis - OWE-Activities_Compatibility - (EvaluatorName)

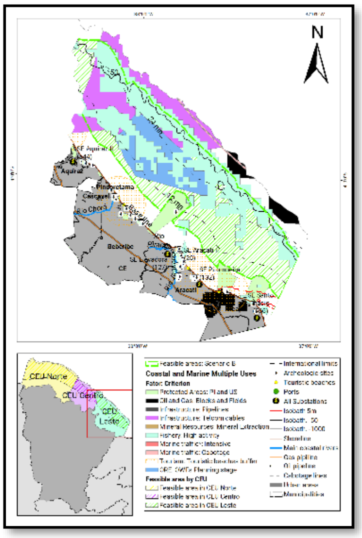
The "OWE-Act matrix" shows:

- Marine Activities (Column A).
- Proposed compatibility assessment based on the Coastal and Marine compatibility suggested by UNESCO (Column B).
- Proposed compatibility assessment based on current research, based on current offshore wind projects in State of Ceará (Brazil), at planning stage by 2021 (Column C).
- Available cells for Compatibility Assessment of the OWE activity within the Coastal Environmental Units (CEUs), previously defined by the research's team. (Columns D, E, F).

Reference mapping for selected Scenario (Ex.: Scenario B.1 – Sustainable optimization scenario):







OWE-activity Matrix	OWE UNESCO Reference	Scenario *i* CEU *j* OWA *k*
Renewable Energy Offshore	3	Start here
Current OWFs (early planning)	1	
Commercial Fishing: Nets	1	
Commercial Fishing: Hooks/Fishing Line	1	
Commercial Fishing: Traps/Lobster Pots	1	
Commercial Fishing: Harpoons/Spears	1	
Commercial Fishing: Trawls/Dredges	1	
Commercial Fishing: Seine Nets	1	
Commercial Fishing: Beach Seine	1	
Commercial Fishing: Seine	3	
Fish Farms/Mariculture	1	
Commercial Fishing: Hooks/Fishing Line	1	
Recreational Fishing: Traps/Lobster Pots	1	
Recreational Fishing: Shell fishing	1	

OWE-activity Matrix	OWE UNESCO Reference	Scenario *i* CEU *j* OWA *k*
Artisanal Fishing (Brazil):	1	
Recreation: Sailing	1	
Recreation: Boats	1	
Recreation: Personal Watercraft	1	
Recreation: Diving	1	
Recreation: Wildlife Watching	1	
Recreation: Water Sports**	2	
Recreation: Beach Tourism**	1	
Maritime Transport	1	
Dock and Port Operations	1	
Dock and Port Dredging	1	
Dredged Material Disposal	1	
Offshore Airports	1	
Offshore Industrial Plants	2	
Offshore LNG Terminals	1	
Offshore Oil and Gas Exploration	1	
Offshore Oil and Gas Production	1	
Cables, Pipelines, Gas Lines, Transmission Lines	1	
Sand and Gravel Extraction	1	
Offshore Renewable Energy: Wave Farms	1	
Offshore Renewable Energy: Tidal Energy	1	
Offshore Renewable Energy: Currents	1	
Seawater Desalination Plants	1	
Carbon Capture Plants	2	
Military Operations	1	

Table I-1. Support Mapping for carrying out OWE-Activity Matrix assessment.

Appendix J – Scientific and academic publications

International journals publications

O. M. Hernandez C., Milad Shadman, Mojtaba Maali Amiri, Corbiniano Silva, Segen F. Estefen, Emilio La Rovere (2021). "***Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil***". *Renewable and Sustainable Energy Reviews*, Elsevier. <https://doi.org/10.1016/j.rser.2021.110994>.

Computer Program Regristry

O. M. Hernandez C., Eliab Ricarte, Emilio La Rovere (2022). Industrial Property Authoryon ***GIS-SPOWER-BR toolbox: GIS-based system for Strategic Planning of Offshore Wind Renewable Energy in Brazil***. Industrial Property of software, INPI. <RPC: BR 512022001514-5>.

Conference and congress publications

O.M. Hernandez C., E. Ricarte, E. La Rovere. (2022). "***Abordagem estratégica sustentável para avaliação locacional de Parques Eólicos Offshore e oportunidades da cadeia de valor no Brasil***". Brazil WindPower 2022. Rio de Janeiro, Brazil (October 2022). <Trabalhos técnicos: Eólica Offshore>.

O.M. Hernandez C., E. Ricarte, E. La Rovere. (2022). "***Aplicação dos conceitos de Planejamento Espacial Marinho para a identificação de áreas disponíveis para desenvolvimento de energia eólica offshore no Brasil***", COPPE/UFRJ. - XIII Congresso Brasileiro de Planejamento Energético – Online, Brazil (August 2022). <Tema: Eólica>.

O.M. Hernandez C., A. Magrini, E. La Rovere. (2018). ***"Análise das ACV aplicadas na avaliação dos Sistemas de Geração de Energia de Elétrica em um contexto internacional e suas novas perspectivas"***, COPPE/UFRJ. - XI Congresso Brasileiro de Planejamento Energético – Cuiabá, Brazil (September 2018).

Co-authored publications and contributions

J. Barboza Mariano, M. Hernandez, A. Szklo, T. Santos, and B.S.L. Cunha. (2023). "***Brazilian Policies and Regulations in the Offshore Energy Generation Chain: Implications for Short and Mid-term Investments***". Oil, Gas & Energy Law Intelligence Journal 20 (5): 1-45. ISSN: 1875-418X. www.ogel.org. URL: <www.ogel.org/article.asp?key=4052>.

Carolina Lemos, O. M. Hernandez C., Cristiano Vilardo, Leandro Bugoni, Isabel Sousa-pinto. (2023). "***Environmental assessment of proposed areas for offshore wind farms off southern Brazil based on ecological niche modeling and a species richness index for albatrosses and petrels***". Global Ecology and Conservation. <https://doi.org/10.1016/j.gecco.2022.e02360>.

Silvia Blajberg Schaeffel, Fernanda Fortes Westin, Omar Mauricio Hernandez & Emilio Lèbre La Rovere. **"*Replacing Fossil Fuels by Wind Power in Energy Supply to Offshore Oil & Gas Exploration and Production Activities – Possibilities for Brazil*"**, LIMA/COPPE/UFRJ. Offshore Technology Conference Brazil (OTC-29879-MS). Rio de Janeiro, Brazil (November 2019). <https://doi.org/10.4043/29879-MS>.

J. Lassio, L. Cristo, F. Siqueira, **O.M. Hernandez**, A. Magrini. **(2017).** *Avaliação do Ciclo de Vida do biodiesel: uma análise metodológica*. COPPE/UFRJ. - XVII Congresso Brasileiro de Energia - Rio de Janeiro, Brazil (September 2017).