Journal of
*Marine Science
and Engineering*

MDPI

Article

Reducing Emissions in the Maritime Sector: Offshore Wind Energy as a Key Factor

Isabel C. Gil-García [1,*] and Ana Fernández-Guillamón [1,2]

[1] Faculty of Engineering, Distance University of Madrid (UDIMA), c/Coruña, km 38500, Collado Villalba, 28400 Madrid, Spain; ana.fguillamon@uclm.es
[2] Department of Applied Mechanics and Projects Eng, Universidad de Castilla—La Mancha, Av. de España, s/n, 02071 Albacete, Spain
* Correspondance: isabelcristina.gil@udima.es

Abstract: The maritime environment is the setting for a variety of economic activities, such as offshore wind energy, aquaculture, salt extraction, and oil and gas platforms. While some of these activities have a long-term presence, others require decarbonization as they head towards their demise. In this context, the aim of this study is to develop a methodology to replace the electrical energy from offshore high-emission industrial processes with clean electricity generated by offshore wind energy. The proposal is structured in three phases: initiation, which involves the collection of quantitative, technical, and geospatial information of the study area; indicators, where the main indicators are calculated, and the best alternative is selected using multi-criteria evaluation methods; and finally, short-, medium-, and long-term scenarios are proposed. The methodology is evaluated in Spain, and the best alternative, which has a nominal power of 225 MW, is capable of avoiding up to 1.44 MtCO$_2$ by 2050.

Keywords: offshore wind energy; optimal selection; maritime sector; multi-criteria evaluation methods

check for updates

Citation: Gil-García, I.C.; Fernández-Guillamón, A. Reducing Emissions in the Maritime Sector: Offshore Wind Energy as a Key Factor. *J. Mar. Sci. Eng.* **2024**, *12*, 1985. https://doi.org/10.3390/jmse12111985

Academic Editor: Markel Penalba

Received: 8 October 2024
Revised: 1 November 2024
Accepted: 1 November 2024
Published: 3 November 2024

1. Introduction

In the current context of the climate emergency, transitioning the energy system towards a fossil-fuel-free model emerges as a crucial and urgent response to the global challenges posed by climate change [1]. This energy transformation is not only necessary but imperative to meet international commitments, such as the Paris Agreement. This commitment aims to limit the global temperature increase to 1.5 °C above pre-industrial levels [2] and is considered essential by the scientific community. In fact, exceeding this threshold could trigger irreversible and catastrophic climate impacts, affecting both ecosystems and human societies worldwide [3]. The shift towards clean, sustainable, and fossil-fuel-free energy is a complex challenge that requires a comprehensive rethinking of the current energy system. Renewable energy sources (such as solar, wind, geothermal, and hydroelectric power) play a central role in this transition, providing clean and accessible energy that, unlike fossil fuels, does not emit greenhouse gases [4].

However, the widespread adoption of these technologies requires significant investment in infrastructure and technology, as well as a structural transformation in how countries produce, distribute, and consume energy. A key component of this transformation is clean electrification. The acceleration of electrification through renewable energy sources not only reduces carbon emissions in sectors traditionally dependent on fossil fuels (such as transportation and industry), but also fosters the development of more efficient and resilient power grids. These grids need to include emerging technologies like energy storage systems and smart systems to ensure the stability of the electricity supply, mainly due to the intermittent nature of renewable sources like solar and wind [5]. Moreover, and despite the technological advances, the energy transition cannot rely solely on technology; a coordinated and collaborative global effort is necessary. Governments, industries, and other key stakeholders must work together to drive ambitious public policies that encourage investment in renewable energy, promote technological innovation, and facilitate the shift to a low-carbon economy. This kind of global cooperation is crucial for overcoming the economic, political, and social barriers that currently hinder the widespread adoption of clean technologies [6].

In this regard, it is vital that energy policies are aligned with climate goals, promoting the decarbonization of key sectors such as energy, industry, and transportation. Implementing regulatory frameworks that incentivize investment in clean technologies, creating subsidies for renewable energy, and gradually phasing out subsidies for fossil fuels are some necessary steps to advance this process [7]. Moreover, the maritime environment emerges as a space of opportunities and challenges in the global energy transition. This environment supports a wide range of economic activities, from offshore wind energy to aquaculture and the extraction of resources like oil, gas, and salt [8]. Offshore wind energy, in particular, is one of the most promising alternatives for generating renewable energy at a massive scale. However, these activities must be managed sustainably to ensure that marine ecosystems, which are crucial for climate balance and global biodiversity, are not compromised.

Offshore wind energy has emerged as one of the key solutions to address the challenges of climate change and the transition to a cleaner and more sustainable energy mix. This type of energy, which harnesses the power of wind in areas far from the coast, has not only gained interest in recent years, but has also begun to deeply transform the global energy landscape [9]. Technological advancements in wind turbine design, offshore wind farm installations, and improvements in electricity transmission infrastructure have made offshore wind energy more efficient and economically competitive. At the same time, growing awareness of the need to reduce greenhouse gas emissions has driven governments and companies to heavily invest in this renewable energy source [10].

Over the period from 2010 to 2023, the offshore wind industry experienced astonishing exponential growth, exceeding 2400% in terms of total installed capacity globally. China stands out as the undisputed leader in this ranking, with an installed capacity of 37.8 GW, accounting for more than half of the global total at an impressive 55%. Following closely behind China are other wind powerhouses, led by the UK, which has 14.8 GW (22%), followed by Germany with 8.3 GW (12%), the Netherlands with 4.8 GW (7%), and Denmark with 2.6 GW (3.8%). The rest of the world has also contributed significantly to this growth, adding 6.9 GW to the total installed capacity (see Figure 1). This phenomenal increase in wind infrastructure reflects unprecedented growth in the sector, marking a significant milestone in the transition towards renewable energy sources worldwide [11].

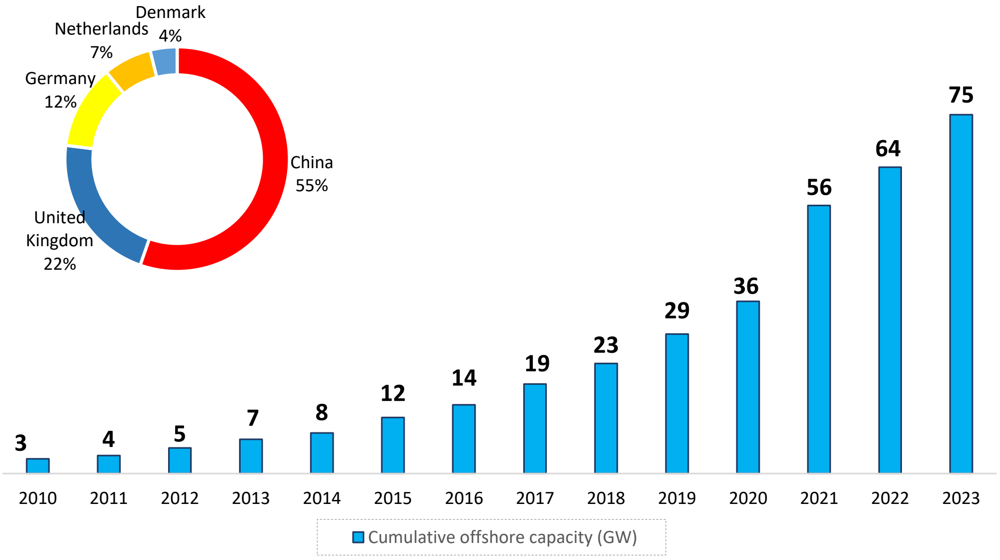

Figure 1. Evolution of offshore wind capacity in the period 2010–2023. Top five by country. Data source [11]. Own elaboration.

1.1. Literature Review

The potential of offshore wind energy to generate large amounts of clean and renewable electricity has caught the attention of not only governments and investors, but also coastal communities that see these projects as an opportunity for economic development and job creation. Countries like Denmark, the United Kingdom, and Germany have led the deployment of offshore wind farms, setting precedents for how this technology can be integrated into their energy grids. As more regions explore the development of offshore wind energy, the environmental and economic benefits associated with its implementation are becoming increasingly clear. However, the marine activity landscape is diverse and encompasses a wide range of sectors that also face their own challenges. For example, aquaculture, which includes the farming of fish, shellfish, and algae, is a key sector for food production but must grapple with issues such as sustainable marine resource management, water quality, and environmental impacts. Aquaculture practices must evolve to ensure that the use of marine resources does not compromise biodiversity or ecosystem health. Innovation in farming technologies and the adoption of more ecological approaches are essential to ensure that aquaculture can grow sustainably [12]. On the other hand, salt extraction, an activity that has been part of many civilizations' histories, is also undergoing transformations. Although traditionally a less visible sector, salt extraction is being influenced by changing market demands and growing environmental concerns. The need to improve production techniques and reduce ecological impacts has become a priority, especially in regions where salt extraction can affect coastal habitats and water quality [13]. Similarly, offshore oil and gas platforms, which have played a crucial role in the global economy for decades, now face increasing pressure to adapt to a context where sustainability is highly valued. The extraction of fossil fuels has been a pillar of modern industrialization, but concerns about its environmental impact, including the emission of carbon dioxide and other greenhouse gases, have led to a reevaluation of its role in the future economy [14]. Today, companies in the sector are being forced to consider measures to reduce their carbon footprint, invest in clean technologies, and, in some cases, diversify their operations towards more sustainable energy sources, such as wind and solar power. The growing recognition of the negative effects of prolonged fossil fuel use on the environment and climate has driven society to demand a change. Public pressure, along with stricter regulations, has led major oil and gas companies to seriously consider transitioning to cleaner energy sources. This transition is not only essential to reduce global emissions, but also to ensure the long-term economic and environmental viability of these industries [15]. In this context, offshore wind energy is not just a necessary alternative, but also a crucial opportunity to transform the use of oceans towards more sustainable and responsible activities. The challenge for maritime activities today lies in finding the right balance between the economic exploitation of marine resources and the preservation of the fragile marine ecosystem. In the face of increasing pressure from the climate crisis, the transition towards a greener and more sustainable economy is not only inevitable but also urgent. Many of the economic activities linked to the ocean, particularly those with high carbon emissions, are facing the need to either adapt or completely transform. This transformation aims not only to minimize environmental impact, but also to contribute actively to climate change mitigation and the advancement of clean energy solutions.

1.2. Motivation and Contributions

The objective of this research is to propose a methodology to partially or totally replace the electricity used in polluting offshore industrial processes with clean energy generated from offshore wind sources. This electricity would be injected directly into industries, creating an industrial community and reducing energy transfer losses, which would also lead to a significant reduction in greenhouse gas emissions, contributing to the decarbonization of maritime operations.

The proposal includes an optimized geospatial analysis that considers factors such as protected areas and coexistence with activities such as fishing, maritime traffic, and national defence. This methodology identifies optimal locations for operating offshore wind farms without negatively affecting other activities or compromising biodiversity.

The approach prioritizes carbon emission reduction and energy efficiency, aligning with the Sustainable Development Goals (SDGs), particularly SDGs 7, 9, and 13, which promote clean energy and climate action. Although the study focuses on the Spanish coasts, it can be applied to other regions, as long as the limitation of spatial layers allows it.

The structure of the work is organized as follows: in Section 2 the methods and the proposed methodology are developed; then, Section 3 evaluates the proposal through a case study; Section 4 discusses the results, and finally, Section 5 presents the main conclusions obtained.

2. Materials and Methods

2.1. Phases

Figure 2 shows an overview of the proposed methods, consisting of three phases: Start, Indicators, and Exit.

2.1.1. Phase 1—Start

This phase involves a comprehensive review of the data required to calculate the indicators corresponding to phase 2, whether they are spatial, qualitative, or quantitative. It is divided into three fundamental steps:

1. Identifying areas with potential for offshore wind energy generation: Identifying areas with potential for offshore wind energy involves a highly complex spatial process that encompasses a wide variety of factors:
    - Climatic—such as wind speed, bathymetry (sea depth), wave height, and turbulence, as these directly influence the efficiency and safety of offshore wind installations;
    - Environmental—must also be taken into account to minimize ecological impact, such as proximity to protected areas and habitat conservation;
    - Social—such as the visual impact of wind turbines on communities, noise levels, existing maritime routes, and fishing zones that may be affected by the installation of infrastructure, which are also assessed [16].

    These elements are categorized into exclusion criteria, which serve to eliminate unsuitable areas, and selection criteria, which help identify the most promising areas within the study region [17,18].

    Depending on the study area, these regions may already be regulated. In Spain, for example, the Maritime Spatial Planning Plans (POEM) are a key tool within the European Union's Integrated Maritime Policy. These plans are implemented to comply with Directive 2014/89/EU of the European Parliament and of the Council, which establishes a framework for maritime spatial planning [19]. In Spain, this directive has been incorporated through the Marine Environment Protection Law 41/2010 [20] and Royal Decree 363/2017, which establish a framework for maritime spatial planning [21]. This spatial planning process has required significant coordination among various ministries with maritime competences, coastal autonomous communities, and various sectors related to the use of the sea.

    If the study area does not have a maritime spatial planning plan, it is essential to obtain the relevant data and convert them into appropriate spatial layers. This process involves the collection, structuring, and transformation of information for subsequent analysis. Generally, these transformations require the use of advanced computer tools and the execution of complex processes, such as data processing using programming languages such as R, or carrying out specialized queries in geospatial databases. These tasks can involve everything from data cleaning and preparation to its visualization and modeling to ensure proper management of maritime space.
2. Evaluating which maritime activities could be partially or fully decarbonized through the use of electricity generated from offshore winds: In this step, a comprehensive anal-

ysis is conducted to identify maritime activities that could benefit from the electricity generated by offshore wind turbines, aiming to reduce their reliance on conventional energy sources and promote sustainability. For instance:

- In aquaculture, wind energy can be used to power water-pumping, heating, and cooling systems, as well as logistics and transportation operations, significantly reducing greenhouse gas emissions associated with these activities [22].
- In salt extraction, energy used for the extraction, pumping, and treatment of seawater, as well as for heating and evaporation systems, could also be replaced with wind energy, contributing to a lower carbon footprint in salt production processes [23].
- Port activities, which require substantial energy for the operation of cranes, machinery, warehouse refrigeration, lighting, and loading and unloading of ships, could be decarbonized with the use of wind energy [24].

Integrating renewable energy into these sectors would not only enhance their sustainability but also reduce operational costs in the long term.

3. Selecting the most appropriate wind turbine technology for the project implementation: Once potential areas have been identified and decarbonization opportunities have been assessed, the next step is to select the most suitable wind turbine technology. This process includes considering technical factors such as turbulence, which must be evaluated to comply with standards set by the IEC 61400-1 norm [25], and the bathymetry of the study area, which determines whether a fixed or floating foundation is required for the wind turbines [26]. Fixed foundations are appropriate for shallow waters, while floating foundations allow turbines to be installed in deeper waters, where winds tend to be stronger and more consistent. Other aspects, such as the generation capacity of each type of wind turbine, their resistance to adverse weather conditions, and their long-term maintenance requirements, must also be considered. The correct selection of technology not only ensures the technical and economic viability of the project but also minimizes environmental and social impacts, thus guaranteeing the project's long-term success.

2.1.2. Phase 2—Indicators

During this phase of the process, the relevant indicators for each of the alternatives are calculated in order to establish a ranking that allows them to be compared. These indicators are divided into several categories: first, those related to the technical aspects of the wind farm design; second, the selection criteria that determine which alternatives are better or worse; and finally, those corresponding to the multi-criteria evaluation methods, which include the weights assigned to each selection criterion and the method used to rank the alternatives.

The steps to follow are detailed below:

1. The establishment of the design of an offshore wind farm is a multifaceted process that requires careful consideration of several factors. Initially, the nominal capacity of the plant is determined, followed by a thorough analysis of the wind direction to ensure that the alignments of the wind turbines are optimal in relation to the predominant energy rose [27]. The distances between the wind turbines are determined based on the rotor diameter (D) selected during the initial phase of the project. It is established that between the alignments of wind turbines, the distance should be in the range of 7 to 10 times D, while between the wind turbines in the same row it is recommended to maintain a distance of 3 to 5 times D [27]. This specific arrangement helps to minimize the wake effect, thus optimizing the overall performance of the park. It is essential to use specialized tools, such as technical design programs, to accurately perform this distribution. Using spatial layers in these programs, the three-dimensional arrangement of the wind turbines can be visualized and analyzed, facilitating decision making and optimization of the offshore wind farm design. A polygon mesh is created that comprehensively covers the potential area, ensuring complete and

detailed coverage for subsequent analysis. This approach allows all possible locations within the study area to be explored and facilitates comparative evaluation of the different alternatives.

2. During the generation of the decision matrix, the selection criteria that characterize each alternative are defined, covering technical, economic, and environmental aspects. Among the recommended criteria are:
    - Annual electric energy generated: This criterion evaluates the amount of electric energy expected to be produced each year with each alternative. It is a key indicator of the project's energy generation capacity [28].
    - Wake effect losses: This criterion considers the efficiency losses caused by the wake effect between the wind turbines. A lower wake effect indicates a more efficient arrangement of wind turbines and, therefore, less energy loss [29].
    - Capex: This refers to the costs associated with the initial investment in the wind farm infrastructure, including the purchase and installation of equipment and the construction of the necessary infrastructure [30].
    - Opex: This criterion evaluates the expected operating and maintenance costs over the life of the wind farm, including repairs, regular inspections, and operating costs.

    The calculation of the electrical energy fed into the grid is a complex process that can be carried out using general equations, although the use of specialized programs in the wind sector (such as WasP© [31] or FLORIS© [32]) is recommended. These programs can provide detailed and accurate analysis, taking into account a variety of factors, such as wind speed, air density, and specific characteristics of the wind farm design [33].
3. The development of a ranking of alternatives based on the indicators from the previous step is a complex procedure that is usually addressed using multi-criteria evaluation methods (MCDM) [34]. These methods are widely used and have numerous variants for their application. In general terms, the process begins with the definition of the relative weights of the different factors or criteria used in the evaluation [35]. Subsequently, a ranking of the alternatives is established based on these weights and the values obtained for each criterion [36]. For example, the entropy method is used to determine the relative weights of criteria, allowing decision makers to assign importance to each of them in relation to the others. Once these weights have been established, the VIKOR technique is used to rank the alternatives based on achieving a solution close to the ideal and considering group satisfaction. It evaluates each alternative in relation to the ideal and anti-ideal criteria, and calculates a metric that weighs the proximity of each option to these values [37].

2.1.3. Phase 3—Exit

Considering the ranking of alternatives and the objectives set regarding the installation capacity of offshore wind energy, various short-, medium-, and long-term scenarios have been outlined. These scenarios propose a varied allocation of electrical energy, according to the consumption needs of different maritime sectors. It is crucial to highlight that these sectors must commit to updating their technologies, with a unified approach towards a fundamental objective: the decarbonization of maritime-related economic activities. This approach is crucial to reduce carbon dioxide (CO_2) emissions and align their actions with the SDGs, especially numbers 7, 9, and 13.

In the short term, it is important to prioritize the transition towards cleaner energy sources in high-emission maritime sectors, such as shipping and the fishing industry. These sectors can greatly benefit from the adoption of electrically powered technologies, thus reducing their carbon footprint. In addition, the electrification of ports and port facilities can help significantly reduce local emissions.

In the medium term, efforts must focus on expanding and optimizing the infrastructure needed for the generation and distribution of offshore wind energy. This involves developing more efficient offshore wind farms and improving the capacity for storing and transmitting electrical energy. At the same time, it is crucial to promote the research and development of innovative technologies that increase the profitability and sustainability of offshore wind energy.

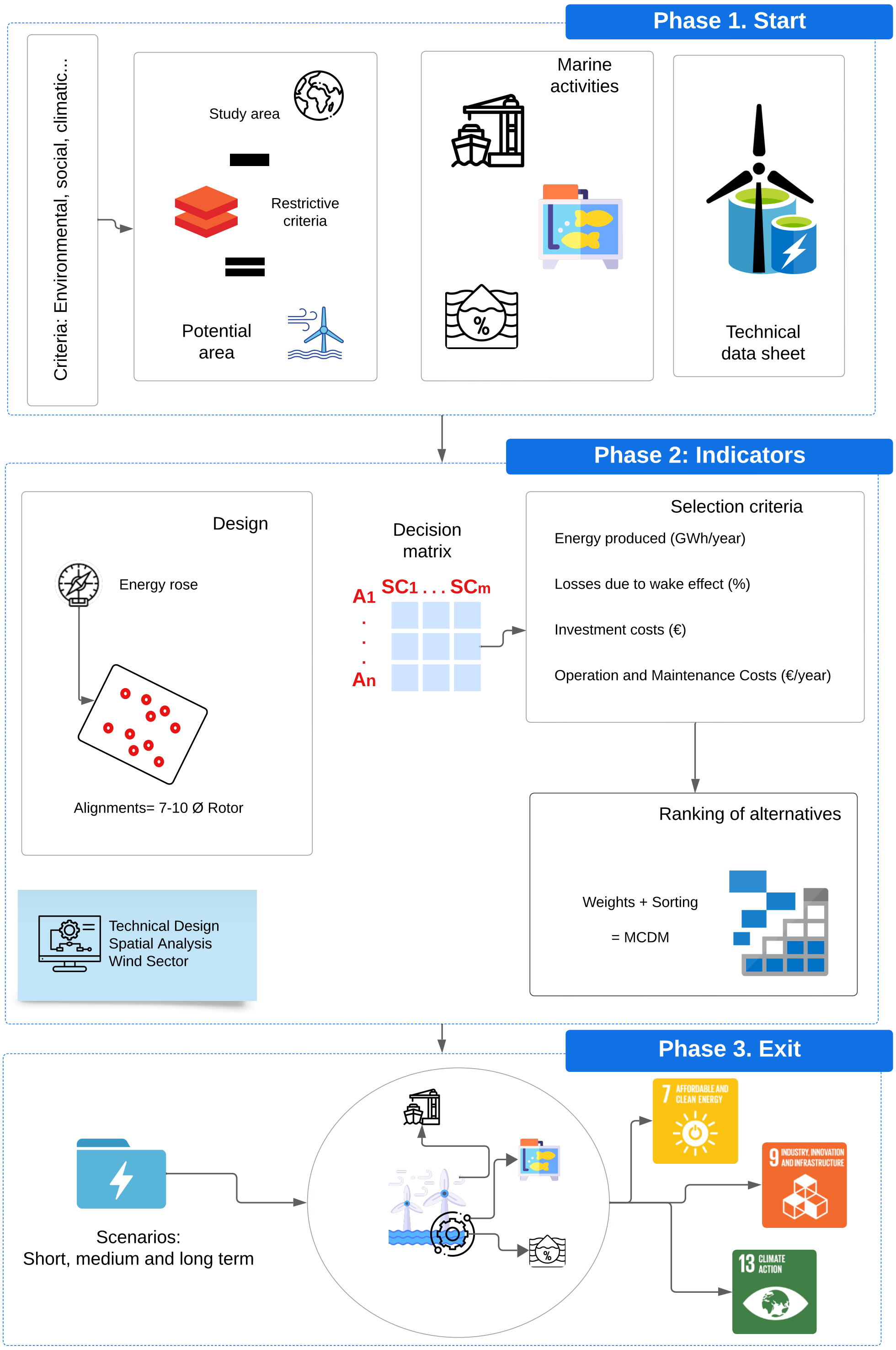

Figure 2. Proposed methods. Overview. Own elaboration.

In the long term, the ultimate goal is to achieve complete decarbonization of the maritime sectors, ensuring that all maritime-related economic activities are powered by renewable and sustainable energy sources. This will require close collaboration between governments, businesses, and civil society, as well as significant investments in infrastructure and training. In addition, policies and regulations that encourage the adoption of sustainable practices and discourage the use of fossil fuels will need to be implemented.

2.2. WAsP Wind Energy Calculation

2.2.1. Wind Distribution (Weibull)

WAsP uses the Weibull distribution to represent how wind speeds vary at the measurement site. The Weibull distribution describes the probability of wind having a particular speed at a given location, as shown in Equation (1).

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{1}$$

where:

- k is the shape parameter (indicates the dispersion of wind speeds);
- c is the scale parameter (a measure of the "characteristic wind speed");
- $f(v)$ is the probability of wind speed v.

2.2.2. Available Wind Power

This step calculates the amount of kinetic energy in the wind flowing through the area swept by the turbine blades. The available power depends on the cube of the wind speed, indicating the high sensitivity of wind energy to changes in wind speed. See Equation (2).

$$P = \frac{1}{2}\rho A v^3 \tag{2}$$

where:

- P is the wind power (W);
- ρ is the air density (typically 1.225 $\mathrm{kg/m^3}$ at sea level and 15 °C);
- A is the swept area of the blades, $A = \pi R^2$ ($\mathrm{m^2}$), where R is the rotor radius;
- v is the wind speed (m/s).

2.2.3. Turbine Power Curve

Not all the wind's kinetic energy is converted into electricity. The power curve of a turbine describes how its generated power varies with wind speed. Each turbine has a specific curve that relates the wind speed to the produced power. See Equation (3).

$$E = \int_0^{\infty} P(v) \cdot f(v)\, dv \tag{3}$$

where:

- $P(v)$ is the power produced by the turbine at wind speed v;
- $f(v)$ is the probability of that wind speed given by the Weibull distribution.

This integral calculates the total energy generated by integrating power over all possible wind speeds.

2.2.4. Wind Speed Adjustment at the Site (Logarithmic Law)

WAsP adjusts the measured wind speed at the meteorological station to the height of the turbine and accounts for terrain roughness. This is done to better reflect how the terrain and obstacles affect wind speed at the rotor height. See Equation (4).

$$v(z) = v(z_{\mathrm{ref}}) \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{\mathrm{ref}}}{z_0}\right)} \tag{4}$$

where:

- $v(z)$ is the wind speed at height z (turbine height);
- $v(z_{\text{ref}})$ is the wind speed at reference height z_{ref};
- z_0 is the roughness length of the terrain.

This equation adjusts the measured wind speed to the operational height of the turbine.

2.2.5. Annual Energy Production (AEP) Calculation

The AEP is calculated by summing the energy generated for each wind speed interval over the year. This provides an estimate of the total energy production for a typical year based on historical wind data. See Equation (5).

$$\text{AEP} = \sum_{i=1}^{N} P(v_i) \cdot t_i \tag{5}$$

where:

- $P(v_i)$ is the power generated at wind speed v_i;
- t_i is the time (in hours) that the wind blows at that speed v_i.

The sum is carried out over all possible wind speeds (i) throughout a year.

2.2.6. Adjustment for Losses and Availability

Not all calculated energy is converted into usable electricity due to aerodynamic, mechanical, and electrical losses, as well as turbine downtime. Therefore, the AEP is multiplied by an efficiency factor, as shown in Equation (6).

$$\text{AEP}_{\text{corrected}} = \eta \cdot \text{AEP} \tag{6}$$

where:

- η is an overall efficiency factor, accounting for losses and the operational availability of the turbine.

Each step in the WAsP process for estimating wind energy production is based on specific equations, from modelling the wind distribution and converting wind speed to power, to calculating the annual energy production adjusted for efficiency.

2.3. Entropy Method for Determining Criteria Weights

The entropy method is a technique used in MCDM to assign objective weights to criteria based on the information content provided by each criterion. The more dispersed or varied the information from a criterion, the more relevant it is, and thus it is assigned a higher weight. This method is used when subjective preferences from decision makers are unavailable, and an objective approach is needed [38]. The entropy method assigns more weight to criteria whose information is more varied, i.e., those that offer greater differentiation between alternatives. A criterion with similar values across alternatives will receive a lower weight, as it provides less valuable information. The steps are as follows [39].

2.3.1. Normalization of the Decision Matrix

Given a decision matrix $X = [x_{ij}]$, where x_{ij} represents the value of criterion j for alternative i, the data are normalized to eliminate the unit scale, as shown in Equation (7).

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{7}$$

where:

- r_{ij} is the normalized value of criterion j for alternative i;

- m is the number of alternatives.

2.3.2. Entropy Calculation for Each Criterion

The entropy measures the uncertainty or the amount of information contained in the normalized values of a criterion. It is computed for each criterion j, see Equation (8).

$$e_j = -k \sum_{i=1}^{m} r_{ij} \ln(r_{ij}) \tag{8}$$

where:

- e_j is the entropy of criterion j;
- $k = \frac{1}{\ln(m)}$ is a normalization constant to ensure that e_j is between 0 and 1;
- If $r_{ij} = 0$, it is assumed that $r_{ij} \ln(r_{ij}) = 0$.

2.3.3. Calculation of the Degree of Diversification (Information)

The degree of diversification d_j indicates how much information a criterion provides, i.e., how different the values of this criterion are. It is calculated as (9):

$$d_j = 1 - e_j \tag{9}$$

where:

- d_j measures the dispersion of the values of criterion j. If all values are the same, $d_j = 0$, and if the values are highly varied, d_j will be higher.

2.3.4. Calculation of the Criteria Weights

The weights w_j of the criteria are obtained by normalizing the degree of diversification for each criterion, as shown in Equation (10).

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{10}$$

where:

- w_j is the weight of criterion j;
- n is the number of criteria.

Advantages of the Entropy Method:

- It is an objective approach that does not require decision makers to provide subjective weightings.
- It uses the dispersion of data to determine the importance of each criterion, providing a quantitative approach.

2.4. VIKOR Method for Ranking Alternatives

The VIKOR method (VIseKriterijumska Optimizacija I Kompromisno Resenje) is a MCDM technique used to rank and select alternatives in the presence of conflicting criteria. This method focuses on finding a compromise solution that is acceptable to the decision maker, considering both the ideal and anti-ideal solutions [40].

The steps of the method are summarized below [41]:

2.4.1. Determine the Best and Worst Values for Each Criterion

For each criterion, identify the ideal (f_j^*) and anti-ideal (f_j^-) values as follows:

$$f_j^* = \max_i f_{ij}, \quad f_j^- = \min_i f_{ij} \quad \text{for a maximization problem}$$

$$f_j^* = \min_i f_{ij}, \quad f_j^- = \max_i f_{ij} \quad \text{for a minimization problem}$$

where f_{ij} is the value of the j-th criterion for the i-th alternative.

2.4.2. Calculate the Utility and Regret Measures for Each Alternative

The utility measure (S_i) and the regret measure (R_i) are computed as:

$$S_i = \sum_{j=1}^{n} w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-}$$

$$R_i = \max_j \left[w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right]$$

where w_j is the weight of the j-th criterion, and n is the number of criteria.

2.4.3. Compute the VIKOR Index for Each Alternative

The VIKOR index (Q_i) is calculated using the following equation:

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*}$$

where:

- $S^* = \min_i S_i$, $S^- = \max_i S_i$;
- $R^* = \min_i R_i$, $R^- = \max_i R_i$;
- v is a weight that represents the importance of the majority rule (usually $v = 0.5$).

2.4.4. Rank the Alternatives Based on Q_i

The alternatives are ranked according to the values of Q_i, with the lowest value being the best option. Additionally, a compromise solution can be selected if the following two conditions are met:

- Acceptable advantage: $Q(A_2) - Q(A_1) \geq D_Q$, where A_1 and A_2 are the top two ranked alternatives, and D_Q is a predefined threshold.
- Acceptable stability: The alternative ranked first based on Q_i should also be the best-ranked by at least one of S_i or R_i.

3. Results

The case study focuses on Spain, specifically on the Maritime Spatial Planning Plans (POEM) framework, which is part of the Offshore Wind Energy Roadmap and other marine energy sources. The marine space of the Canary Islands is used to evaluate the proposal, since it is one of the areas where the most projects have been presented according to the Spanish Ministry of Ecological Transition [42].

3.1. Phase 1—Start

The restrictive criteria excluded from the study area are categorized into environmental, social, technical, and economic factors. Key layers include: biodiversity protection, aggregate deposits, protection of cultural heritage, research and development zones, national defence, navigation safety, etc. Spatial layers in red indicate areas where offshore wind energy is prohibited, while yellow layers represent zones with restrictions. The black polygon outlines the potential area for offshore wind energy development, covering an area of 164 km^2 (see Figure 3).

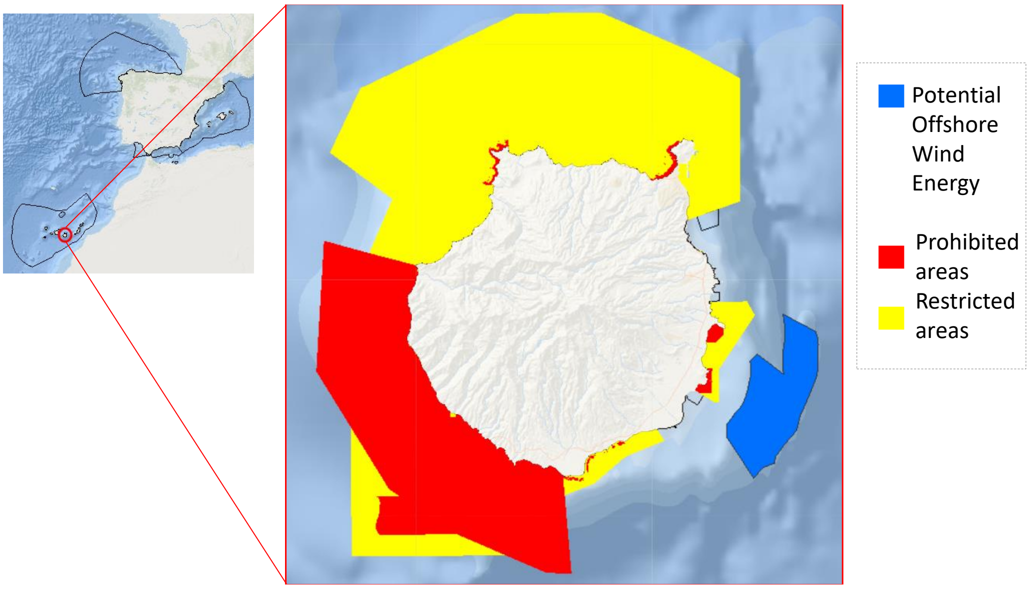

Figure 3. Study area. Prohibited and restricted areas for offshore wind activities. Potential area for offshore wind. Own elaboration based on [43].

Several activities with decarbonization potential are identified: aquaculture, salt mines, and port activities (see Figure 4).

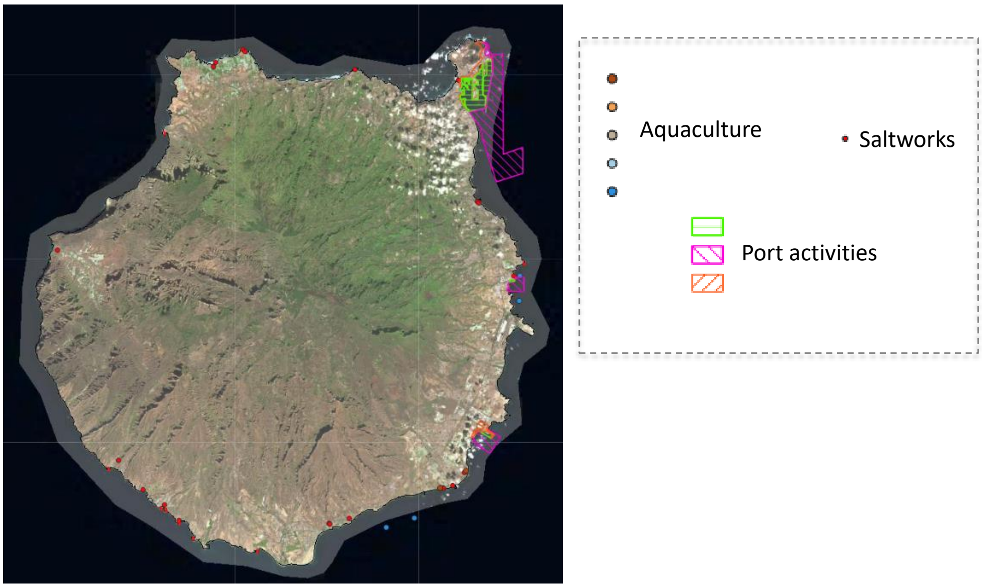

Figure 4. Marine activities with the possibility of decarbonization. Own elaboration.

The selected turbine offshore has a power of 15 MW, a rotor diameter of 240 m, and a height of 150 m, as is designed by IEA (International Energy Agency) Wind [44].

3.2. *Phase 2—Indicators*

In accordance with the methodology outlined in Section 2.1.2, this phase involves constructing a decision matrix to select the most suitable alternative. A prototype of an offshore wind farm was designed based on the wind turbine chosen in the previous phase (15 MW capacity), along with the data from the wind measurement campaign, which included wind speed and direction. The energy rose indicates that the highest contribution comes from the north (see Figure 5), so the turbine configurations will be aligned perpendicularly, with distances ranging between 1600 m and 2400 m. Two scenarios are proposed, as shown in Figure 5:

- A wind farm with a nominal capacity of 525 MW, covering nearly the entire potential area and resulting in a single alternative (A_1) with 35 turbines.
- A wind farm with a nominal capacity of 225 MW, generating three distinct alternatives (A_2–A_4), with 15 turbines each.

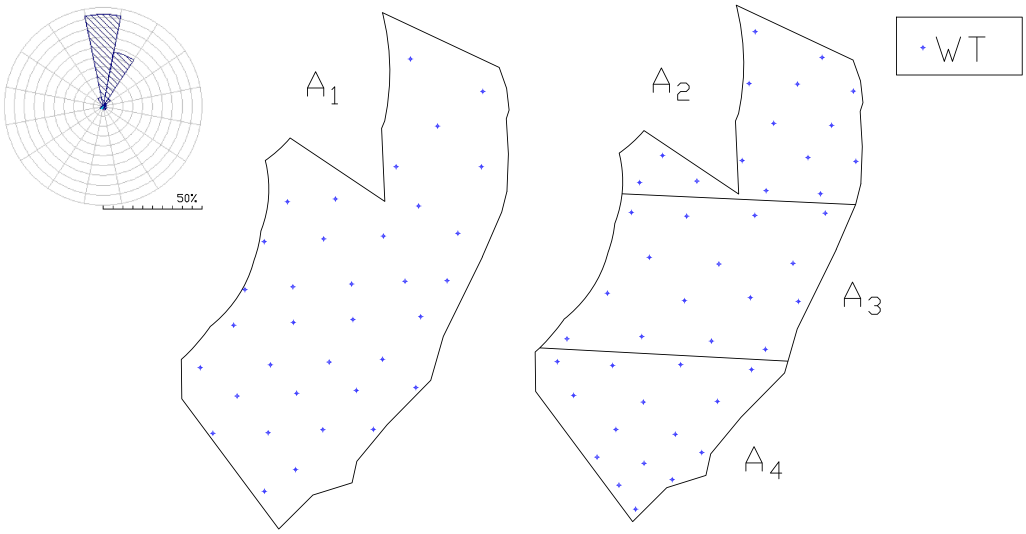

Figure 5. Energy rose. Alternatives A_1–A_4. Own elaboration.

For each alternative, the following criteria are calculated to construct the decision matrix (see Table 1):

- Wind speed (m/s) [C_1]: average wind speed from the data campaign at 150 m height; 1 year of ten-minute data; source: Vortex [45];
- Bathymetry (m) [C_2]: source: [46].
- Wave height [C_3]: source: [47].
- Distance to port (km) [C_4] : calculated with a GIS.
- Electricity generated (GWh) and wake effect losses (%) [C_5] [C_8]: data obtained using the WAsP©software [31]; input datasets include bathymetric maps, wind data (speed and direction), and the wind turbine power curve (new power curve created with the "WasP Turbine editor" tool, based on the IEA turbine [44] technical data sheet). AutoCAD©software [48] was used to assist with the design.
- CAPEX and OPEX [C_6] [C_7] (Mdd): based on the floating wind farm described by the National Renewable Energy Laboratory (NREL) [49].

Table 1. Decision matrix.

	A_1	A_2	A_3	A_4
C_1 (m/s)	9.78	9.78	9.83	9.20
C_2 (m)	−549.98	−389.48	−359.60	−732.43
C_3 (m)	2.50	2.60	2.60	2.60
C_4 (km)	11.63	10.53	11.14	13.75
C_5 (GWh)	2738.20	1194.50	1205.40	1100.80
C_6 (Mdd)	2927.93	1716.08	1715.15	1714.96
C_7 (Mdd)	65.63	27.00	27.00	27.00
C_8 (%)	3.81	1.99	1.96	1.95

The design of each alternative has been carried out according to good wind design practices [27]: the alignments between wind turbines are 7–10 times the rotor diameter (D), and between wind turbines, 3–5 (D). Iterations were carried out in the WasP software until the wake losses were lower than 6%.

The selection of the best alternative was carried out using a combination of the entropy and VIKOR methods. The weights obtained for the criteria were as follows: C_7 (30.20%), C_5 (27.87%), C_8 (16.12%), C_2 (13.69%), C_6 (10.26%), C_4 (1.70%), C_1 (0.12%), and C_3 (0.05%). The criteria with the highest weights were the economic factors, the amount of electricity generated, and the losses due to wake effect. As a result, the best alternative was A_3, with an LCOE of USD 93.54/MWh.

4. Discussion

4.1. Scenarios

Based on the optimal alternative, three scenarios are proposed, as shown in Figure 6.

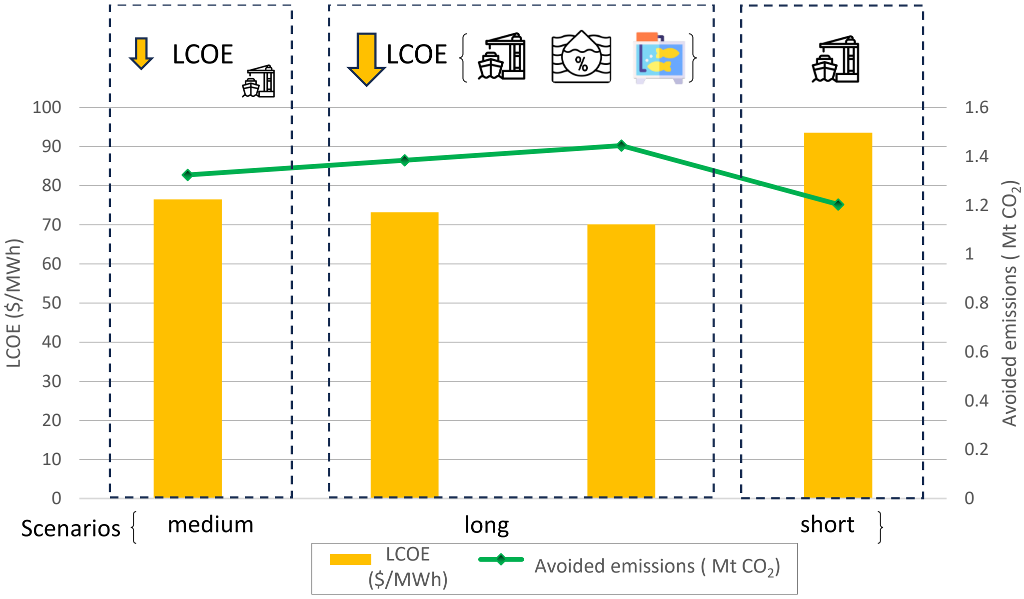

Figure 6. Scenarios in the short, medium, and long term. Own elaboration.

In the short term, if the offshore wind farm begins operation with current technology, all the electricity generated (1205 GWh annually) would be allocated to the port sector and maritime navigation. This scenario presents an LCOE of USD 93.54/MWh. The costs of an offshore wind installation vary depending on region [50], and tend to decrease as the total installed capacity increases. For instance, for a 250 MW plant analyzed in 2022 by the authors, the estimated cost was EUR 132/MWh [51], which was 48% higher than the current study (carried out in 2024). However, according to Det Norske Veritas group (DNV) [52], the LCOE is projected to be around USD 100/MWh by 2025, although this will depend on several factors such as the technology used, the distance to the port, and the bathymetry, among others. The resulting emission reductions are equivalent to 1.2 $MtCO_2$ avoided compared to coal.

In the medium term, offshore wind technology is expected to improve, increasing efficiency and reducing costs [53]. If a 10% increase in electricity generation and a 10% reduction in costs are projected, the LCOE could decrease to USD 76.5/MWh, while avoided emissions would increase to 1.23 $MtCO_2$. In this case, the energy generated could supply not only the port and navigation sectors, but also the fishing industry.

In the long term, with a projected increase in electricity generation of between 15% and 20% and a similar reduction in costs, the LCOE would drop to between USD 73.2 and USD 70.15/MWh, avoiding between 1.38 and 1.44 $MtCO_2$. This energy could be used in other sectors such as aquaculture and salt production, in addition to continuing to supply the port and maritime sectors. It is noteworthy that if the offshore wind farm is initiated in the short-term scenario, in the long term, marine repowering could be performed, further reducing investment costs.

4.2. SDG and Offshore Wind Energy

Offshore wind energy can play a crucial role in developing a model of energy self-sufficiency for local cooperative activities that depend on the sea, such as fishing, aquaculture, salt farms, and other coastal economic activities. This approach would not only contribute to the sustainability of communities, but is also aligned with some SDGs, specifically: SDG 7 (Affordable and Clean Energy), by providing clean and affordable energy; SDG 9 (Industry, Innovation, and Infrastructure), through the development of infrastructure and promotion of innovation; and SDG 13 (Climate Action), as an effective solution for climate change mitigation. These goals are interconnected in the transition towards a more sustainable and resilient future, where offshore wind plays a key role [54].

SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Offshore wind energy plays a crucial role in this goal as it is a clean and renewable energy source. It helps reduce reliance on fossil fuels and decreases greenhouse gas emissions, promoting a more sustainable energy system. Additionally, as offshore wind technology matures, the costs of producing energy are expected to decrease, making offshore wind power more affordable over time [55].

SDG 9 focuses on building resilient infrastructure, promoting inclusive industrialization and fostering innovation. Offshore wind energy requires advanced technological infrastructure, such as floating platforms, submarine cables, and transmission systems to bring electricity to shore. It also drives technological innovation, with developments like larger, more efficient turbines and advancements in energy storage. This fosters sustainable industrialization in sectors like component manufacturing, wind farm construction, and grid operation, contributing to inclusive and sustainable economic growth in local economies [56].

SDG 13 calls for urgent action to combat climate change and its impacts. Offshore wind energy is one of the key solutions for mitigating the effects of climate change by reducing the carbon footprint of the energy sector. Wind power generation does not produce greenhouse gas emissions, playing a vital role in the decarbonization of the global energy mix. Furthermore, by increasing renewable energy capacity, offshore wind contributes to climate resilience and adaptation by reducing dependence on carbon-intensive energy sources that are vulnerable to climate impacts [57].

In addition, investment in wind infrastructure could create direct local jobs in the construction and operation phase of the parks, aligning with SDG 8 and fostering resilient and sustainable coastal economies.

5. Conclusions

The maritime environment is a point of convergence of diverse economic activities, including both traditional practices and new initiatives with great potential for transformation. Offshore wind energy is a prominent example of how innovation and environmental awareness are redefining the future of economic activities at sea. This study presents a practical solution to reduce the carbon footprint of marine activities, aligned with Sustainable Development Goals 7, 9, and 13. The proposed methodology is developed in three phases: first, the identification of optimal areas to generate and distribute clean energy; second, the calculation of key indicators to select the best alternative; and finally, the planning of short-, medium-, and long-term scenarios. The assessment is carried out in the Canary Islands marine area, Spain, where the best technically, economically, and environmentally viable alternative could generate up to 1447 GWh per year in the long-term scenario, with a levelized cost of energy of USD 70.15/MWh, avoiding the emission of 1.2 million tons of CO_2 equivalent. This energy would be destined for other maritime activities, such as aquaculture, salt mines, and port and navigation operations. The proposal has the potential to be applied in any marine area, provided that the appropriate technical and spatial data are available.

Despite the benefits that offshore wind energy can bring to all maritime activities, there are significant barriers to its development, such as competition for space, limited infrastructure, and high costs. Key solutions are therefore urgently needed. First, marine spatial planning is essential to coordinate different uses of space and avoid conflicts between sectors. It is also essential to increase infrastructure investments, both in offshore wind energy and in other maritime sectors, to promote greater integration. Furthermore, public–private financing should facilitate access to capital through collaboration between governments and companies. Finally, it is crucial to empower local communities, ensuring that they directly benefit from the development of offshore wind energy.

For future research, a priority line will focus on carrying out a territorial assessment that also considers various sources of marine renewable energy, such as tidal energy and floating solar energy.

Author Contributions: Conceptualization I.C.G.-G.; methodology I.C.G.-G.; investigation I.C.G.-G.; software I.C.G.-G.; visualization I.C.G.-G.; data curation I.C.G.-G.; writing—original draft preparation I.C.G.-G.; Writing—review and editing I.C.G.-G. and A.F.-G. Authorship must be limited to those who have contributed substantially to the work reported.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, I.C.G.-G., upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nikologianni, A.; Betta, A.; Pianegonda, A.; Favargiotti, S.; Moore, K.; Grayson, N.; Morganti, E.; Berg, M.; Ternell, A.; Ciolli, M.; et al. New Integrated Approaches to Climate Emergency Landscape Strategies: The Case of Pan-European SATURN Project. *Sustainability* **2020**, *12*, 8419. [CrossRef]
2. Horowitz, C.A. Paris Agreement. *Int. Leg. Mater.* **2016**, *55*, 740–755. [CrossRef]
3. Armstrong McKay, D.I.; Staal, A.; Abrams, J.F.; Winkelmann, R.; Sakschewski, B.; Loriani, S.; Fetzer, I.; Cornell, S.E.; Rockström, J.; Lenton, T.M. Exceeding 1.5 °C global warming could trigger multiple climate tipping points. *Science* **2022**, *377*, eabn7950. [CrossRef] [PubMed]
4. Chien, F.; Hsu, C.C.; Ozturk, I.; Sharif, A.; Sadiq, M. The role of renewable energy and urbanization towards greenhouse gas emission in top Asian countries: Evidence from advance panel estimations. *Renew. Energy* **2022**, *186*, 207–216. [CrossRef]
5. Salkuti, S.R. Emerging and Advanced Green Energy Technologies for Sustainable and Resilient Future Grid. *Energies* **2022**, *15*, 6667. [CrossRef]
6. Xie, F.; Liu, Y.; Guan, F.; Wang, N. How to coordinate the relationship between renewable energy consumption and green economic development: From the perspective of technological advancement. *Environ. Sci. Eur.* **2020**, *32*, 1–15. [CrossRef]
7. *The Evolution of Energy Efficiency Policy to Support Clean Energy Transitions—Analysis*; International Energy Agency (IEA): Paris, France, 2023.
8. Kronfeld-Goharani, U. Maritime economy: Insights on corporate visions and strategies towards sustainability. *Ocean. Coast. Manag.* **2018**, *165*, 126–140. [CrossRef]
9. Weiss, C.V.; Guanche, R.; Ondiviela, B.; Castellanos, O.F.; Juanes, J. Marine renewable energy potential: A global perspective for offshore wind and wave exploitation. *Energy Convers. Manag.* **2018**, *177*, 43–54. [CrossRef]
10. Esteban, M.D.; Diez, J.J.; López, J.S.; Negro, V. Why offshore wind energy? *Renew. Energy* **2011**, *36*, 444–450. [CrossRef]
11. Global Wind Energy Council (GWEC). Global Wind Report 2023. Available online: https://www.gwec.net (accessed on 2 September 2024).
12. Boyd, C.E.; D'Abramo, L.R.; Glencross, B.D.; Huyben, D.C.; Juarez, L.M.; Lockwood, G.S.; McNevin, A.A.; Tacon, A.G.; Teletchea, F.; Tomasso, J.R.; et al. Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *J. World Aquac. Soc.* **2020**, *51*, 578–633. [CrossRef]
13. Rghif, Y.; Colarossi, D.; Principi, P. Salt gradient solar pond as a thermal energy storage system: A review from current gaps to future prospects. *J. Energy Storage* **2023**, *61*, 106776. [CrossRef]
14. Okeke, A. Towards sustainability in the global oil and gas industry: Identifying where the emphasis lies. *Environ. Sustain. Indic.* **2021**, *12*, 100145. [CrossRef]
15. Megura, M.; Gunderson, R. Better poison is the cure? Critically examining fossil fuel companies, climate change framing, and corporate sustainability reports. *Energy Res. Soc. Sci.* **2022**, *85*, 102388. [CrossRef]

16. Gil-García, I.C.; García-Cascales, M.S.; Fernández-Guillamón, A.; Molina-García, A. Categorization and Analysis of Relevant Factors for Optimal Locations in Onshore and Offshore Wind Power Plants: A Taxonomic Review. *J. Mar. Sci. Eng.* **2019**, *7*, 391. [CrossRef]
17. Gil-García, I.C.; Ramos-Escudero, A.; García-Cascales, M.; Dagher, H.; Molina-García, A. Fuzzy GIS-based MCDM solution for the optimal offshore wind site selection: The Gulf of Maine case. *Renew. Energy* **2022**, *183*, 130–147. [CrossRef]
18. Xu, Y.; Li, Y.; Zheng, L.; Cui, L.; Li, S.; Li, W.; Cai, Y. Site selection of wind farms using GIS and multi-criteria decision making method in Wafangdian, China. *Energy* **2020**, *207*, 118222. [CrossRef]
19. *Real Decreto 363/2017, de 8 de Abril, por el que se Establece un Marco para la Ordenación del Espacio Marítimo*; BOE-A-2017-3950; Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente: Madrid, Spain, 2007.
20. *Ley 41/2010, de 29 de Diciembre, de Protección del Medio Marino*; BOE-A-2010-20050; Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente: Madrid, Spain, 2010.
21. *Directiva 2014/89/UE del Parlamento Europeo y del Consejo, de 23 de Julio de 2014, por la que se Establece un Marco para la Ordenación del Espacio maríTimo*; DOUE-L-2014-81825; European Union: Brussels, Belgium, 2014; pp. 135–145.
22. Scroggins, R.E.; Fry, J.P.; Brown, M.T.; Neff, R.A.; Asche, F.; Anderson, J.L.; Love, D.C. Renewable energy in fisheries and aquaculture: Case studies from the United States. *J. Clean. Prod.* **2022**, *376*, 134153. [CrossRef]
23. Mahmoudi, A.; Bostani, M.; Rashidi, S.; Valipour, M.S. Challenges and opportunities of desalination with renewable energy resources in Middle East countries. *Renew. Sustain. Energy Rev.* **2023**, *184*, 113543. [CrossRef]
24. Parhamfar, M.; Sadeghkhani, I.; Adeli, A.M. Towards the application of renewable energy technologies in green ports: Technical and economic perspectives. *IET Renew. Power Gener.* **2023**, *17*, 3120–3132. [CrossRef]
25. *UNE-EN IEC 61400-1:2020*; Sistemas de Generación de Energía Eólica. Parte 1: Requisitos de diseño; UNE: Madrid, Spain, 2020.
26. Manzano-Agugliaro, F.; Sánchez-Calero, M.; Alcayde, A.; San-Antonio-gómez, C.; Perea-Moreno, A.J.; Salmeron-Manzano, E. Wind Turbines Offshore Foundations and Connections to Grid. *Inventions* **2020**, *5*, 8. [CrossRef]
27. García, I.C.G. *Energía Eólica*; Centro de Estudios Financieros: Madrid, Spain, 2023.
28. Gil-García, I.C.; Fernández-Guillamón, A.; García-Cascales, M.S.; Molina-García, A.; Dagher, H. A green electrical matrix-based model for the energy transition: Maine, USA case example. *Energy* **2024**, *290*, 130246. [CrossRef]
29. Baptista, J.; Jesus, B.; Cerveira, A.; Pires, E.J.S. Offshore Wind Farm Layout Optimisation Considering Wake Effect and Power Losses. *Sustainability* **2023**, *15*, 9893. [CrossRef]
30. Huang, Q.; Wang, X.; Fan, J.; Zhang, X.; Wang, Y. Reliability and economy assessment of offshore wind farms. *J. Eng.* **2019**, *2019*, 1554–1559. [CrossRef]
31. *WAsP*; DTU Wind and Energy Systems: Roskilde, Denmark, 2023.
32. *FLORIS: FLOw Redirection and Induction in Steady State*; Wind Research; The National Renewable Energy Laboratory (NREL): Washington, DC, USA. Available online: https://www.nrel.gov/wind/floris.html (accessed on 2 September 2024).
33. Argin, M.; Yerci, V. Offshore wind power potential of the Black Sea region in Turkey. *Int. J. Green Energy* **2017**, *14*, 811–818. [CrossRef]
34. Sánchez-Lozano, J.M.; Ramos-Escudero, A.; Gil-García, I.C.; García-Cascales, M.S.; Molina-García, A. A GIS-based offshore wind site selection model using fuzzy multi-criteria decision-making with application to the case of the Gulf of Maine. *Expert Syst. Appl.* **2022**, *210*, 118371. [CrossRef]
35. Caceoğlu, E.; Yildiz, H.K.; Oğuz, E.; Huvaj, N.; Guerrero, J.M. Offshore wind power plant site selection using Analytical Hierarchy Process for Northwest Turkey. *Ocean. Eng.* **2022**, *252*, 111178. [CrossRef]
36. Tian, S.; Zhou, Y.; Fu, Y.; Ji, L.; Li, Z. Comprehensive Cost-Benefit Assessment of Offshore Wind Power Based on Improved VIKOR Method. In Proceedings of the 2023 IEEE IAS Industrial and Commercial Power System Asia, I and CPS Asia 2023, Chongqing, China, 7–9 July 2023; pp. 1268–1273. [CrossRef]
37. Vagiona, D.G.; Tzekakis, G.; Loukogeorgaki, E.; Karanikolas, N. Site Selection of Offshore Solar Farm Deployment in the Aegean Sea, Greece. *J. Mar. Sci. Eng.* **2022**, *10*, 224. [CrossRef]
38. Li, H.; Wang, W.; Fan, L.; Li, Q.; Chen, X. A novel hybrid MCDM model for machine tool selection using fuzzy DEMATEL, entropy weighting and later defuzzification VIKOR. *Appl. Soft Comput.* **2020**, *91*, 106207. [CrossRef]
39. Rogulj, K.; Kilić Pamuković, J.; Ivić, M. Hybrid MCDM Based on VIKOR and Cross Entropy under Rough Neutrosophic Set Theory. *Mathematics* **2021**, *9*, 1334. [CrossRef]
40. Mardani, A.; Zavadskas, E.K.; Govindan, K.; Amat Senin, A.; Jusoh, A. VIKOR Technique: A Systematic Review of the State of the Art Literature on Methodologies and Applications. *Sustainability* **2016**, *8*, 37. [CrossRef]
41. Liu, R.; Sun, H.; Zhang, L.; Zhuang, Q.; Zhang, L.; Zhang, X.; Chen, Y. Low-Carbon Energy Planning: A Hybrid MCDM Method Combining DANP and VIKOR Approach. *Energies* **2018**, *11*, 3401. [CrossRef]
42. Gobierno de España. *Sede Electrónica del Ministerio para la Transición Ecológica*; Gobierno de España: Madrid, Spain. Available online: https://sede.miteco.gob.es/portal/site/seMITECO (accessed on 2 September 2024).
43. Visor INFOMAR—MITECO, CEDEX. 2023. Available online: https://infomar.miteco.es/visor.html (accessed on 15 September 2024).
44. Gaertner, E.; Rinker, J.; Sethuraman, L.; Zahle, F.; Anderson, B.; Barter, G.; Abbas, N.; Meng, F.; Bortolotti, P.; Skrzypinski, W.; et al. *Definition of the IEA 15-Megawatt Offshore Reference Wind*; Technical Report NREL/TP-5000-75698; National Renewable Energy Laboratory: Golden, CO, USA, 2020. Available online: https://www.nrel.gov/docs/fy20osti/75698.pdf (accessed on 15 August 2024).

45. Vortex FDC. Wind Resource Data for Wind Farm Developments; Vortex FDC: Barcelona, Spain, 2023.
46. *EMODnet Web Service Documentation*; European Marine Observation and Data Network (EMODnet): Brussels, Belgium, 2024.
47. Puertos de España. *Spectral Significant Wave Height Grid*; Mapa: 2020. Available online: https://www.puertos.es/ (accessed on 15 August 2024).
48. Autodesk. *AutoCAD 2025*; Autodesk, Inc.: San Francisco, CA, USA, 2024.
49. Musial, W.; Spitsen, P.; Philipp Beiter, P.D.; Marquis, M.; Hammond, R.; Shields, M. *Offshore Wind Market Report: 2022 Edition*; Technical report; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2022.
50. *Renewable Power Generation Costs in 2023*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2024.
51. Petracca, E.; Faraggiana, E.; Ghigo, A.; Sirigu, M.; Bracco, G.; Mattiazzo, G. Design and Techno-Economic Analysis of a Novel Hybrid Offshore Wind and Wave Energy System. *Energies* **2022**, *15*, 2739. [CrossRef]
52. DNV. When Trust Matters. Available online: https://www.dnv.com/ (accessed on 13 September 2024).
53. *Strong 2023 Offshore Wind Growth as Industry Sets Course for Record-Breaking Decade*; Global Wind Energy Council: Brussels, Belgium, 2024.
54. Frades, J.L.; Barba, J.G.; Negro, V.; Martín-Antón, M.; Soriano, J. Blue Economy: Compatibility between the Increasing Offshore Wind Technology and the Achievement of the SDG. *J. Coast. Res.* **2020**, *95*, 1490–1494. [CrossRef]
55. Olabi, A.G.; Obaideen, K.; Abdelkareem, M.A.; AlMallahi, M.N.; Shehata, N.; Alami, A.H.; Mdallal, A.; Hassan, A.A.M.; Sayed, E.T. Wind Energy Contribution to the Sustainable Development Goals: Case Study on London Array. *Sustainability* **2023**, *15*, 4641. [CrossRef]
56. Abrahamsen, A.; Natarajan, A.; Kitzing, L.; Madsen, B.; Martí, I. Towards sustainable wind energy. In *DTU International Energy Report 2021: Perspectives on Wind Energy*; Holst Jørgensen, B., Hauge Madsen, P., Giebel, G., Martí, I., Thomsen, K., Eds.; DTU Wind Energy: Roskilde, Denmark, 2021; pp. 144–150. [CrossRef]
57. Velenturf, A.P.M.; Emery, A.R.; Hodgson, D.M.; Barlow, N.L.M.; Mohtaj Khorasani, A.M.; Van Alstine, J.; Peterson, E.L.; Piazolo, S.; Thorp, M. Geoscience Solutions for Sustainable Offshore Wind Development. *Earth Sci. Syst. Soc.* **2021**, *1*, 10042. [CrossRef]