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Review

Effects of Offshore Wind Farms: Environmental and Social Perspectives from Uruguay

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Abstract: The installation of offshore wind farms is rising, driven by the goal of changing the global energy matrix. However, many of their possible impacts are still unknown. Increased noise levels, disruptions to food chains, pollution due to traffic, and impacts on fishing communities and tourism are all potential effects to consider. Marine habitats are essential carbon dioxide sinks. Therefore, losing marine biodiversity due to offshore wind farms can be counterproductive in mitigating climate change. Balancing biodiversity conservation, wind potential, and political interests is challenging. Today, Uruguay has significantly decreased the fossil share in its electricity generation, incorporating electricity generation from wind, solar, and biomass energy alongside hydroelectricity. In line with this, the country's Hydrogen Roadmap highlights green hydrogen as relevant, potentially serving as a fuel for both domestic and export transportation. Combining the country's strong base of wind energy production experience with its sustainable policy, it plans to implement offshore wind farms to produce green hydrogen, making studies of its impacts crucial. This paper reviews the current social and environmental information on the Uruguayan coastal habitat, analyzes onshore wind farms' ecological studies, and examines offshore wind farms' global environmental and social impacts. Finally, it proposes studies for environmental approval of offshore wind farms.

Keywords: environmental impacts; social impacts; offshore wind farms

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1. Introduction

Uruguay is a country located in South America, between 30° and 35° south latitude and meridians 53° and 58° west longitude, in the temperate zone of the Southern Hemisphere [1]. With a land area of 176,215 km^2, it borders Brazil to the north and northeast, Argentina to the west, and on the Río de la Plata and the Atlantic Ocean to the south and southeast [2]. According to the 2023 Census, the preliminary estimated population was 3,444,263 people, with an estimated intercensal growth rate of 1% [3].

The country is progressing in its energy transition toward a more efficient and sustainable economy. It occupies a prominent position worldwide for its share of electricity production from wind [4]. As a result, the country has significantly cut the fossil share in its electricity generation, complementing the traditional participation of hydroelectric energy with the incorporation of wind, solar, and biomass energies. These four sources together accounted for 80.5% of the total injections to the National Interconnected System (SIN) in 2023 [5]. Biomass energy is also present in Uruguay's electricity matrix, being a carbon-neutral source since it captures CO_2 from the air and then releases it during combustion [6].

At the end of 2023, the total installed capacity was 1538 MW of hydraulic origin, 1517 MW of wind power, 1177 MW of fossil thermal, 731 MW of biomass thermal, and

301 MW of solar photovoltaic generators. Considering the installed capacity by source, 78% corresponded to renewable energy (hydro, biomass, wind, and solar), while the remaining 22% was nonrenewable energy (diesel, fuel oil, and natural gas) [7].

Considering the context of the country's electricity matrix, Uruguay is preparing for new challenges, such as generating green hydrogen from wind energy production. The offshore wind resource and a broad continental shelf with low water depths make it attractive for producing hydrogen and derivatives from offshore wind energy [8]. By 2040, hydrogen production on its coast could reach up to one million tons annually [9]. Considering some criteria, such as protected areas and nautical routes, the National Administration of Fuels, Alcohol and Portland (ANCAP), the representative of the Uruguayan government, selected a particular zone divided into four regions for the initial round of offshore bids.

The offshore green hydrogen production and transportation concepts are entirely new, and even the methodology for comprehensive sustainability assessments is mainly undeveloped [10]. The conversion of offshore wind-generated electricity into hydrogen (or one of its derivatives, like ammonia) enables the flexibility of the electrical system. It facilitates the management of the variability in the wind energy source [11]. Offshore wind farms (OWFs) are currently a better-known technology in some regions of the world than hydrogen production technologies. Likewise, offshore wind generation is still a novelty in many countries with no established environmental regulations. This article aims to examine the situation in Uruguay in this context.

A comprehensive literature review was conducted of journal and review papers, documents from offshore wind farms in operation, books, and scientific reports to understand the environmental and social impacts of wind farms installed worldwide. Additionally, the ecological characteristics of the current state of the Uruguayan coast and its regulations related to installing wind farms onshore were examined. Considering that Uruguay did not have established rules or papers on the subject of environmental aspects of offshore wind electricity production, the main objective of this paper is to evaluate the potential environmental and social impacts of offshore wind farms in countries that already have this technology, understand the situation in Uruguay considering the main effects of these studies, and then provide insights and recommendations that can support the development of a comprehensive legislative framework adjusted to Uruguay's context.

These objectives are achieved in the following sections. Section 2 discusses general aspects of offshore wind farms; highlights structural features, such as the list of principal components; and provides information on the growth in the installed capacity of offshore wind farms worldwide in recent years. Section 3 reviews the literature on the main environmental and social impacts of offshore wind installations, presents the technological challenges for the development of offshore wind farms in Uruguay, and characterizes the wind resource assessment process. Section 4 presents information on the characterization of the coast of Uruguay, such as environmental conditions, social aspects, economic effects, and seasonal climatic conditions, and how the country proceeded with the regulation of onshore wind farms. Section 5 describes what studies would be required for offshore licensing in Uruguay. Section 6 discusses the main issues that need to be addressed in Uruguay to move forward with plans for offshore wind facilities.

2. Background Context

2.1. Offshore Wind Farms

In recent decades, growing efforts have been made to reduce CO_2 emissions and other pollutants that increase global warming's effects. The offshore wind energy industry now plays a central role in long- and short-term international energy strategies [12]. Future power scenarios and roadmaps promote offshore wind farms as alternative and additional power generation sources [13]. For this, developers have looked into wind, wave, and sea bed conditions, the availability of a foundation, turbine types, installation ships, and the wind farm layout, considering cabling and projected operation and maintenance costs [14].

Up to 2023, fourteen countries were part of the Global Offshore Wind Alliance; the more mature markets included countries like Denmark, the U.K., and the Netherlands [15].

New technologies for floating structures are being explored for depths exceeding 50 m. Until now, the technologies implemented have been large-diameter steel monopiles or gravity bases characterized for depths less than 30 m.

Among the most promising are tension leg platforms (TLPs), spars (large, deep craft cylindrical floating caisson), and semisubmersible structures, which have been the subject of intensive studies [16].

During the first stage of the design, several different exclusion zones have to be managed, such as nature reserves, shipping lanes, oil exploration areas, risks of unexploded ordnance, or the chances of finding archaeological remains [14]. As shown in Figure 1, an offshore wind farm comprises different components that can cause environmental and social impacts.

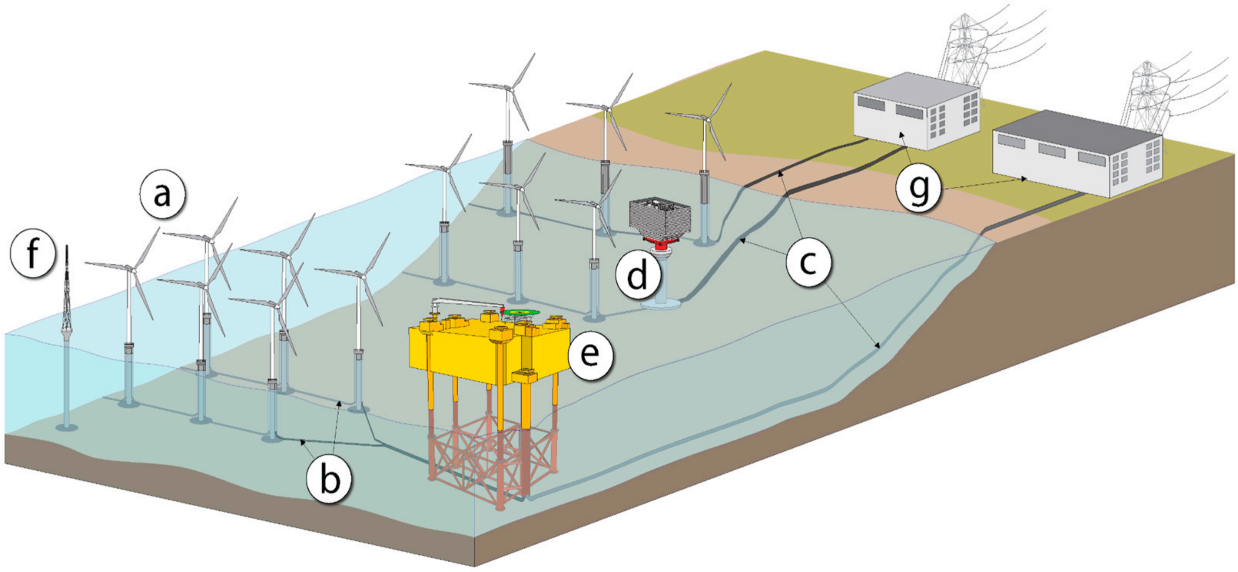


Figure 1. Main components of an offshore wind farm: (a) wind turbines; (b) collection cables; (c) export cables; (d) transformer station; (e) converter station; (f) meteorological mast; (g) onshore stations [17].

2.2. Global Overview of Offshore Wind Energy Production

By the end of 2023, the installed capacity of offshore wind farms worldwide was 72.5 GW, corresponding to approximately 7.3% of the total installed wind power capacity (onshore + offshore) worldwide [18]. Of this installed offshore wind capacity, China led in offshore wind electric generation with 50.3%, followed by the United Kingdom with 19.6% and Germany with 11.1%. By region, Europe stands out with 45.3%, Asia-Pacific with 54.6%, and North America with 0.1% of the total installed capacity worldwide. Figure 2 shows the evolution of new offshore wind installations worldwide over the last ten years.

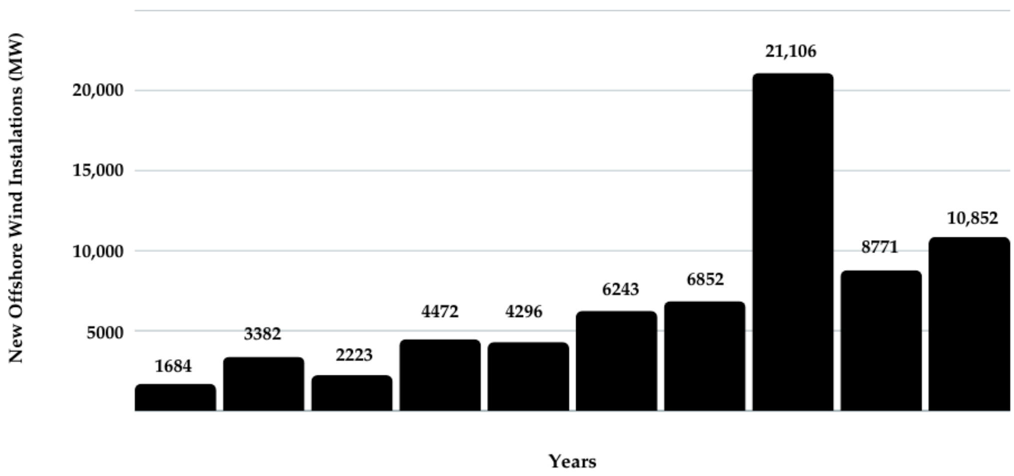


Figure 2. New offshore wind installations (MW) worldwide in the last ten years [19].

One of the main technological advances has been in the manufacturing characteristics of offshore wind turbines, increasing the rated power (MW), rotor diameter (m), and hub height (m). Due to technological development, the global weighted average levelized cost of electricity (LCOE) of offshore wind power has decreased from 0.197 USD/kWh in 2010 to 0.081 USD/kWh in 2022, a reduction of 59% [20]. In the given context of decreasing costs due to the advancements in technology and in search of mitigating CO_2 emissions in the Earth's atmosphere, the trend is that the installed capacity of offshore wind power generation will continue to increase in the coming years [13].

Wind energy, a relatively recent energy source that participates in electricity generation worldwide, still faces significant challenges in achieving greater efficiency in its integration into electricity systems. Among these challenges are issues specifically related to offshore wind, such as deepwater foundation technologies, resource characterization in the marine atmospheric boundary layer [21,22], environmental aspects, and socioeconomic impacts [23,24].

The primary differences between offshore and onshore wind farm projects can be observed in the construction, operation, maintenance (O&M), and decommissioning processes. During the construction phase, offshore projects require the use of platforms, cables, networks, substations, dredging, and other construction elements unique to the offshore environment. When operating and carrying out maintenance, the personnel must be in charge of traveling to it by boat or air transport, and the necessary equipment must be transported [25]. The potential for these activities to generate noise that could affect underwater fauna has been the subject of recent investigations and will be a primary focus of this study.

3. Literature Analysis

3.1. Social and Environmental Impacts

The European offshore wind industry has existed and slowly expanded for more than two decades [26]; therefore, most of the information collected about OWF impact is based on publications about the North Sea. The North Sea has a largely sandy bottom, a hard substrate, and heterogeneous sediment [27,28], which shares similarities with the Uruguayan sea bottom characteristics, as it is also dynamic and heterogeneous and has hard substrates that integrate tosca bottoms, stone sandbanks, and sandy bottoms with fauna diversity [29–31].

These similarities make the impacts studied in European seas helpful in gaining an initial understanding of the main effects caused by implementing offshore wind farms in Uruguay, which are listed in Tables 1–4.

It is also emphasized that shared learning is needed to best address the challenges in building the requisite scientific frameworks to apply to the effects of OWFs, requiring crossjurisdictional collaborations, highlighting the spatiotemporal variability in the interactions that have been studied, and identifying where knowledge gaps remain [26].

The presence of the large infrastructure in the North Sea of offshore wind farms produces some short- and long-term impacts. With a focus on the long-term course of these offshore wind farms, both fish and seabirds may alter their behavior. Collision during the operation and maintenance period is one of the main adverse effects, either with the towers or the movement of the blades, leading to a decrease in the density of species, as well as disturbances in birds through rotor turbulence [32]. This can be a significant point at the population level for species that naturally have low reproductive potential, slow sexual maturation, and great longevity [33]. The areas of fishing activities are also affected, causing their transfer due to the generation of restricted areas in the location of the wind farm, resulting in a modification or deviation in the navigation routes [34], where birds that use a low-altitude flight have increase in mortality due to collisions with boats or even entanglement with trammel nets or trawl nets [35].

In the construction and maintenance phases, a deterioration in water quality can be generated through the accidental spill or leak of polluting substances due to the movements of support vessels and the installation and operation of support bases [34], affecting the health of birds and the ecosystems that provide the food resources on which they depend [35].

Migratory routes can also be interrupted due to the physical barrier provided of wind farms, forcing birds to divert their path during the farm's operation [33], increasing the energy demand for the flight by providing critical rest areas, affecting their physical condition and reproductive success.

Table 1. Possible effects on marine mammals affected by the implementation of offshore wind farms, as well as their causes and possible mitigation actions.

Causes	Possible Effects	Possible Mitigation Actions
Noise from rotating parts emitted into the water	Interference with auditory system, foraging, communication, and migration [36]	Prohibit construction work that generates noise during breeding periods [27,37]
	Physiological stress [36]	
Accumulation of noise from ships and turbine	Avoidance of affected areas [27]	Avoid excavation of piles during periods when marine mammals are present in large numbers [27,37]
	Injuries to the auditory tissue [38]	
Pile installation	Reduction in hearing and echolocation capacities [38]	Use porpoise detectors or similar equipment [37]
		Avoid work during reproduction season and the birth of marine mammals [37]

Table 2. Possible effects on fish affected by the implementation of offshore wind farms, their causes, and potential mitigation actions.

Causes	Possible Effects	Possible Mitigation Actions
Increased sediment concentrations	Reduced efficiency of the respiratory system [39,40]	Prefer foundation projects with the smallest possible surface area [37]
		Conduct detailed investigations of gravel distribution in the area before working [37]
Underwater noise from turbine installation and operation	Avoidance of affected areas with the sound of 90 dB or more [39,41]	Use techniques such as bubble curtains or foam screens to reduce underwater noise during pile driving (it should not exceed 160 dB at 750 m from the site) [37,39]
		Group noisy activities together and limit the duration of their operation [37]
		Start with a low noise level to allow fish and marine mammals to move out of the area before noise levels increase [37]
New hard-bottom habitats	Attraction of demersal, pelagic fish and large predators. Reduction in soft habitat species [27,40,41]	Minimize the introduction of artificial hard substrates to reduce the increase of non-native species. [37]
		Fill the foundation pits with as much sand as possible and of the same quality as the original sand [37]
Electromagnetic fields around cables	Influences sense of direction and ability to move (perception varies with species between 20 and 75 µT) [27,39]	Select a placement depth sufficient to minimize electromagnetic fields [37,42]

Table 3. Possible effects on birds affected by the implementation of offshore wind farms, their causes, and possible mitigation actions.

Causes	Possible Effects	Possible Mitigation Actions
Structures between 20 m and 200 m in height	Collisions in migratory traffic [27,40]	Use lighting that does not attract birds and equipment that can be turned off during the rainy season [37,40]
		Position offshore wind farms parallel to the predominant direction of flight and reserve corridors to reduce the risk of collisions [37,40]
		Reduce night lighting in combination with increased separation of turbines to limit the attraction of nocturnal migratory birds [37,43]
	Greater energy costs in order to avoid the farm area [27,40]	Shut down turbine activity during peak migration [37]
		Select suitable locations to prevent or minimize habitat loss, such as resting and feeding areas [37]

Table 4. Possible effects on social structures affected by the implementation of marine wind farms, their causes, and potential mitigation action.

Affected Social Structure	Causes	Possible Effects	Possible Mitigation Actions
Fishing	Prohibition of fishing in security zones around the construction [27,44]	Moving fishing activities to different areas [27,44]	Allow fishing with static equipment within the offshore wind farm [37]
		Intensifies competition [26]	Divide construction into phases to limit exclusion zones [37]
		Increased transportation costs to less profitable areas [26]	Provide substitute income to fishermen, including their participation in the construction and operation of the offshore wind farm [37,44]
Tourism	Implementation in maritime and coastal leisure activity areas [41]	Increased traffic [23]	Avoid periods of high tourist season for construction [37]
		Economic and social loss of seascapes as part of cultural marine goods [41]	Survey community views at key stages of the project life cycle [37]
			Select suitable locations far from the coast that are barely noticeable [37]
Coastal areas	Changes in coastal infrastructure (assembly and operations ports 75–200 km close to the farm and substations) [45]	Complications in navigation [27]	Explore possible collaborations in the area, such as sharing supply ships [37]

3.2. Technological Challenges to Offshore Wind Farm Development in Uruguay

To ensure the compatibility of the main components of OWFs in Uruguay, it is essential to evaluate different technologies. This includes evaluating wind turbines, gathering and exporting cables, transformers, and converter stations [17]. Near-shore offshore wind farms send electricity directly to an onshore substation via an export cable. However, the electricity is first transferred to an offshore substation for parks located further from the coast, where the voltage is increased before being sent to land [46]. Innovative designs have been created for the foundations in these parks, such as the vacuum bucket and the twisted jacket [17]. Suction-box-type structures can reach depths of up to 60 m. They are easy to transport and install and economical since they do not require land preparation. On the other hand, jacket structures are suitable for depths of up to 80 m, but their construction and installation are considerably more expensive [47]. However, monopiles continue to be the most used on the market [17], being used in between 70 and 80% of offshore wind towers [47].

Monopiles are expected to continue dominating in the coming years as improvements are made to support 6 to 8 MW turbines at characteristic depths of up to 40 m. Currently, monopiles are frequently used at depths of 0 to 20 m, supporting wind turbines of small and medium dimensions. However, they can also be adapted for larger turbines, offering the advantage of versatility in different marine soils. This type of foundation is feasible in shallow waters, where soils range from softer clays to some types of soft rocks. Although semisubmersible structures have been used in the oil and gas industry and not frequently in the wind industry, in recent years, several floating solutions have been tested in offshore wind farms, used at depths where it is are feasible to implement foundations greater than 60 m [47]. Monopiles are not yet economically viable, but their market dominance will allow for further study of their environmental impacts and the application of known mitigation measures [17]. As a result, they are likely to become the most common option in Uruguay in the future.

3.3. Wind Resource Assessment

Assessing the wind resource of a given area/region of interest is the process that wind farm developers use to estimate the future energy generation of these developments. Numerical simulations reconstruct past climatic conditions through retrospective forecasts, known as hindcasts [48]. This process enables the understanding of the historical behavior of specific meteorological variables, making it possible to determine, for example, the wind resource available for a given region.

Hindcast studies use data from global atmospheric reanalysis models as initial conditions inserted into a mesoscale numerical atmospheric model, whose output data are used as input information for a third model, the microscale model. At each stage, the spatial resolution of the study area of interest increases, allowing the available wind resources to be known in more detail. Figure 3 shows a diagram of the hindcast methodology.

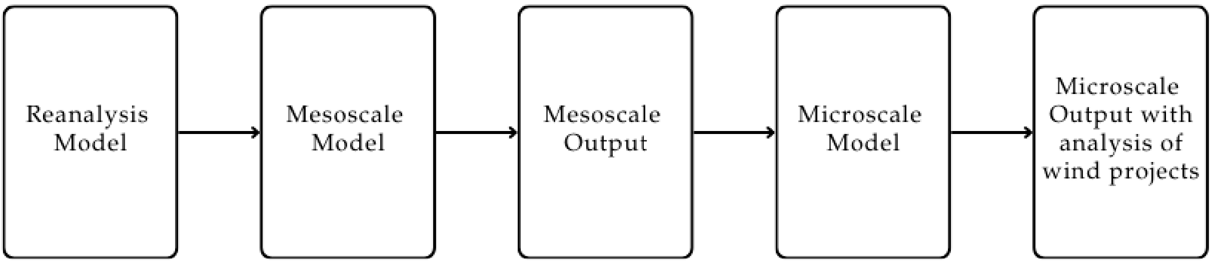


Figure 3. Representation of the stages of a hindcast study to evaluate the wind power of a particular region.

Hindcast studies can be found in, for example, the Global Wind Atlas [49], the Wind European Wind Atlas [50], and the Offshore Wind Energy Resource Assessment for the United States [51]. Currently, hindcast studies are being carried out for Uruguay's offshore territory, which is still in an early stage.

Uruguay had a 1-year study (2019) carried out through the Offshore Wind Energy Research Group of the Technological University of Uruguay—UTEC. This study's initial conditions were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis V5 (ERA5) model [52], with a horizontal spatial resolution of approximately 30 km and hourly estimates of different atmospheric variables. ERA5 contains information on the past state of the atmosphere. It combines large amounts of historical observations of meteorological variables into global estimates using advanced modeling and data assimilation systems. This information is relevant for estimating the wind resources in a given area. To increase the spatial resolution over the study area, the Weather Research Forecasting (WRF) numerical model [53] was used, with dynamic downscaling, which allowed the spatial resolution over the area of interest to be increased to 1.1 km. Figure 4 shows the average wind speed (m/s) at 100 m from the surface simulated with the WRF model for 2019 over the offshore area of Uruguay. The polygons H01, H02, H03, and H04 represent the areas selected by the ANCAP for the possible implementation of OWFs.

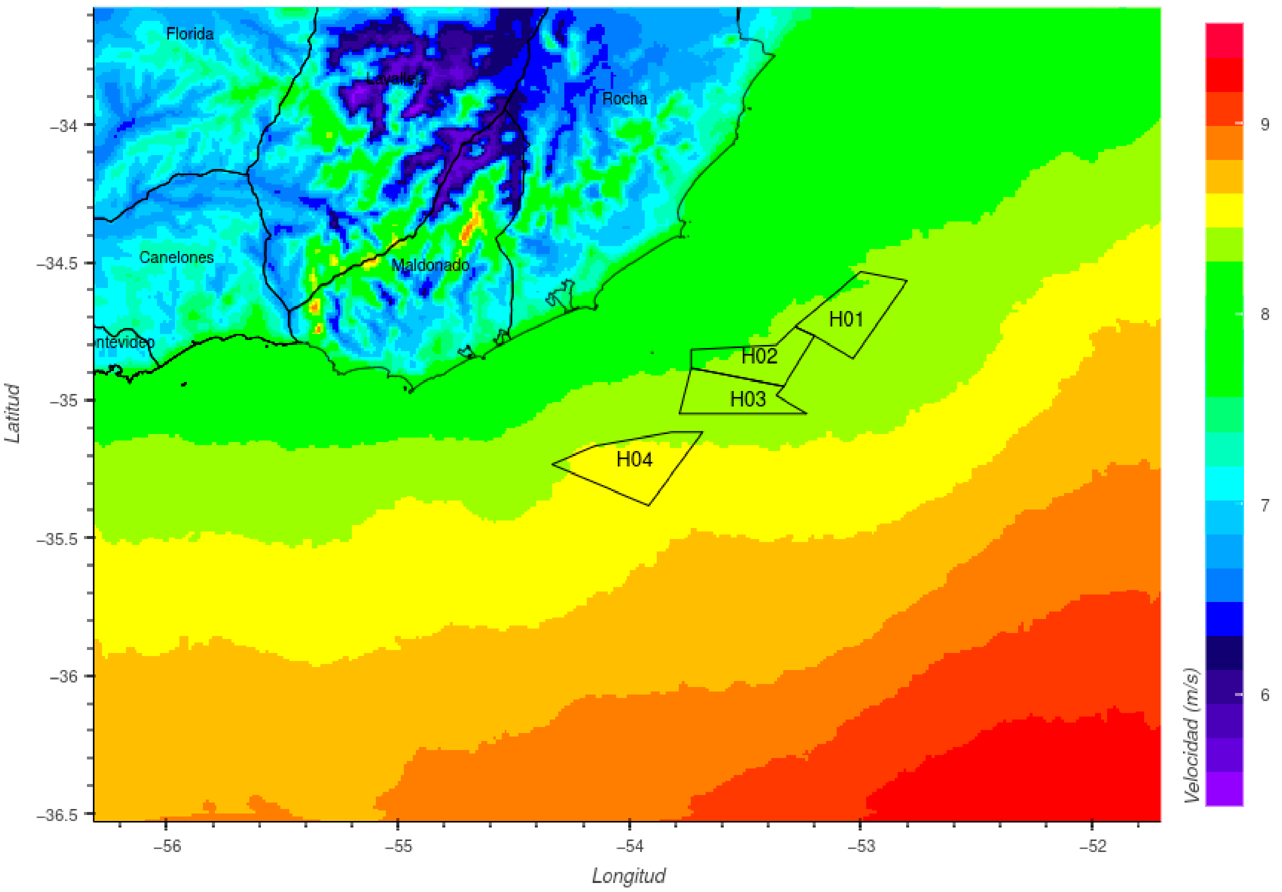


Figure 4. Average wind speed (m/s) at 100 m from the surface simulated for 2019 over the offshore area of Uruguay.

The WRF model outputs are input to the microscale model WindPRO [54]. WindPRO received the spatially available wind resource data within the study region and from some user choices such as the model and number of wind turbines; using optimization calculations of the location of the wind turbines in the available area, it estimates the power generation if a wind farm is installed. WindPRO reports some of the most relevant parameters for a wind energy project, such as the nominal power (NP) of the wind farm (power of each wind turbine multiplied by the total number of selected wind turbines), annual energy production (AEP in MWh/year), energy losses (wake, electrical, etc.), and the capacity factor (CF), which is one of the most used parameters worldwide to compare the performance of different wind farms. The CF is defined as the ratio of average to rated power [55].

An energy calculation was made to verify the energy generation potential of the H04 area (see Figure 5), with a layout of 150 wind turbines of 15 MW with a nominal installed capacity of 15 MW each and a 248 m rotor diameter, totaling 2.25 GW of installed power. The capacity factor obtained was 45.7%, a substantial amount of energy, demonstrating the high potential for Uruguay's offshore wind farms. This value is comparable to that of many European offshore regions, which, on average, have a CF of between 40% and 53% [56].

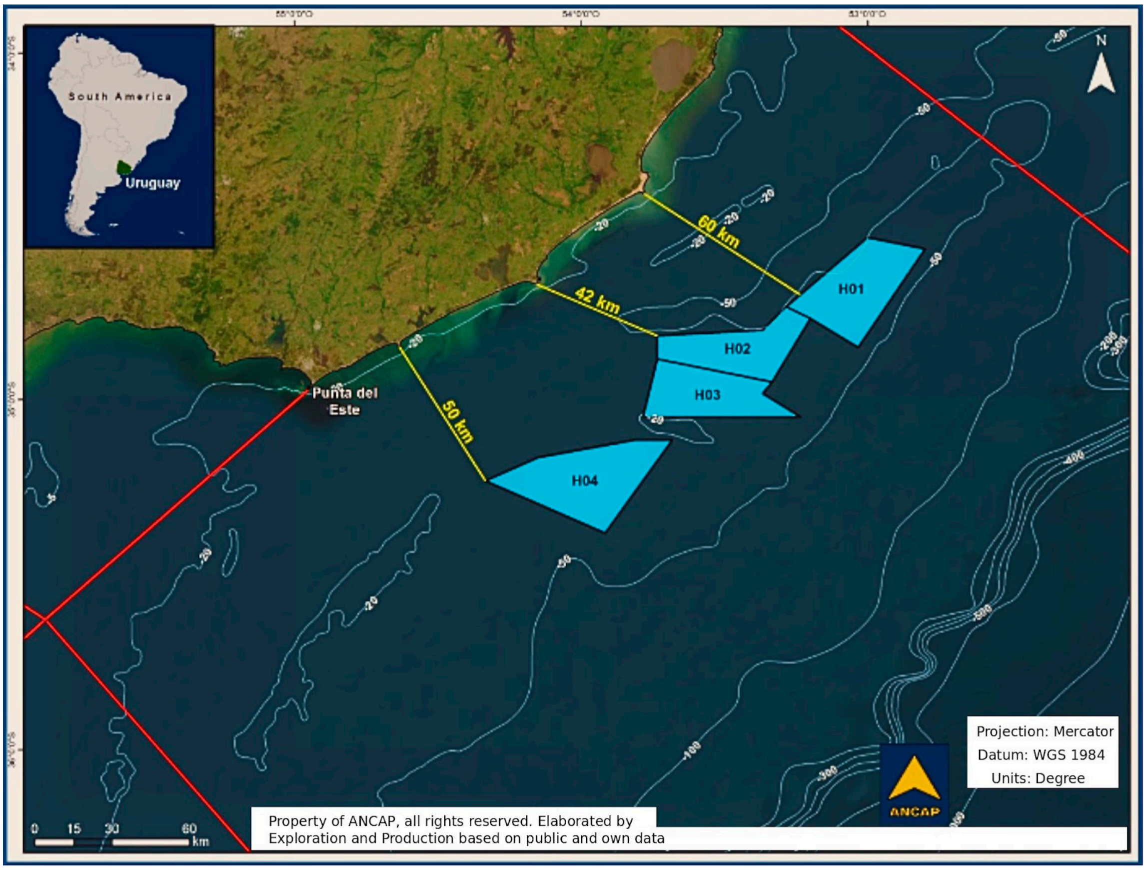


Figure 5. Possible offshore areas selected by ANCAP [8] and distances to the coast. Red lines indicate Uruguay's commercial exploration area.

Regarding turbine capacities, offshore wind turbine generator ratings, rotor diameters, and hub heights have increased over time [57]; global installations in 2023 had a capacity-weighted average turbine rating of 9.7 MW (26% year-over-year increase), rotor diameter of 183.4 m (5% year-over-year increase), and hub height of 124.0 m (6% year-over-year increase). Considering the wind characteristics determined at 100 m in Uruguay, it is foreseen that the turbines chosen for the project in Uruguay will be around these average world parameters.

4. Characterization of the Uruguayan Coastline

Following the identification of OWFs' environmental and social impacts at a global level, a detailed analysis was carried out to understand the communities and ecosystems that are likely to be affected by the development of this technology in Uruguay. This search for local information is essential in developing new technology regarding environmental aspects, using global knowledge adapted to the country's actual condition.

Figure 5 shows the areas of possible OWF implementations and their distances to the coast of the Uruguayan territory. These areas are in the Uruguayan Exclusive Economic Zone, which is characterized by specific fauna.

4.1. Environmental Condition

At the marine level, the Uruguayan Exclusive Economic Zone (UEEZ) constitutes a particularly relevant area for biodiversity on a global and regional scale [29]. It is subject to variability due to the confluence of the warm Brazilian current with the cold Malvinas current and the discharge of fresh water from the Río de la Plata, constituting a highly productive and dynamic region [29]. It has a significant impact on fishing and the availability of food for commercial fish and other marine animals [31].

In particular, this marine region has been globally recognized for its richness in various biological groups, including pelagic species such as cetaceans and sharks. It is also a breeding, feeding, and/or reproduction habitat for turtles, birds, and sea lions [29].

Bird species, such as the royal tern (*Thalasseus maximus*) and the kelp gull (*Larus dominicanus*), nest on the coastal islands of Uruguay and feed in the adjacent sea. Turtles (*Dermochelys coriacea*) use the area to feed while they migrate to reproduce. Regarding marine mammals, along the Uruguayan coast and islands, there are settlements of sea lions (*Arctocephalus australis*, *Otaria flavescens*) who search for food in the area [31]

Additionally, several species of whales and dolphins are found, depending on their migratory patterns. Furthermore, several populations of bony fish, such as croakers (*Micropogonias furnieri*) and tunas (*Thunnus* spp.) and cartilaginous fish—sharks and rays—feed, reproduce, migrate and breed in Uruguayan ocean waters [31].

It is known that for many species of birds, turtles, marine mammals, and sharks, the interaction with fishing activity constitutes one of the main threats to their survival, along with pollution of the marine environment, habitat degradation, and the relationship with introduced species [31].

Seabirds face serious threats such as invasive species, bycatch, hunting, climate change, and disturbance, affecting more than 20% of species. Pollution, overfishing, and problematic native species also have a significant impact. The most severe threats are bycatch, invasive species, overfishing, and climate change. To understand the conservation of this group at the global level, it is crucial to evaluate both the human and natural pressures that affect all species. This is critical because many species that were previously abundant and classified as Least Concern on the IUCN Red List are now in decline [58].

4.2. Social Aspect

The coastal zone of Uruguay on the Río de la Plata and the Atlantic Ocean is approximately 714 km long (of which 478 km correspond to the Río de la Plata and 236 km to the Atlantic Ocean). It consists of a strip of land and sea space of variable width where sea–land interactions occur. This area generates 75% of the national GDP and houses 70% of the population. Montevideo has the most significant maritime commercial exchange port in Uruguay, and the surrounding area is active in industrial and artisanal fishing [29]. The fishing industry in Uruguay is based on extracting croaker, hake, and fish, which are landed mainly through the port of Montevideo [59]. It contributes to the national economy by creating employment in the commercial balance and as part of the national food supply.

The species that landed the most in 2016–2018 were shad, croaker, and menhaden, totaling between 74 and 76% of the total artisanal catches [60]. Industrially, hake is the main fished species. On the other hand, the croaker is the second-fished species. Although it has decreased recently, it has remained much more stable.

Regarding tourism, statistical data from the Ministry of Tourism, issued on April 21, 2023, on the number of visitors were revised. Of the areas tourists chose in 2023, 48% chose the coasts, including destinations such as Punta del Este, Costa de Oro, Rocha, and Piriápolis. On the other hand, cities such as Montevideo or Colonia represented 24% of the tourist reception during the year. Regarding total spending, the Ministry of Tourism estimated that 75% of the expenditure of all tourists in the country was made in the coastal areas mentioned above.

4.3. Economic Effects

In the economic field, Uruguay can benefit from several aspects of installing offshore wind farms. One of these aspects is the diversification of the productive matrix, thus increasing resilience over time and decreasing future risks [9]. Diversifying the productive matrix creates the opportunity for the country to have relationships with new commercial agents at a global level, forming a more robust network, which can be beneficial to the country in the short, medium, and long terms, adding value and contributing to economic growth.

The offshore eolic electricity production is currently designed in Uruguay to generate green hydrogen. It could allow the country to increase the value added to exported products, opening new industrial chains and expanding the export market for sustainable energy, which would positively impact the economy. This factor may favor foreign investments, contributing to the country's infrastructure development.

The direct positive impact on the population will be seen in the generation of employment and in the formation of technical capacity at the national level to meet the demand involved in offshore wind energy, from studies before the installation of wind farms to operation and maintenance. According to the Roadmap for Green Hydrogen [9], the offshore wind industry could create more than 30,000 direct jobs in construction, operation, maintenance, and logistics.

As possible adverse economic effects, these may occur mainly in local communities during the construction of wind farms, such as affecting fishing-related activities. To mitigate this, a form of compensation for local fishers during the construction phase of OWFs could be studied. According to Glasson et al. [23], the socioeconomic impacts on local communities have received little attention compared to the biophysical effects, particularly in Europe, where most of the studies on OWF sustainability have been conducted.

In general terms, the economic effects are mostly positive, and the possible negative effects may be transitory and have the possibility of mitigation with well-implemented actions in a timely manner. These aspects reinforce the possibility of Uruguay leading the transition toward a green economy, taking advantage of the offshore wind resources.

4.4. Seasonal Weather Conditions for Offshore Wind Farm Development in Uruguay

Due to various atmospheric factors, the wind in Uruguay has different directions depending on the season [61]. The wind direction and intensity data used in the first stage of the wind resource assessment (Section 3.3) were included in the ERA5 reanalysis model, which were used as input data for the subsequent simulations. Figure 6 shows some of the weather stations that the ERA5 model assimilated in areas close to those of interest to this study.

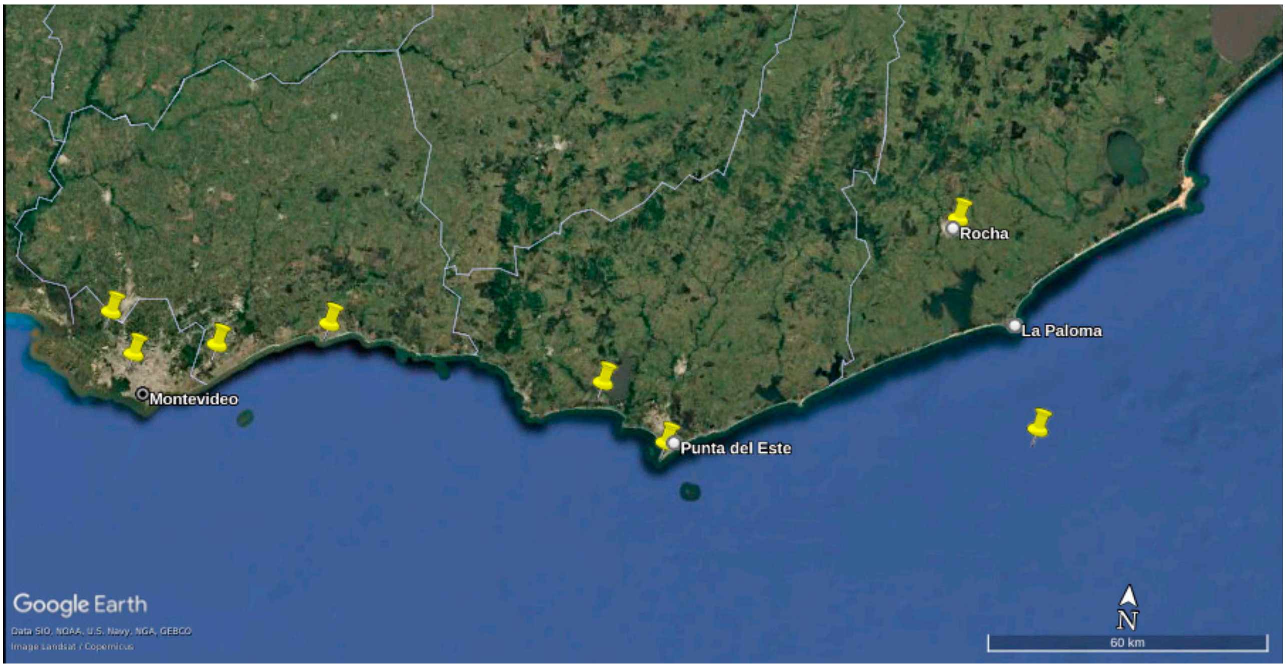
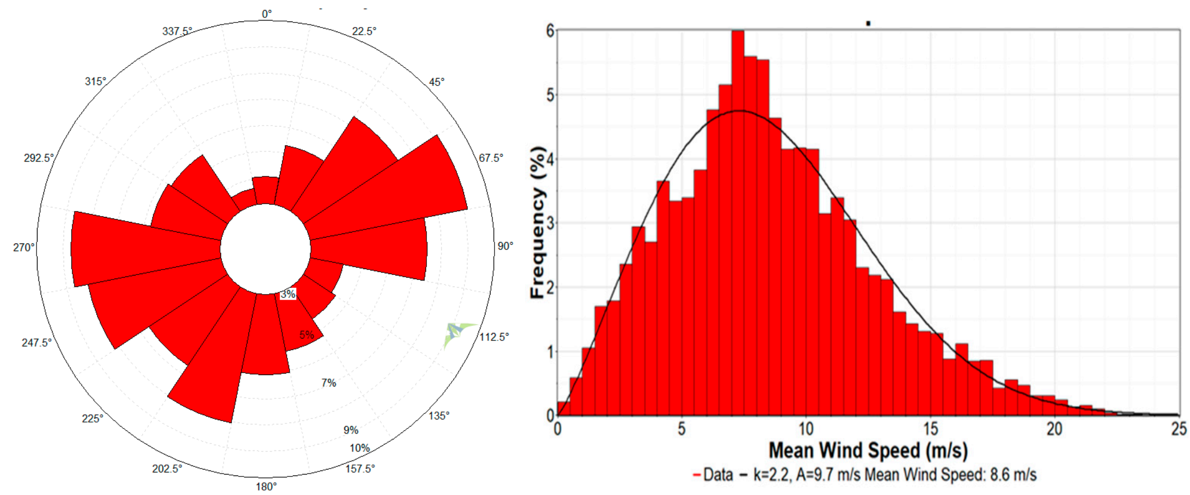


Figure 6. Meteorological stations (yellow marks) assimilated by the ERA5 model in the region near the study area [62,63].

In summer, predominantly easterly winds occur, influenced by the South Atlantic anticyclone, resulting in warm and humid winds on the coast. Due to the seasonal transition and the presence of low-pressure systems, an increase in southeasterly (SE) winds is observed during the fall, particularly in the east of the country. In winter, easterly winds are generated in the north and westerly winds in the south, motivated by the movement of the anticyclone toward the continent, where the local climate is affected. During spring, easterly winds strengthen as the atmosphere stabilizes after winter [64].

Data were obtained through WRF simulations using the ERA-5 reanalysis as input data, carried out through the Offshore Wind Energy Research Group of the Technological University of Uruguay (UTEC); Figure 7a shows the wind speed frequency considering the direction of the H04 region, evidencing the multidirectional nature of the wind. In part (b), the Weibull distribution of the wind at a height of 100 m in the same area is represented, having a mean wind speed of 8.6 m/s.



(**a**) (**b**)

Figure 7. Wind rose (**a**) and Weibull distribution (**b**) for the H04 region in the offshore territory of Uruguay.

4.5. Onshore Wind Farm Regulation in Uruguay

The focus was placed solely on onshore legislation, as offshore regulations have not yet been established. Offshore guidelines were unavailable for consideration in Uruguay. Regulations already applied in the local terrestrial environment are a possible consideration for those carried out in marine plant activities. These must meet a balance of requirements and obligations, depending on the differences in the regulatory framework between the two. The Ocean Renewable Energy Action Coalition indicates that it is essential that policies and regulations are synchronized with clear objectives, contributing to the reduction in risk and stimulating investment [45].

In Uruguay, three key environmental authorizations are required to implement the installation of wind farms: the Environmental Feasibility of the Site (VAL), the Prior Environmental Authorization (AAP), and the Environmental Authorization of Operation (AAO). The National Directorate of the Environment (DINAMA), belonging to the Ministry of the Environment, is responsible for issuing these authorizations [65].

Implementing power generation plants with a capacity greater than 10 MW in Uruguay requires determining the Environmental Feasibility of the Site (VAL), as established by the Regulation of Environmental Impact Assessment and Environmental Authorizations, approved by Decree 349/2005. This regulation requires that the location and description of the plant's influence area include an analysis of possible alternatives. Also, plants exceeding 10 MW need a Prior Environmental Authorization (AAP), which must comply with the territorial planning criteria established in the Territorial Planning and Sustainable

Development Law. Finally, once the AAP is obtained, it is necessary to have the Environmental Operating Authorization (AAO) renewed every three years to continue operating legally [65].

5. Studies Required for Offshore Environmental Licensing in Uruguay

This section presents this study's main results, which focus on identifying the necessary studies and requirements for obtaining environmental licenses for offshore wind energy projects in Uruguay. It involved a literature review on OWF impacts and the country's actual situation on these aspects (tourism, fishing, etc.).

To mitigate the impacts of offshore wind farms and strengthen the resilience of coastal ecosystems, it is crucial to adopt approaches that conserve biodiversity as well as promote habitat restoration and to consider the interactions between urbanization and climate change. Protecting and effectively managing coastal areas are essential to guarantee the continuous provision of ecosystem services and the sustainability of Uruguay's coastal ecosystem [29]. Because of the higher complexity of an offshore system compared to an onshore one, additional regulations must be defined in the preview of the realization of offshore wind farms to guarantee the sustainability of this project.

Developers use regional and national strategic planning to identify potential impact-related objections in areas that could stop or delay the project. As some are inevitable, mitigation is crucial at all stages of the project. The selection of a suitable site determines not only technical aspects such as energy production but also the economic, social, and environmental repercussions [25]. The crucial steps for this selection are depicted in Figure 8.

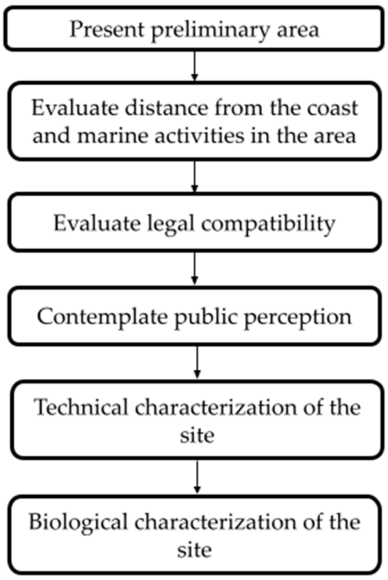


Figure 8. Flow chart presenting the steps to consider in the selection of a suitable site for an OWF.

In the beginning, the polygonal security area of the project must be represented, presenting possible navigation routes and options for location adjustments in the distribution of towers and in the protection of cables/moorings [37]. Concerning the protection of birds, some areas have to be avoided since they are known to be migratory routes. Even when birds and mammals are capable enough to avoid the wind farm, they spend much more energy in staying away from it, resulting in a possible population reduction [25]. To control and mitigate the environmental impacts and recurring use conflicts in this type of undertaking (mainly those related to tourist activities, impacts to the landscape, shorebirds, corals, greater environmental sensitivity of shallow areas, and creation of regions excluding fishing), the evaluation of the distance from the coast is recommended [37].

A visual impact evaluation of the wind farm must be conducted by potential developers as part of the Environmental Impact Assessment (EIA), whose main purpose is to identify the impacts of an activity, propose mitigation measures if possible, and ensure that adverse effects are minimized [25]. EIAs are used globally to manage the environmental impacts of human activities, identify project risks to avoid adverse effects, as well as adopt mitigation and compensation measures [24].

In this EIA, the compatibility of the undertaking with the applicable legislation, plans, government programs, and zoning, proposed or in execution, as well as possible legal prohibitions regarding the implementation and operation of the undertaking or activity must be analyzed [37] considering technical standards that address the maximum parameters of the negative externalities for noise, water quality, and navigation safety. For Uruguay, this refers mainly to compatibility with the current environmental regulations, such as those established by the Environmental Impact Assessment Regulation of the National Directorate of the Environment [66].

In this regard, the site selection procedure involves taking into account public attitudes toward the project, helping with the design, and using planning and simulation tools. Thus, the visual impact assessment is conducted using appropriately designed software platforms that can simulate various views and evaluate public reactions before the project is implemented [25].

Furthermore, the area designated for the construction site should be characterized, including the layout and description of its units, mechanical workshops, and supply stations, presenting an estimate of road, port, and maritime traffic [37]. An evaluation of the technological alternatives taking into account the technical, economic, and environmental aspects must to be conducted to minimize ecological impacts in wind energy generation projects, considering the type of cement, the height of the towers, rotation speed, the color of the structures, lighting, and the identification of the risk of bird collisions [37].

The EIA must include the spatial and temporal identification of areas of concentration, reproduction, feeding, and migratory routes by species [37], as well as the description of the structure of the populations through indicators (diversity, distribution, and abundance), identifying potentially sensitive species based on their auditory perception spectra and modeling of noise emission by frequency.

As part of the preliminary process, Uruguay is considering possible activities in the area, such as fishing, tourism, migratory routes, and environmentally protected zones to delimit the areas. Uruguay must characterize the sea lion islands in depth, the migratory patterns of marine mammals and coastal birds, and the fish species found in the region, which are essential for the economy and habitat conservation.

In the specific field, the preliminary process must involve scientists from different subject areas, such as communication, sociology, psychology, biology, and strategic planning; the interaction of all these experts promotes the understanding and comprehension of the opinion of local societies [25].

Updated, integrative, and systematic scientific information on the risks associated with each potential interaction between OWFs and different ecosystem elements is needed to inform managers and decision makers during the planning stages. However, it is important to recognize that there are scientific disagreements about the extent of the impacts of OWFs (how significant they are on the environment), as demonstrated by the lack of empirical evidence [24].

6. Discussion and Conclusions

Uruguay is positioned to advance to the next stage of decarbonizing its energy matrix. The development of OWFs along its coast represents an opportunity to diversify and enhance energy security while contributing to regional climate change mitigation efforts. However, the possible effects of wind energy production on the coasts must be studied before its development in the country, taking as reference previous studies around the world, relating this information to characteristics of the country's coasts. This article offers an academic perspective aimed at directly contributing to the design of regulatory policies for offshore wind energy in Uruguay. The information presented seeks to support future debates, especially regarding environmental aspects and social perspectives. This paper reflects the approach of academia to emerging issues in the Uruguayan economy, which require a thorough discussion to ensure their implementation in a sustainable and economically viable manner.

The installation of OWFs can significantly change the environment. The specific biological effects must be studied considering the area's fish, marine mammals, and birds, which necessarily requires a prior study characterizing the fauna that inhabits, visits, or feeds in the area. Regarding these species, it is essential to conduct site-specific research to identify the presence and behaviors of sensitive species; assess the risks, such as the release of sediments, introduction of hard substrates, accumulation of construction and operation noises, and electromagnetic fields; and propose measures to mitigate the negative impacts.

Furthermore, the areas chosen for energy generation due to their wind potential must be considered protected and sensitive areas; in turn, balanced with possible conflicts of interest, the impacts on economic activities such as fishing, tourism, and port logistics must be considered. The prohibition of fishing in the park or in surrounding exclusion zones is a point to discuss if these technologies are implemented along the coasts. Mitigation measures for the effects on fishing must be considered, such as the possibility of a static fishery or the passage of certain boats through the area. The planning process should involve direct consultation with the affected communities to ensure their needs and concerns are adequately addressed. It is essential to consider the environmental impacts of OWF projects and the possible impacts on the socioeconomic aspects of local communities.

Tourism, another major industry for Uruguay, could be affected if wind farms are visible from popular coastal destinations. As coastal landscapes are integral to the tourism experience, visible wind turbines could alter the aesthetics of these areas. To minimize such disruptions, strategic planning should consider positioning wind farms far from tourist sites and aligning construction timelines with low-season periods to limit interference.

In summary, this article's results indicate that Uruguay has excellent potential for developing OFWs. Its favorable wind resources allow for stable wind power generation, as highlighted by a capacity factor of 45.7%. Section 5 shows that several environmental and social aspects must be addressed before implementation, based on the findings in worldwide projects (Section 3) and local aspects (Section 4).

Considering these factors, Uruguay can sustainably move toward a low-carbon economy that is committed to and equitable for local populations and existing ecosystems, in view of all environmental and social aspects and studies before installing OWFs. The country must establish a comprehensive regulatory framework for these projects. This framework should include precise guidelines for environmental impact assessments, clear criteria for optimal site selection, and structured protocols for meaningful stakeholder engagement. It is crucial to adopt a multidisciplinary approach that seamlessly integrates ecological, social, and urban planning perspectives, ensuring that project designs are not only environmentally sustainable but also aligned with the needs and expectations of local communities. Additionally, developing a skilled local workforce is essential to support the sustainable growth of the offshore wind industry and ensure that the benefits of these projects reach the local population.

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