sustainability

Article

Critical Environmental Factors in Offshore Wind–Hydrogen Projects: Uruguay's Exclusive Economic Zone

Luisa Rivas *, Alice Elizabeth González and Alejandro Gutiérrez

Facultad de Ingeniería, Universidad de la República (UDELAR), Julio Herrera y Reissig 565, Montevideo 11300, Uruguay; elizabet@fing.edu.uy (A.E.G.); aguti@fing.edu.uy (A.G.)
* Correspondence: luisarivas10@gmail.com

Abstract

Green hydrogen is a promising solution for decarbonizing emission-intensive sectors, with its production through offshore wind energy offering viable opportunities. This study presents a preliminary assessment of the main environmental factors potentially affected by offshore wind and green hydrogen projects in Uruguay's Exclusive Economic Zone (EEZ), where such developments pose environmental challenges that require evaluation, particularly given the limited prior research in Uruguay and Latin America. Through a comprehensive review of international literature and national technical data, the study identifies key interactions between project activities and the physical, biotic, and anthropic environmental components during the development, construction, and operational phases. Using cross-reference matrices and impact categorization, the analysis highlights that activities such as foundation installation, submarine cable deployment, and offshore electrolysis could significantly affect the seabed, underwater noise levels, water quality, and marine biodiversity. The biotic and physical environment were found to be the most frequently impacted. To contextualize these findings, technical information specific to Uruguay's EEZ was reviewed to identify the most vulnerable regional environmental factors. The results offer a science-based foundation to support early-stage environmental assessments and guide sustainable offshore energy development in the region.

Keywords: green hydrogen; environmental impact; offshore wind energy; electrolysis; desalination

check for updates

Academic Editor: Firoz Alam

Received: 4 June 2025
Revised: 26 June 2025
Accepted: 1 July 2025
Published: 3 July 2025

Citation: Rivas, L.; González, A.E.; Gutierrez, A. Critical Environmental Factors in Offshore Wind–Hydrogen Projects: Uruguay's Exclusive Economic Zone. *Sustainability* **2025**, *17*, 6096. https://doi.org/10.3390/su17136096

1. Introduction

The growth of renewable energy and the transition to a low-carbon economy have driven the development of new technologies for the generation and storage of clean energy. Among these solutions, green hydrogen has emerged as a viable alternative for the decarbonization of energy-intensive sectors. Hydrogen, the most abundant element in the universe [1], is a lightweight gas with a high energy density, making it an attractive energy carrier. However, storage and transportation pose significant challenges because of its low volumetric density and tendency to leak through conventional materials. In its gaseous state, hydrogen must be compressed to pressures of up to 700 bar or liquefied at −253 °C to facilitate transport, which implies considerable energy consumption and requires specialized infrastructure [1].

The production of green hydrogen is based on water electrolysis using electricity from renewable sources, allowing for the avoidance of CO_2 emissions associated with conventional hydrogen production methods, such as natural gas reforming [2]. Integrating this technology with offshore wind energy represents a key opportunity for the development of large-scale sustainable solutions. Offshore wind energy, unlike its onshore counterpart, is installed in bodies of water, mainly oceans, allowing it to harness stronger and more consistent winds, improving power generation efficiency. In terms of installed capacity, modern offshore wind turbines can exceed 16 MW, with rotor diameters of up to 250 m. There are already prototypes reaching 20 MW, which significantly enhances wind energy capture compared to onshore turbines, whose typical capacities range between 2 and 9 MW [3].

To better understand wind energy, it is essential to consider wind dynamics and its interaction with the Earth's surface. Wind energy originates from the kinetic energy of the wind, which is driven by solar radiation and the Earth's rotation [4]. This phenomenon results in different wind scales, ranging from global atmospheric circulation systems to local winds influenced by terrain topography and surface roughness. Most usable wind energy is found in the atmospheric boundary layer, which is the part of the atmosphere closest to the Earth's surface, where wind turbines can efficiently capture the available energy [5].

As air moves over the Earth's surface, it is subject to friction and terrain roughness, slowing its movement near the ground. As it rises, it moves away from the direct influence of the terrain, experiencing less friction and, therefore, moving at higher speeds. This is why wind energy projects aim to increase turbine heights to capture higher wind speeds [6].

The development phase of an offshore wind farm is a complex process involving multiple studies and assessments to ensure the project's technical, economic, and environmental feasibility. According to BVG Associates [7], this phase includes the concession of marine space, geophysical and geotechnical seabed studies, wind resource assessment, metocean analysis, and the corresponding environmental impact assessment. Uruguayan regulations, through Law 16.466 [8] and Decree 349/005 [9], require Prior Environmental Authorization (AAP), which involves conducting many detailed studies including those on marine fauna, air quality, underwater acoustics, and benthic ecosystems, among others. Technologies used for data collection include side-scan sonars, multibeam bathymetry, and cone penetration tests (CPTs) for seabed characterization [7]. Additionally, floating LiDAR systems, meteorological towers, and metocean buoys are implemented to evaluate wind speeds and ocean conditions, crucial for optimizing wind farm design and minimizing environmental impacts.

Regarding turbine foundation types, there are fixed and floating structures. Fixed foundations include monopiles, gravity-based foundations, and jacket structures, while deep-water projects use floating platforms such as Spar, semi-submersible, and tension-leg platforms (TLPs) [10]. The choice of foundation type directly impacts the economic and structural feasibility of the wind farm, as well as the stability of the turbines and the durability of the infrastructure [11]. These structures must withstand not only wind loads but also hydrodynamic forces from waves and ocean currents, requiring high-strength materials and advanced anchoring systems [11].

The electrical infrastructure is a key component for system efficiency and stability, enabling the transmission of generated energy to onshore substations. The medium-voltage subsea cable network connects wind turbines in a ring system, facilitating energy transmission to the offshore substation. These cables are corrosion-resistant, feature galvanized steel mechanical shielding, and integrate fiber optics for data transmission and monitoring [12]. For high-voltage transmission, offshore wind farms use AC (alternating current) or DC (direct current) systems, with DC being more efficient over long distances due to lower Joule effect losses. The installation of these cables requires specialized cable-laying vessels and remotely operated vehicles (ROVs) for seabed placement, minimizing navigation interference and marine life disruption [13].

Green hydrogen production from offshore wind energy relies on water electrolysis technologies, primarily alkaline electrolysis (AEL), proton-exchange membrane (PEM), and solid oxide electrolysis (SOE). AEL technology is the most mature and cost-effective, with 70–80% efficiency, but has limitations in responding to renewable energy variability [2]. PEM technology, on the other hand, provides higher flexibility and faster response times, making it suitable for offshore wind farms, though its higher investment cost is due to the use of noble metal catalysts [14]. SOE technology is an emerging alternative with potential efficiencies of 90–100% but remains in development, facing challenges related to high-temperature material durability [15].

Uruguay is actively evaluating offshore wind energy for green hydrogen production in the Exclusive Economic Zone (EEZ), recognizing its maritime energy potential. In 2022, the Ministry of Industry, Energy, and Mining (MIEM) launched the Green Hydrogen Roadmap, including the H2U Offshore initiative, led by ANCAP (*Administración Nacional de Combustibles, Alcohol y Portland*, Uruguay's national oil and energy company), which aimed at promoting offshore wind-based green hydrogen projects. The Uruguayan government has authorized ANCAP to auction four maritime areas for offshore wind farm installation, with a potential capacity of 3 GW to produce 200,000 tons of green hydrogen per year [16].

The EEZ of Uruguay was defined by the United Nations Convention on the Law of the Sea (UNCLOS) in 1982 [17]. It covers an area of 142,166 km^2, extending up to 200 nautical miles from the baselines established in Article 14 of Law No. 17.033. This maritime space, along with the Uruguayan continental margin, is vital from hydrodynamic, topographic, ecological, and economic perspectives.

Uruguay has sovereign rights to explore and exploit both living and non-living resources within the EEZ, including economic activities such as energy production. The sustainable management and use of the zone's resources, along with the protection and preservation of biodiversity and the marine environment, are fundamental.

This study aims to identify the environmental factors potentially affected by offshore wind-to-hydrogen projects within Uruguay's Exclusive Economic Zone (EEZ). It considers physical, biotic, and anthropic components to determine which environmental factors are most likely to be impacted. Additionally, it seeks to inform the prioritization of environmental protection and mitigation measures in the early stages of project development. This work provides a preliminary technical basis for environmental decision-making in a context where no similar assessments have yet been conducted in Uruguay or the broader region.

Environmental factors are defined as the specific attributes of the environment that may be subject to alteration due to human interventions [18]. For the purpose of this study, these factors are classified under three main environmental components:

- Physical Component: Includes seabed and soil characteristics, ambient noise levels, surface water quality, air quality, surface water temperature and hydrochemistry, and pressures on natural resources.
- Biotic Component: Covers fauna (e.g., plankton, benthos, nekton, fish, birds, reptiles, marine mammals, and cephalopods) and flora (e.g., aquatic vegetation and coastal plant communities).
- Anthropic Component: Encompasses human-related aspects such as landscape, fishing activities, maritime navigation, and terrestrial and marine traffic.

Given the scale and novelty of these projects in the region, this analysis seeks to contribute a structured and science-based approach to anticipate potential interactions with the environment. The insights derived here aim to support future impact assessments and regulatory planning, promoting the sustainable development of offshore renewable energy initiatives in Uruguay.

2. Methodology

A bibliographic review was conducted focusing on offshore wind projects and green hydrogen at the international level, encompassing scientific literature and technical reports published between 2012 and 2024. Articles were selected that described activities associated with the development, construction, and operational phases of offshore wind farms and green hydrogen projects and related these activities to the categories of impact on the affected environmental components.

It is important to note that a specific evaluation of environmental impacts requires the inclusion of elements such as frequency, intensity, and environmental context in order to propose effective assessment and mitigation measures. This level of analysis is beyond the scope of this study as the primary objective was to provide a general identification of the most relevant environmental impacts and the most affected environmental factors within the EEZ in Uruguay for projects of this nature.

For this initial assessment, each potential activity (e.g., foundation installation, dredging, and offshore electrolysis) was identified, along with its frequency of occurrence and potential interaction pathways with the environment (e.g., noise, sediment disturbance, and maritime traffic). Cross-reference tables were then developed to link activities and processes with associated impacts, environmental components, and factors, enabling the classification of impact frequency and the magnitude of the affected environmental factors. The reference tables that served as the basis for this cross-referencing and impact classification are included in Appendix A, providing detailed traceability of the input data used to construct the diagrams and synthesize the results.

Subsequently, the relationship between each project activity and its potential effects on the environmental components was identified, as well as the possible environmental impacts during the different phases of the project lifecycle: development, construction, and operation. The environmental impacts were then analyzed based on their degree of incidence, identifying those with the greatest potential to cause significant effects during each project phase.

Once the main environmental impacts and the affected components were identified, a cross-analysis was conducted with the environmental factors associated with each component to determine which factors would be impacted by each environmental effect. Figure 1 presents the flowchart of the methodology adopted for identifying the most affected environmental factors.

Figure 1. Flowchart of the methodology used to identify the most impacted environmental factors. Source: Authors.

This structured methodology is used to identify and classify environmental factors associated with different types of study activities (environmental studies, metocean, and geotechnical studies). In Figure 2, the diagram illustrates the linkage between these activities and the environmental impacts they generate (such as habitat alteration, increased noise levels, or fauna mortality) for the development phase. These impacts are grouped into categories of affected factors—biotic, physical, and anthropic—and are ultimately connected to specific environmental receptor components (such as marine fauna, water quality, or landscape).

During the development phase, the activities predominantly affect the biotic and physical components, with notable interactions such as disturbance to marine fauna, alteration of marine habitats, increased noise levels, and impacts on water and air quality. Within the biotic component, marine fauna and seabirds are the most frequently linked environmental factors, while in the physical component, sound pressure levels, water quality, and air quality appear as recurrently impacted. The anthropic component is less represented at this stage, with limited but traceable effects on navigation and landscape.

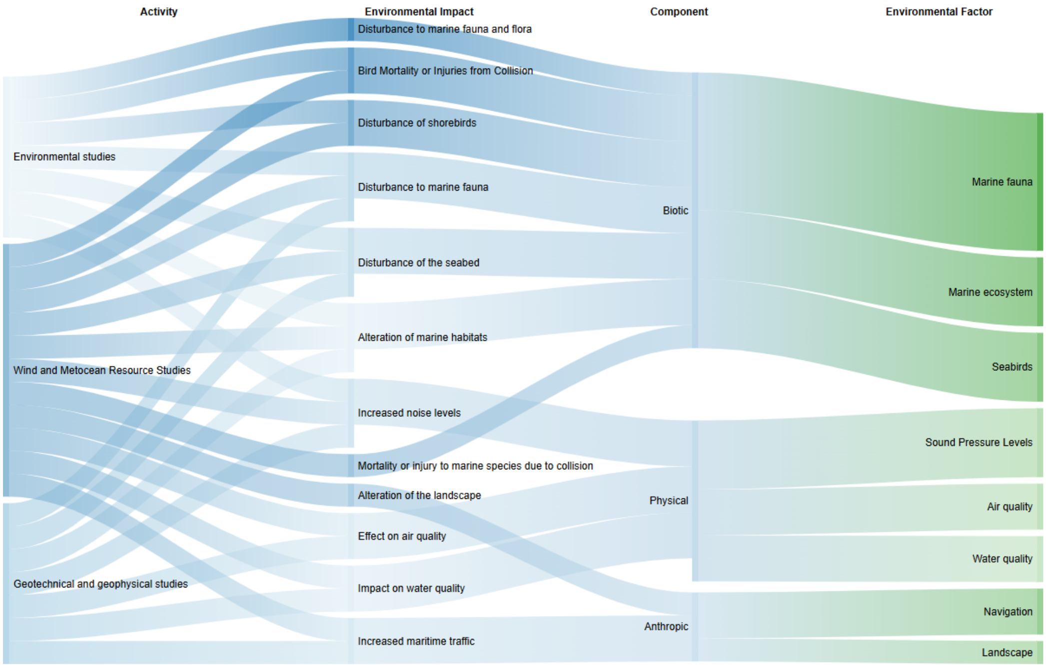

Figure 2. Diagram of environmental impacts and receptors from study activities during development phase. Source: Authors. Note: The color scheme is arbitrary and does not convey any quantitative or categorical information.

Among the activities assessed for the construction phase, the installation of foundations for wind turbines emerges as one of the most impactful. This activity involves direct intervention in the seabed, leading to disturbances of benthic habitats, increased underwater noise levels, and degradation of water quality due to sediment resuspension. Recent studies also highlight adverse effects on marine mammals, including avoidance behavior and temporary displacement from construction areas. Additional relevant impacts are associated with the installation of submarine cables and offshore electrolysis plants, which may alter substrate conditions, pose risks to navigation, and contribute to localized emissions during construction. As shown in Figure 3, the physical component registers the highest frequency of impacts, particularly on the seabed, water quality, and sound pressure levels. However, it is important to note that although many of these impacts are categorized under the physical component, they often result in secondary effects on the biotic component, especially marine fauna and ecosystems. For the anthropic component, notable impacts are observed on landscape, fisheries, and maritime traffic, emphasizing the importance of considering interactions between infrastructure deployment and human uses of the marine space.

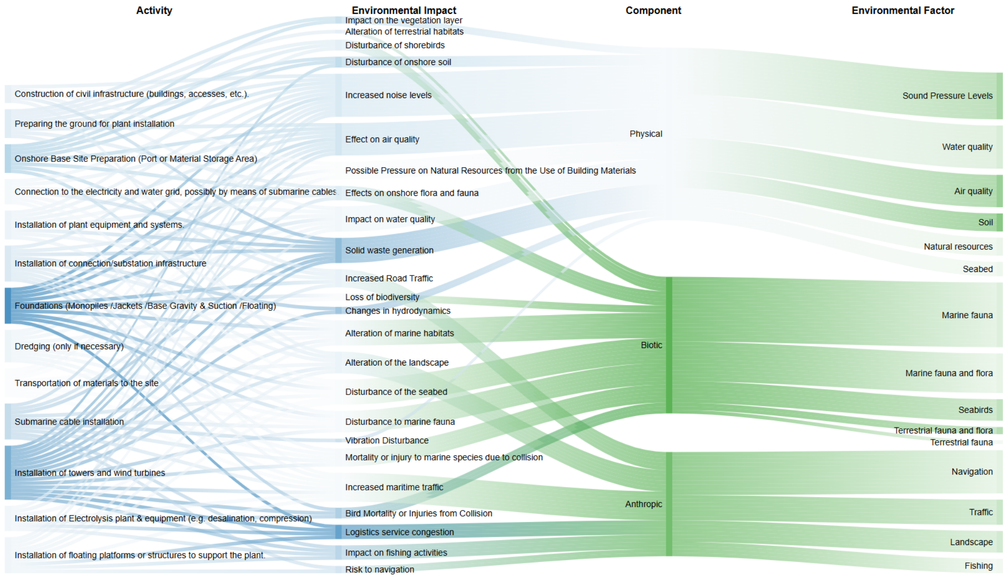

Figure 3. Diagram of environmental impacts and receptors from study activities during construction phase. Source: Authors. Note: The color scheme is arbitrary and does not convey any quantitative or categorical information.

In Figure 4, the operational phase of offshore wind–hydrogen projects reveals a broader distribution of environmental impacts across all three environmental components. The physical component remains the most frequently affected, with impacts such as increased noise levels, temperature rise, vibration disturbances, and potential air and water quality degradation linked to the continuous operation of electrolyzers, compression systems, and desalination plants. However, the biotic component also registers significant interactions, particularly due to collision risks for seabirds, disturbances to marine fauna, and electromagnetic fields. The formation of new ecosystems is also identified as a potential biotic outcome during long-term operations. The anthropic component is impacted through increased maritime traffic, logistics congestion, and risks to fishing activities, highlighting the need to address human-use conflicts in marine space planning. Activities such as desalination, electrolyzer operation, and hydrogen storage stand out as key sources of both physical and anthropogenic impacts during this stage.

After identifying the main environmental factors affected by this type of project at the international level, a cross-analysis was conducted with the environmental factors present in Uruguay's Exclusive Economic Zone (EEZ). This included a review of existing technical information relevant to the area. The objective was to determine which factors are most likely to be impacted in the regional context, considering the specific biophysical and socio-environmental characteristics of the country. This approach provides an initial, regionally grounded perspective on potential impacts and helps inform future detailed assessments and strategic environmental planning; the main results are presented in the Section 3.

Although the methodology used is not a standard method for environmental impact assessment, it was aligned with established impact identification frameworks. It integrates tools such as impact matrices, categorization of environmental factors, lifecycle analysis of the project (by phases), and interaction pathways. Established methods, including the Leopold Matrices and adaptive management models, were incorporated to enable a preliminary identification of environmental impacts.

The use of data from international studies facilitated the development of a comprehensive and adaptable evaluation, providing validated results applicable to other regions. This serves as a critical foundation for more detailed analyses in subsequent stages.

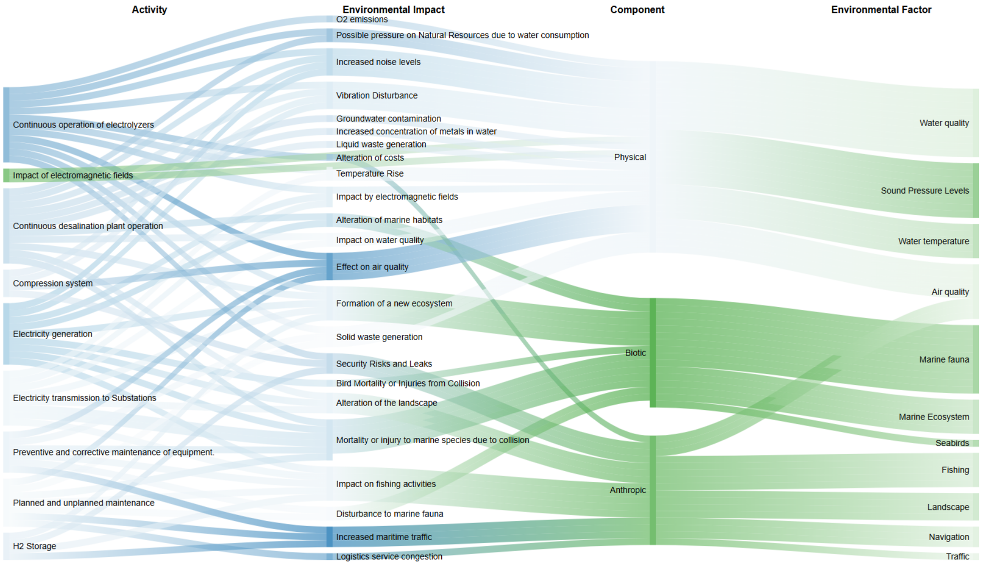

Figure 4. Diagram of environmental impacts and receptors from study activities during operation phase. Source: Authors. Note: The color scheme is arbitrary and does not convey any quantitative or categorical information.

Identification of the Exclusive Economic Zone of Uruguay

Uruguay's Exclusive Economic Zone (EEZ) spans over 140,000 km^2 [19], with depths ranging from continental shelf areas to slope zones and deep oceanic floors. The area represents a particularly complex and dynamic environmental setting, resulting from the interaction of physical, biological, and anthropogenic factors, as well as the confluence of continental and oceanic water masses. The physical environment is influenced by a series of oceanographic processes, including hydrodynamics, temperature and salinity gradients, the circulation of various ocean currents (such as the Brazil and Malvinas currents), and the system's hydrochemistry, according to studies conducted by ANCAP in 2014 [17].

In terms of water quality and physicochemical conditions, the EEZ shows significant spatial and temporal variability. Seasonal variations have been reported in turbidity, pH, total dissolved solids, dissolved oxygen levels, and nutrient concentrations—parameters that are highly relevant for evaluating the health of the marine ecosystem. Marked stratification of oxygen and nutrients has also been identified, as well as variability in chlorophyll concentrations, particularly near the mouth of the Río de la Plata, indicating high productivity in certain coastal and slope regions.

The biotic environment, in turn, is characterized by notable ecological richness and biodiversity. The EEZ hosts highly diverse communities of plankton (bacterioplankton, phytoplankton, zooplankton, and ichthyoplankton) and benthos, with key species such as cyanobacteria, diatoms, copepods, anchovy larvae, polychaetes, and echinoderms. There is also an abundant nektonic community, including commercially important bony and cartilaginous fish, cephalopods (squid), sea turtles, pelagic birds, and marine mammals such as dolphins, sperm whales, and humpback whales. Many of these species are migratory, endemic, or classified as threatened, and several zones within the EEZ have been identified as ecologically valuable areas due to their function as feeding, breeding, or nursery habitats [17].

From an anthropogenic perspective, Uruguay's EEZ also experiences intense human activity, particularly related to both industrial and artisanal fisheries. Key target species include hake, croaker, squid, and tuna species, harvested using methods such as bottom trawling, longlining, and purse seining. This activity is distributed throughout the EEZ but is especially concentrated along the continental slope, where oceanographic conditions favor high-value pelagic species. In addition, there is significant maritime traffic in the Río de la Plata and coastal areas, as well as existing infrastructure such as submarine cables.

This intricate network of physical, biotic, and anthropogenic factors makes the EEZ a zone of high ecological sensitivity and strategic economic importance. Therefore, any large-scale industrial development—such as offshore wind energy or green hydrogen production projects—must carefully consider an updated baseline environmental conditions. These ecosystems host species that play key roles in the food chain and support commercial fishing activities. Within the EEZ, several protected areas stand out, including the following [20]:

- Restingas del Pez Limón: An essential habitat for benthic species of ecological interest.
- Pozo de Fango: A highly productive area where commercial species such as hake are concentrated.
- Breeding Zones: Critical for the conservation of juvenile fish and cephalopods.

Based on this analysis, a delimitation of the EEZ was carried out to identify areas suitable for project construction. A significant technological limitation exists for fixed turbine foundations, which can only be installed at depths of 60–80 m [10]. Floating foundations can reach greater depths, but their high costs may render projects economically unfeasible. Therefore, areas with depths exceeding 100 m were excluded, leaving only zones from the country's coastline to Region 1, as indicated in Figure 5, as feasible for development. Protected areas were also excluded from consideration. The delimitation accounted for major merchant shipping routes, fishing zones, and other relevant spatial constraints. As shown in Figure 5, a safety buffer of approximately 50 km was maintained between the coastline and the feasible development zone (shown in green), with red lines indicating the buffer margins. This precaution aims to minimize potential impacts on coastal activities such as artisanal fishing, tourism, and nearshore navigation. The feasible area lies within Region 1 of Uruguay's continental shelf, where water depths remain below 100 m and conditions are favorable for fixed-bottom turbines. This initial delimitation serves as a strategic reference for future planning and will require refinement through more detailed technical, environmental, and regulatory assessments.

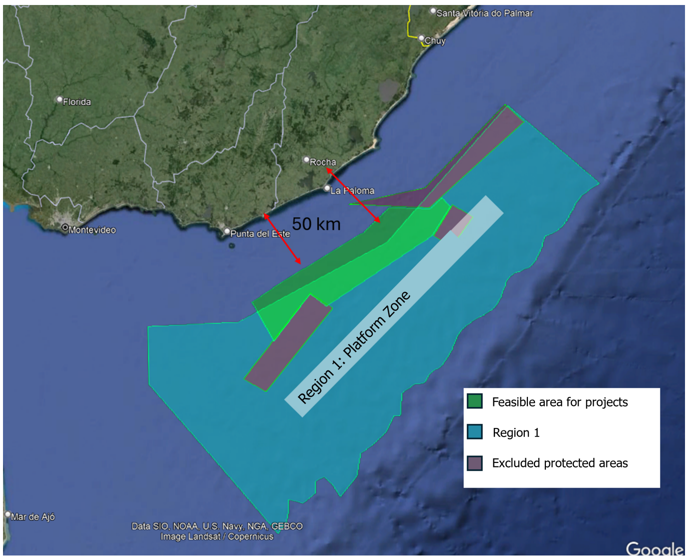

Figure 5. Delimitation of the feasible zone for offshore wind projects within the EEZ. Based on Google Earth imagery, 2024, adapted from L. Rivas, "Identificación de los posibles impactos ambientales de la producción de hidrógeno verde a partir de proyectos eólicos offshore. Caso de estudio: Zona económica exclusiva de Uruguay," 2024. Note: The selected reference picture is located at approximately 35°12′06.59″ S, 54°16′39.22″ W. Approximate geographic coordinates. This point is used for illustrative purposes and does not define legal or official maritime boundaries.

3. Results

3.1. Development Phase

The results obtained from the analysis of impact tables indicated that the development phase will have a significant effect on the biotic environment, particularly on environmental factors of the EEZ related to marine fauna. There will also be a moderate impact on the physical environment, specifically on the seabed and water quality, while the anthropic environment will experience occasional logistical disruptions. These findings are summarized in Figure 6, which illustrates the relationship between the environmental components and their interaction with specific factors or activities present in the EEZ. The anthropic component highlights human-related activities like fishing and natural resource exploitation, with varying degrees of impact. The biotic component shows a strong influence across all categories, including marine mammals, birds, and plankton, indicated by intense red bars. The physical component reflects the significance of factors like hydrochemistry, water temperature, and sound pressure levels, with a moderate-to-low impact. The intensity of the colors (from light pink to dark red) represents the magnitude of influence or relevance, where darker tones indicate the most impacted components and lighter tones the less affected ones. However, even the less affected components, shown in lighter shades, must not be overlooked as they still play a crucial role in the overall environmental balance.

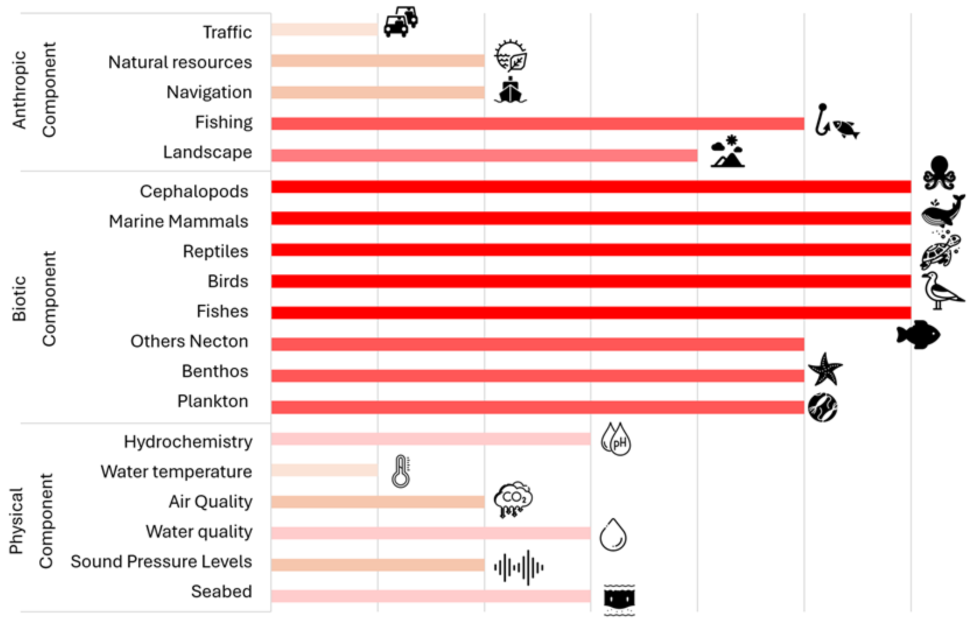

Figure 6. Key environmental factors significantly affected in the Uruguayan EEZ during the development phase. Source: Authors. Note: The intensity of the colors (from light pink to dark red) represents the magnitude of influence or relevance, where darker tones indicate the most impacted components and lighter tones the less affected ones.

- Disturbance to marine fauna due to geophysical and geotechnical studies: The results indicate that the methods used for seabed characterization (e.g., airgun seismic surveys and high-resolution geophysical studies) [21,22] generate low-frequency, high-intensity sound waves that can cause stress or injuries in marine mammals and fish [23]. Notable impacts include potential physical damage (barotrauma and swim bladder impairment) and behavioral changes (e.g., avoidance of survey areas) in bony fish species, as well as disturbances to cetaceans and marine turtles [24].
- Localized alteration of the seabed and benthic habitats: The installation of measurement buoys and wind towers during the early phases may involve minor drilling and

anchoring, which can displace sediments and affect benthic species (e.g., polychaetes and crustaceans) [25]. Although these localized disturbances are not typically extensive, they become significant if they occur in ecologically sensitive areas or breeding grounds for commercial species (e.g., hake and croaker).

- Increased maritime traffic and associated risks: The need for inspection vessels and technical personnel increases maritime traffic in the study area, raising the risk of collisions with marine mammals and turtles, as well as accidental fuel spills [26]. Additionally, this increased traffic may temporarily interfere with coastal and offshore fishing activities, potentially generating socioeconomic tensions.

3.2. Construction Phase

The results show that during the construction phase, the physical environment (water quality and seabed) experiences the most intense impacts, with highly significant effects on the biotic environment, particularly marine fauna. The anthropic environment is impacted in terms of logistics, temporary fishing restrictions, and congestion in port areas. However, after conducting a cross-analysis of the impacts on environmental factors, it becomes evident that the most affected factors overall are related to the biotic environment, as shown in Figure 7.

Figure 7. Key environmental factors significantly affected in the Uruguayan EEZ during the construction phase. Source: Authors. Note: The intensity of the colors (from light pink to dark red) represents the magnitude of influence or relevance, where darker tones indicate the most impacted components and lighter tones the less affected ones.

- Intense underwater noise generation: The use of hydraulic hammers for driving monopiles or anchoring foundations for offshore wind turbines and platforms generates very high acoustic peaks, affecting marine mammals, fish, and cephalopods within a radius that can reach tens of kilometers [11] in the EEZ. This noise is exacerbated in areas with hard seabeds, where higher impact force is required, and is further compounded by noise from dredging and intensive ship traffic [23].
- Water quality alteration and sediment suspension: Dredging for the installation of submarine cables and excavation of foundations disturbs fine sediments and contaminants deposited on the seabed, increasing turbidity and potentially releasing heavy metals [25]. In high-productivity environments, turbidity alteration has been observed

to impact photosynthesis and primary productivity, thereby affecting trophic networks (plankton–nekton).

- Port congestion and waste generation: The transport of large components (foundations and wind turbines) and equipment for electrolysis plants exerts significant pressure on ports, requiring large-scale storage and logistics spaces [11]. Construction generates volumes of solid waste (packaging materials, welding remnants, etc.) and liquid waste (oils and lubricants), which, in the absence of proper management protocols, could leak into the marine environment.

3.3. Operation Phase

During the operational phase, the results reveal a coexistence of possible positive effects (such as the formation of artificial reefs) and negative effects (such as bird mortality, continuous noise, risks of hydrogen leaks, and brine discharges). Water quality, sea birds, and marine fauna remain the most vulnerable factors, exacerbated by maintenance-related maritime traffic and the presence of electrolysis infrastructure. Figure 8 illustrates the environmental factors most affected by significant impacts identified during the operational phase.

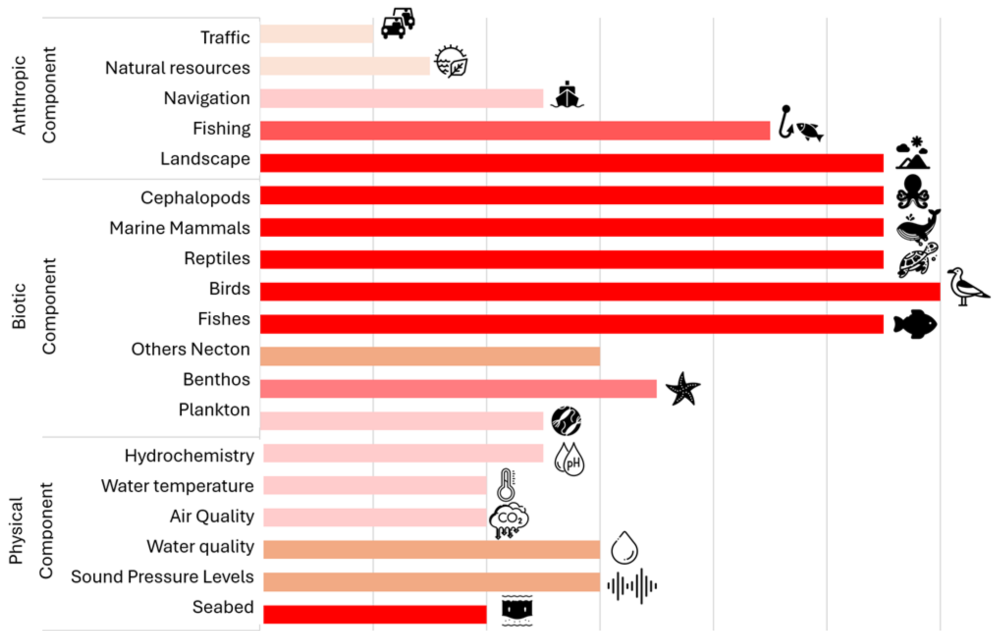

Figure 8. Key environmental factors significantly affected in the Uruguayan EEZ during the operation phase. Source: Authors. Note: The intensity of the colors (from light pink to dark red) represents the magnitude of influence or relevance, where darker tones indicate the most impacted components and lighter tones the less affected ones.

- Collision risks with wind turbines and infrastructure: Seabirds, particularly migratory species, are at risk of colliding with wind turbine blades under conditions of low visibility or strong winds [27]. Marine mammals and reptiles face collision risks with maintenance vessels, which typically operate throughout the entire lifespan of the wind farm [26].
- Acoustic disturbances and continuous vibrations: Although the operational noise of wind turbines is lower than during construction, low-frequency underwater emissions persist, potentially affecting the communication and behavior of marine mammals [24]. Additionally, electrolysis, compression, and hydrogen storage systems generate additional mechanical noise, which propagates through the structures of the platforms.

- Brine generation and management: If the electrolysis process is implemented offshore, seawater desalination is required, producing brine with high ionic concentrations that can increase local salinity when discharged [28]. International studies suggest that implementing diffusers and staggered discharge plans can mitigate the impact. However, in areas with limited circulation, this brine could harm benthic biota and reduce oxygen availability.
- Creation of artificial reefs: Submerged structures—such as fixed and floating foundations, as well as anti-erosion coverings—provide hard surfaces for invertebrate colonization, potentially aiding the regeneration of certain communities [24]. In areas with restricted fishing, fish tend to aggregate around these new habitats, increasing local biodiversity and creating refuge zones [25]. This impact is not always beneficial as it could also lead to an increase in invasive species populations that may alter the ecosystem.

4. Discussion of Results

4.1. Vulnerability of the Biotic Environment and Impact Synergies

The findings indicate that the biotic environment is one of the most affected components throughout the entire project lifecycle (development, construction, and operation). For instance, during the development phase, the use of seismic and geophysical prospecting technologies generates impulsive noises that can harm marine mammals and fish [23]. Subsequently, during the construction phase, the installation of monopile foundations using hydraulic hammers exposes whales and dolphins to intense acoustic impulses over distances of tens of kilometers [24]. These results align with studies from the North Atlantic and the North Sea, where marine mammal populations have been observed to temporarily or permanently abandon their feeding areas due to cumulative noise [11].

During operation, the offshore wind farms pose significant risks to seabird populations, primarily through collision mortality and habitat displacement. Turbine height, rotor blade length, and increased tip speeds, combined with ambient marine noise, can hinder birds' ability to detect and avoid turbines, increasing the likelihood of collisions—especially for large, migratory species such as albatrosses and petrels [27], both present in the EEZ. Additionally, birds may alter their foraging and migration routes to avoid wind farm areas, which can result in increased energy expenditure and reduced breeding success [24]. Studies indicate that offshore turbines may affect a broader area than the immediate project footprint, with avoidance behavior observed up to 800 m from turbines in some species [27]. The potential for cumulative impacts is heightened when projects intersect key migratory corridors or high-biodiversity regions, such as Uruguay's EEZ, where protected and vulnerable seabird species are distributed throughout the area.

Additionally, the overlap of impacts (noise, vibrations, and increased maritime traffic) can exacerbate the vulnerability of fauna. While each disturbance on its own might be considered moderate, the cumulative effect of continuous alterations (e.g., closely spaced construction phases) often leads to changes in the distribution and reproduction patterns of species [29]. Therefore, strategic planning is required to stagger these activities over time to reduce simultaneous exposure.

The increase in noise levels is identified as one of the main and most concerning impacts. During the installation of foundations, a significant increase in underwater noise levels is expected, especially during the development and construction phases of the project. The use of technologies such as hydraulic hammers for monopile driving generates high-energy, impulsive sounds with rapid rise times that propagate through the water column and marine substrate, reaching levels exceeding 220 dB re 1 µPa at 1 m [23]. This type of noise can induce hearing damage in marine mammals at short distances and alter their behavior over ranges of up to several tens of kilometers [30].

During the geophysical and geotechnical survey phase, airguns that generate low-frequency sounds (50–400 Hz) with peak levels of up to 175 dB are used, which can sensorially affect bony fish, cephalopods, and marine reptiles such as turtles. In addition, these sounds can induce physiological stress in invertebrates, altering their immune responses [31].

In the operational phase, although the noise is continuous and lower in intensity than during construction, acoustic emissions persist from wind turbines, compression systems, and submarine cables. While operational noise from wind turbines is estimated to be 10–20 dB lower than that of vessels in the same frequency range, it can still be detected over several kilometers and may contribute to cumulative acoustic pressure in the ecosystem [32]. Infrasonic emissions generated by wind turbines should also be considered as they may affect sensitive species such as whales and migratory birds [33].

Mitigation measures and recommendations include the following: (a) Use of pingers, which emit deterrent acoustic signals prior to pile driving to displace marine mammals from the area, thereby reducing the risk of permanent hearing damage [11]. (b) Deployment of bubble curtains, created by perforated hoses releasing compressed air, which form a barrier of bubbles that attenuates underwater sound. Their efficiency, however, may vary depending on current strength and bubble rise rate [11]. (c) Jet propulsion systems, which have been shown to reduce injuries and mortality in marine turtles compared to conventional propellers and may offer benefits to other aquatic species as well [26].

4.2. Alterations to the Physical Environment and Ecosystem Consequences

Water quality impacts represent a critical environmental concern throughout both the construction and operational phases of offshore wind-to-hydrogen projects. During the construction phase, activities such as dredging, seabed excavation, and accidental releases of fuels or chemicals significantly increase turbidity and can introduce hazardous substances into the marine environment. These disturbances compromise water clarity, reduce light penetration, and affect photosynthesis in phytoplankton—thereby altering the base of the marine food web [11,25]. The installation of foundations and trenching for submarine cables can resuspend fine sediments and change local sediment dynamics, which negatively impacts benthic organisms such as polychaetes and echinoderms. Furthermore, antifouling paints and maintenance activities may release chemical pollutants that degrade water quality and pose ecotoxicological risks [26].

In the operational phase, vessel traffic contributes to water quality degradation through ballast water discharge, bilge water, and wastewater. These discharges may contain invasive species, pathogens, and nutrients that disrupt ecosystem balance and increase the risk of eutrophication [26]. A major water-related impact stems from the desalination process required to supply high-purity water for PEM electrolyzers. This process produces large volumes of concentrated brine, which, when discharged back into the sea, increases local salinity and density, creating stratification that inhibits vertical mixing and oxygen exchange in the water column. This, in turn, can severely impact marine life, particularly benthic fauna such as shellfish, crustaceans, and demersal fish [28].

The brine discharge can also contain residual metals like copper—commonly used in heat exchangers for its anti-corrosive properties—which may accumulate in marine ecosystems and become toxic if not properly managed. In addition, the desalination process often involves chemical additives for membrane cleaning and pre-treatment, which may enter marine waters through effluents if not adequately treated [34].

To mitigate these issues, several measures are recommended:

- The implementation of brine diffuser systems designed through site-specific hydrodynamic modeling can promote rapid dilution and dispersion of high-salinity effluents, minimizing localized impacts and protecting benthic habitats [28]. In the context of Uruguayan regulation, where effluent dilution is restricted, controlled return of brine through a regulated outfall system may be a viable alternative.
- Installing robust wastewater treatment systems aboard vessels and onshore facilities is essential for removing pollutants before discharge.
- Strict chemical management protocols must be enforced for the safe storage, handling, and disposal of maintenance-related substances used in electrolyzers and offshore turbines.
- Brine mining technologies can be explored to recover valuable salts and reduce the environmental load of salinity waste [35].
- Continuous environmental monitoring programs should be established to assess real-time changes in water quality parameters and guide adaptive management actions. Baseline ecological surveys are also key to understanding site-specific sensitivities and tailoring mitigation accordingly.

4.3. Interactions with the Anthropic Environment

The construction and operation of this projects may significantly affect local fisheries, maritime traffic patterns, and operational safety. Construction activities and the associated increase in vessel traffic can disrupt fishing operations by limiting access to traditional fishing grounds and degrading marine habitats. Hydrodynamic changes caused by construction may affect larval dispersion, alter primary and secondary productivity, and impact benthic communities [25].

Species such as corvina (Micropogonias furnieri) and hake (Merluccius hubbsi) may suffer stress, reproductive disruptions, or habitat displacement due to increased underwater noise. Maritime traffic related to material and personnel transport also raises the risk of vessel collisions and acoustic disturbances, affecting both marine life and human maritime activities. In the European Union, a 500 m safety zone is commonly enforced around construction sites to minimize these impacts [25].

Hydrogen production facilities present additional safety risks, particularly from fires or explosions. Hydrogen's wide flammability range, low ignition energy, and tendency to cause material embrittlement require rigorous safety strategies, including proper facility design and emergency preparedness [34]. Establishing minimum safety distances based on fluid properties and component failure likelihood can mitigate potential consequences [36].

Mitigation Measures and Recommendations:

- Fisheries Coexistence Planning: Engage the fishing sector in early planning to minimize conflicts and ensure continued access where possible. Consider turbine spacing (800–1000 m) to allow passive fishing activities and vessel navigation [25].
- Navigation Restrictions: Implement regulated navigation and fishing exclusion zones during construction and operation phases to protect both marine fauna and project infrastructure.
- Ban on Bottom Trawling: Restrict bottom trawling in wind farm areas to reduce habitat disturbance and sediment resuspension while protecting subsea cables.
- Safety Protocols for Hydrogen: Adopt national codes and standards tailored to hydrogen technologies and assess safe distances from storage and production units using quantitative risk assessment [36].
- Stakeholder Engagement: Foster transparent dialogue and participatory processes with local fishers and maritime users throughout project design and implementation.

Another significant aspect of the anthropic environment is the potential congestion of ports and logistical routes, especially if multiple projects are developed simultaneously. The results indicate that the need for a large service port (60,000–70,000 m^2 for projects involving approximately 80 wind turbines) poses space availability challenges and may conflict with other port activities [11]. Furthermore, the social perception of changes to the marine landscape, though less frequent compared to biotic or physical impacts, remains a key factor for the acceptance of these projects [4].

4.4. Potential Positive Effects: Artificial Reefs and Economic Diversification

Despite the predominance of negative impacts, the creation of artificial reefs on support structures (fixed or floating foundations) could offer ecological opportunities by encouraging the aggregation of benthic species and increasing habitat complexity. Studies in the North Sea have shown that certain fish and crustacean species utilize these foundations as new zones for refuge and feeding [24]. Additionally, the prohibition of trawling around wind turbines could further enhance local repopulation. From a socioeconomic perspective, the operational phase generates specialized employment opportunities in wind turbine maintenance and electrolysis plant management [34]. This can boost coastal economies and create synergies with other sectors, such as tourism, provided that territorial planning is implemented to minimize potential conflicts [37].

4.5. Cumulative Impacts and the Need for Coordination

One of the most critical aspects is the lack of analysis regarding cumulative impacts when multiple projects are initiated simultaneously within the same EEZ. International studies demonstrate that fragmented permitting processes and the absence of marine spatial planning lead to underwater noise saturation, competition for space with fisheries, and overburdened port logistics [29]. While this study focuses on wind projects linked to green hydrogen production, the findings highlight the need to incorporate Strategic Environmental Assessment (SEA) approaches that consider the entirety of uses and pressures on Uruguay's EEZ.

4.6. Recommendations and Future Vision

- Development of a Comprehensive Regulatory Framework

To enable the construction and operation of offshore wind and green hydrogen projects, Uruguay must develop a robust regulatory framework. This includes obtaining maritime space concessions, power generation permits, environmental authorizations, grid connection agreements, and licenses for hydrogen storage and related infrastructure. A fragmented permitting process with unclear responsibilities between authorities can lead to delays, uncertainty, and increased project risk. Countries like the UK and Denmark offer successful regulatory models, with Denmark implementing clear marine spatial planning, environmental standards, and competitive bidding, while the UK centralizes project area access through The Crown Estate and supports the sector via initiatives like the Offshore Wind Sector Deal [38]. The US has followed a marine spatial planning approach led by [22], ensuring compatibility with existing maritime uses. Uruguay is encouraged to adopt a One-Stop Shop (OSS) model—successfully used in Denmark and Costa Rica—to centralize and simplify permitting, improve inter-agency coordination, and enhance process transparency [39].

- Marine Spatial Planning (MSP)

Uruguay should initiate offshore development alongside a formal Marine Spatial Planning process. MSP is a strategic and integrative approach to coordinate maritime activities by allocating marine space while considering conflicting uses. GWEC and IRENA

(2023) [39] recommend implementing MSP early in the permitting process to reduce risks and streamline approvals. MSP fosters collaboration among government bodies, conservation groups, energy developers, and community stakeholders. Global guidance has been provided by IOC-UNESCO and the EU, including the 2021 International Guide for MSP Implementation. Spain's Offshore Wind Roadmap (2021) and its 2023 marine zoning decree exemplify how MSP can align infrastructure access, project siting, and marine use compatibility. For Uruguay, it is essential to include public consultations, particularly with fishers, from early planning stages and integrate cumulative impact assessments into spatial planning.

- Promotion of Research and Baseline Studies

Scientific research is key to understanding the environmental and social impacts of offshore wind and hydrogen projects in Uruguay. The current data availability is limited, and baseline studies must be developed to support impact assessments. Developers should be required to share baseline data to enrich national datasets and improve transparency. Lessons from the UK and Europe emphasize site selection, design flexibility, robust baseline data collection, and digital databases for concessions and environmental conditions [40]. These measures enhance stakeholder engagement and reduce the risk of project rejection due to community concerns or knowledge gaps.

- Environmental Impact Assessment (EIA)

All offshore projects must undergo comprehensive Environmental Impact Assessments in accordance with international standards. These assessments must analyze environmental and social risks, include impact prevention and mitigation strategies, and identify sensitive or protected areas. Stakeholder participation should be integrated throughout the EIA process. In Europe, engagement is required from the initial research phases, while the US and Canada conduct consultations throughout the entire project lifecycle. Groups such as fishers, local communities, and indigenous populations must be included. Uruguay is encouraged to promote the use of sustainable technologies, such as efficient electrolysis and seawater-based hydrogen production. Environmental management systems should be designed to monitor and mitigate cumulative effects.

- Infrastructure and Logistics Development

Port infrastructure plays a critical role in offshore project logistics. Uruguay must assess and modernize its ports to accommodate turbine components, foundations, and hydrogen handling. International examples, like Denmark's Esbjerg Port, demonstrate that port optimization can reduce project costs by up to 15 percent [41]. Site selection for ports should consider environmental and social criteria, avoiding sensitive or high-tourism areas. A strategic coastal mapping process is recommended, along with public–private partnerships (PPPs) to fund upgrades. Developers could be required to share infrastructure investment costs. The US offers additional best practices, with millions invested in port upgrades in Humboldt Bay, Massachusetts, and Rhode Island. Uruguay could replicate this model by developing pilot projects and a regulatory framework that supports offshore wind–hydrogen integration.

- Capacity Building and Skills Development

Uruguay should implement training and education programs to strengthen its workforce in offshore wind and hydrogen technologies. Despite strong onshore wind expertise, the country lacks experience in offshore systems. Training should target evaluators, permitting officers, and technical professionals, with an emphasis on digital and regulatory competencies. Partnerships between academia, regulators, and industry will be key. Uruguay could adopt digital permit platforms, such as those developed by WindEurope, AWS, and the World Economic Forum, to streamline documentation and improve transparency [39]. Investing in workforce development will enhance institutional capacity, reduce approval delays, and create new employment opportunities in the renewable energy sector.

5. Conclusions

The results highlight that marine fauna is particularly affected during all phases of an offshore project. Impulsive noise, vibrations, seabed changes, and continuous exposure to maritime infrastructure can disrupt feeding, migration, and reproduction patterns, necessitating mitigation measures integrated from the development phase.

Dredging, cable, and foundation installations, along with desalination for electrolysis, cause changes in turbidity, hydrodynamics, and the physicochemical composition of water. These modifications affect primary productivity and marine trophic networks, emphasizing the need for strict sediment control, pollutant management, and brine disposal.

The implementation of offshore projects demands large-scale ports, increased maritime traffic, and potential fishing restrictions. While the infrastructure creates opportunities for employment and technological innovation, it also poses logistical challenges and conflicts with sectors like commercial fishing. Early engagement with coastal communities and the development of spatial planning policies are crucial for social acceptance and project success.

Despite the observed negative impacts, the creation of artificial reefs on submerged structures can aid in benthic community regeneration and fish aggregation, especially with restrictions on aggressive fishing techniques like trawling. Additionally, green hydrogen production offers a pathway to decarbonization, attracting investment and fostering innovation.

The feasibility of these projects in Uruguay's EEZ heavily depends on the effective implementation of mitigation measures and regulations, beginning at the development and research stages. Given the country's vast oceanic resources and renewable energy expertise, there is substantial potential for development. However, this must be accompanied by a robust regulatory framework, continuous monitoring plans, and strict impact management to ensure long-term sustainability.

The analysis underscores the importance of assessing cumulative risks, particularly when multiple projects are planned simultaneously in the same region. Policies regulating underwater noise, brine disposal, and interactions with fisheries and maritime traffic are essential to ensure the ecological sustainability and economic viability of Uruguay's wind–hydrogen industry.

Baseline studies and continuous monitoring are recommended, focusing on marine species mortality due to collisions, the effectiveness of acoustic mitigation techniques, and the optimal integration of desalination on offshore platforms. Such research will refine mitigation strategies and ensure the coexistence of green hydrogen projects with marine biodiversity and traditional coastal economic activities.

The adoption of an integrated regulatory framework, interinstitutional coordination, and specific mitigation measures is essential to align the socioeconomic benefits of offshore green hydrogen with the conservation of Uruguay's EEZ marine ecosystems. This study provides a preliminary foundation for decision-making, demonstrating that these projects are feasible when approached from a holistic perspective of environmental management and sustainable development.

Author Contributions: Conceptualization, L.R., A.E.G. and A.G.; methodology, L.R., A.E.G. and A.G.; validation, L.R., A.E.G. and A.G.; formal analysis, L.R., A.E.G. and A.G.; investigation, L.R., A.E.G. and A.G.; resources, L.R., A.E.G. and A.G.; data curation, L.R., A.E.G. and A.G.; writing—original draft preparation, L.R., A.E.G. and A.G.; writing—review and editing, A.E.G. and A.G.; visualization, L.R., A.E.G. and A.G.; supervision, L.R., A.E.G. and A.G.; project administration, L.R., A.E.G. and

A.G.; funding acquisition, A.E.G. and A.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Facultad de Ingeniería, Universidad de la República del Uruguay (UDELAR), Montevideo 11300, Uruguay. The APC was funded by the Facultad de Ingeniería (UDELAR).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

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

Appendix A

Table A1. Activities and potential impacts in the development phase.

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Geotechnical and geophysical studies	Disturbance to marine fauna	Biotic	Marine fauna	Due to disturbances during sampling times.
	Disturbance of the seabed	Biotic	Marine fauna and flora	Possible removal of the seabed in study areas [42].
	Increased noise levels	Physical	Sound Pressure Levels	Noise from surveys may injure marine species [30].
	Increased maritime traffic	Anthropic	Navigation	Due to presence of vessels in the study area.
	Effect on air quality	Physical	Air quality	Emissions from study vessels.
	Impact on water quality	Physical	Water quality	Spills or sediment movements increasing turbidity.
	Alteration of marine habitats	Biotic	Marine fauna	Disturbance due to noise, sediment, or contamination [30].
Environmental studies	Increased noise levels	Physical	Sound Pressure Levels	Noise during in situ surveys.
	Disturbance to marine fauna and flora	Biotic	Marine fauna and flora	Capture of species or seabed sampling.
	Disturbance of the seabed	Biotic	Marine fauna and flora	—
	Bird mortality or injuries from collision	Biotic	Seabirds	Navigation and vessels may affect flight paths.
	Disturbance of shorebirds	Biotic	Seabirds	Infrastructure and urbanization affect habitats.
	Disturbance to marine fauna	Biotic	Marine fauna	Due to in situ studies.
	Alteration of marine habitats	Biotic	Marine fauna	Noise, sediments, contamination, or damage to fauna.

Table A1. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Wind and Metocean Resource Studies	Impact on water quality	Physical	Water quality	Spills and sediment movement increase turbidity.
	Increased maritime traffic	Anthropic	Navigation	More vessel activity increases congestion and collision risk.
	Increased noise levels	Physical	Sound Pressure Levels	Noise from boats and sonar may disturb marine fauna.
	Disturbance to marine fauna	Biotic	Marine fauna	—
	Effect on air quality	Physical	Air quality	Emissions from exploration vessels.
	Disturbance of the seabed	Biotic	Marine fauna and flora	Installation of towers disturbs seabed organisms.
	Alteration of marine habitats	Biotic	Marine fauna	—
	Mortality or injury to marine species due to collision	Biotic	Marine fauna	Measurement towers or buoys may be obstacles.
	Bird mortality or injuries from collision	Biotic	Seabirds	Vessel and monitoring presence increases risk.
	Disturbance of shorebirds	Biotic	Seabirds	Traffic disturbs feeding and breeding habitats.
	Alteration of the landscape	Anthropic	Landscape	Location of units may affect visual landscape.

Table A2. Activities and potential impacts in the construction phase.

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Onshore Base Site Preparation (Port or Material Storage Area)	Disturbance of onshore soil	Physical	Soil	The preparation of the land for the logistics base may cause soil alteration due to possible earthworks.
	Impact on the vegetation layer	Physical	Soil	Site preparation may require vegetation removal through earthmoving.
	Effect on air quality	Physical	Air quality	Increased gas emissions and particulate matter from vehicles and machinery.
	Increased noise levels	Physical	Sound Pressure Levels	Machinery and equipment operation can raise ambient sound pressure levels.
	Effects on onshore flora and fauna	Biotic	Terrestrial fauna and flora	Earthmoving activities may affect flora and fauna at the base site.
	Disturbance of shorebirds	Biotic	Seabirds	Coastal birds may be displaced by noise and habitat changes.
	Increased road traffic	Anthropic	Traffic	Movement of vehicles, materials, and equipment increases ground traffic.
	Alteration of the landscape	Anthropic	Landscape	Infrastructure installation may impact visual aesthetics and restrict public access.

Table A2. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Dredging (if necessary)	Impact on water quality	Physical	Water quality	Potential spills and sediment movement increase turbidity and Total Suspended Solids (TSS) levels.
	Effect on air quality	Physical	Air quality	Emissions from vessel use and transit affect air quality.
	Alteration of marine habitats	Biotic	Marine fauna	Habitat loss due to seabed removal.
	Mortality or injury to marine species due to collision	Biotic	Marine fauna	Increased vessel transit raises risk of collision with marine species.
	Increased noise levels	Physical	Sound Pressure Levels	Dredging causes underwater noise disturbing wildlife.
	Increased maritime traffic	Anthropic	Navigation	Vessel flow increase could affect other productive activities.
	Disturbance to marine fauna	Biotic	Marine fauna	Dredging disturbs marine fauna behavior and habitats.
	Loss of biodiversity	Biotic	Marine fauna and flora	Seabed disruption impacts benthic communities and stability.
	Disturbance of the seabed	Biotic	Marine fauna and flora	Physical disruption of the seabed and ecosystem.
Transportation of materials to the site	Effect on air quality	Physical	Air quality	Exhaust gas emissions from project vessels may impact air quality.
	Increased maritime traffic	Anthropic	Navigation	Construction vessels increase traffic, affecting other sectors.
	Increased noise levels	Physical	Sound Pressure Levels	Machinery and boats increase sound pressure levels.
	Pressure on natural resources	Physical	Natural resources	Use of concrete, steel, and water pressures natural resources.
	Mortality or injury to marine species	Biotic	Marine fauna	Vessel activity increases collision risks (e.g., whales).
	Alteration of marine habitats	Biotic	Marine fauna	Continuous movement disturbs habitats and behavior.
	Disturbance to marine fauna	Biotic	Marine fauna	Fauna disturbed by transport operations.
	Alteration of the landscape	Anthropic	Landscape	Increased boat flow alters visual appearance of coastal areas.
Foundation Installation (Monopiles / Jackets / Gravity Base / Suction / Floating)	Disturbance to marine fauna	Biotic	Marine fauna	Installation noise and presence affect fauna behavior.
	Disturbance of the seabed	Biotic	Marine fauna and flora	Anchoring and digging alter substrate and habitats.
	Increased noise levels	Physical	Sound Pressure Levels	Hammering and machinery generate high underwater noise.
	Effect on air quality	Physical	Air quality	Diesel equipment and materials emit gases and particles.
	Impact on water quality	Physical	Water quality	Spills and sediment release during excavation.
	Alteration of marine habitats	Biotic	Marine fauna	Foundation presence modifies marine ecosystems.
	Loss of biodiversity	Biotic	Marine fauna and flora	Habitat loss reduces species abundance and resilience.
	Pressure on natural resources	Physical	Natural resources	Project demands concrete, steel, and energy resources.
	Logistics service congestion	Anthropic	Traffic	Congestion at ports and storage affects other operations.

Table A2. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Installation of towers and wind turbines	Disturbance to marine fauna	Biotic	Marine fauna	Equipment like cranes and platforms generate noise that alters the behavior and migration of species.
	Solid waste generation	Physical	Water quality	Packaging and construction waste may pollute the marine environment.
	Increased maritime traffic	Anthropic	Navigation	Vessel traffic for transport increase the risks of collisions and affect other sectors.
	Changes in hydrodynamics	Physical	Seabed	Structures affect seabed morphology and sediment dynamics.
	Alteration of the landscape	Anthropic	Landscape	Construction equipment alters the seascape and coastal scenery.
	Effect on air quality	Physical	Air quality	Ship exhaust and equipment operations pollute air.
	Alteration of marine habitats	Biotic	Marine fauna	Equipment and vessels disturb benthic organisms and habitats.
	Mortality or injury to marine species	Biotic	Marine fauna	Risk of vessel collisions with marine mammals and turtles.
	Bird mortality or injuries from collision	Biotic	Seabirds	Cranes and Blades pose a collision risk during transport and assembly.
	Disturbance of onshore soil	Physical	Soil	Construction of infrastructure compacts and erodes soil.
	Effects on onshore flora and fauna	Biotic	Terrestrial fauna and flora	Habitat alteration and pollution impact terrestrial species.
	Pressure on natural resources	Physical	Natural resources	Logistics and activities demand large amounts of resources.
	Increased road traffic	Anthropic	Traffic	Transport increases vehicle flow and accident risks.
	Logistics service congestion	Anthropic	Navigation	Vessel movement interferes with maritime activity, increasing the risk of accidents.
	Impact on fishing activities	Anthropic	Fishing	Construction disrupts fishing operations, affecting livelihoods.
Submarine cable installation	Disturbance of the seabed	Biotic	Marine fauna and flora	Trenching alters seabed composition and structure.
	Disturbance to marine fauna	Biotic	Marine fauna	Sediment and chemicals affect fauna and water quality.
	Increased noise levels	Physical	Sound Pressure Levels	Cable installation creates noise disturbing marine life.
	Vibration disturbance	Physical	Sound Pressure Levels	Equipment-induced vibrations affect sensitive seabed species.
	Solid waste generation	Physical	Seabed	Waste from materials and equipment may pollute the seabed.
	Impact on water quality	Physical	Water quality	Spills and sediment disturb water quality.
	Mortality or injury to marine species	Biotic	Marine fauna	Collisions with cable vessels may injure whales, turtles, and fish.
	Increased maritime traffic	Anthropic	Navigation	Vessel activity may conflict with existing traffic.
	Risk to navigation	Anthropic	Navigation	Submarine cables pose hazards, especially to small/fishing vessels.
	Impact on fishing activities	Anthropic	Fishing	Cable laying may block fishing zones or damage gear.

Table A2. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Installation of connection/substation infrastructure	Disturbance of the seabed	Biotic	Marine fauna and flora	Heavy structure installation disturbs seabed, especially in unstable soils.
	Disturbance to marine fauna	Biotic	Marine fauna	Noise, vibrations, and vessel activity may affect marine life.
	Increased maritime traffic	Anthropic	Navigation	Increased vessel movement raises the risk of collisions.
	Increased noise levels	Physical	Sound Pressure Levels	Installation noise disturbs marine mammals, fish, and invertebrates.
	Alteration of marine habitats	Biotic	Marine fauna	Structures may degrade areas critical for marine species.
	Mortality or injury to marine species	Biotic	Marine fauna	Construction increases the risk of marine fauna collisions.
	Changes in hydrodynamics	Physical	Seabed	Structures alter water flow and sediment dynamics.
	Bird mortality from collision	Biotic	Seabirds	Disturbances increase risk of collisions with seabirds.
	Solid waste generation	Physical	Water quality	Construction waste can pollute the marine environment if not managed.
	Impact on water quality	Physical	Water quality	Potential chemical spills degrade water quality.
Onshore PEM Electrolysis Plant–Ground preparation	Disturbance of onshore soil	Physical	Soil	Excavation and earthworks can significantly disturb the soil.
	Alteration of terrestrial habitats	Biotic	Terrestrial fauna	Natural habitat fragmentation affects biodiversity.
	Impact on vegetation layer	Physical	Soil	Vegetation removal affects soil structure and flora.
	Effect on air quality	Physical	Air quality	Dust and pollutants from machinery increase air pollution.
	Increased noise levels	Physical	Sound Pressure Levels	Machinery use raises ambient noise levels.
	Effects on onshore flora and fauna	Biotic	Marine fauna and flora	Habitat loss affects local fauna and flora.
	Disturbance of shorebirds	Biotic	Seabirds	Shorebirds may be disturbed by habitat alteration and noise.
	Increased road traffic	Anthropic	Traffic	Material transport increases road congestion.
Construction of civil infrastructure	Alteration of the landscape	Anthropic	Landscape	Infrastructure alters coastal visual appearance.
	Impact on water quality	Physical	Water quality	Runoff and wastewater can contaminate water bodies.
	Increased noise levels	Physical	Sound Pressure Levels	Construction noise affects local wildlife.
	Solid waste generation	Physical	Water quality	Large amounts of packaging and demolition waste are produced.
	Pressure on natural resources	Physical	Natural Resources	Concrete, steel, and water use stress resources.

Table A2. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Installation of equipment and systems	Increased noise levels	Physical	Sound Pressure Levels	Equipment installation involves noisy machinery.
	Solid waste generation	Physical	Water quality	Waste from installation may pollute the marine environment.
	Pressure on natural resources	Physical	Natural resources	Materials and energy use put pressure on resources.
	Increased road traffic	Anthropic	Traffic	Vehicle traffic rises with equipment delivery.
	Effect on air quality	Physical	Air quality	Machinery emissions impact air quality.
	Alteration of the landscape	Anthropic	Landscape	Equipment alters visual aspect of the coast.
	Effects on onshore flora and fauna	Biotic	Marine fauna and flora	Noise and movement disturb local wildlife.
	Disturbance of shorebirds	Biotic	Seabirds	Shorebirds are affected by noise, lights, and human activity.
Offshore PEM electrolysis plant	Alteration of marine habitats	Biotic	Marine fauna	Installation of floating platforms may destroy habitats and affect biodiversity.
	Disturbance of the seabed	Biotic	Marine fauna and flora	Platform placement alters seabed composition and stability.
	Increased noise levels	Physical	Sound Pressure Levels	Construction and anchoring create noise and vibrations.
	Impact on water quality	Physical	Water quality	Spills of oils or chemicals reduce water quality.
	Increased maritime traffic	Anthropic	Navigation	Platform transport increases collision and navigation risks.
	Alteration of the landscape	Anthropic	Landscape	Floating platforms alter marine visual appearance.
	Impact on fishing activities	Anthropic	Fishing	Structures may interfere with local fishing activities.
	Risk to navigation	Anthropic	Navigation	Floating units pose navigation risks if poorly marked.
	Effect on air quality	Physical	Air quality	Machinery and ships emit pollutants.
	Logistics service congestion	Anthropic	Navigation	Port and Sea Route Congestion of the platform logistics.
Installation of electrolysis plant and auxiliary equipment	Bird mortality from collision	Biotic	Seabirds	Installation disturbs seabird habitats and causes collisions.
	Disturbance of the seabed	Biotic	Marine fauna and flora	Seabed changes alter benthic fauna and geochemical processes.
	Solid waste generation	Physical	Water quality	Packaging and construction waste impacts water quality.
	Logistics service congestion	Anthropic	Traffic	Logistics overload increases accident and collision risks.
	Increased maritime traffic	Anthropic	Navigation	More vessels raise collision risk in installation zones.
	Increased noise levels	Physical	Sound Pressure Levels	Machinery and tools disturb marine wildlife.
	Impact on fishing activities	Anthropic	Fishing	Equipment may restrict access to fishing zones.

Table A2. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Connection to electricity and water grid (submarine cables)	Disturbance of the seabed	Biotic	Marine fauna and flora	Cable laying disturbs seabed and benthic ecosystems.
	Increased noise levels	Physical	Sound Pressure Levels	ROVs and cable vessels generate underwater noise.
	Alteration of marine habitats	Biotic	Marine fauna	Installation equipment disturbs local marine habitats.
	Solid waste generation	Physical	Seabed	Cable debris and excavation residues affect the seabed.
	Impact on water quality	Physical	Water quality	Sediment suspension and pollutants reduce water quality.
	Increased maritime traffic	Anthropic	Navigation	More cable vessels can disrupt existing maritime traffic.
	Effect on air quality	Physical	Air quality	Ship and machinery emissions affect air quality.

Table A3. Activities and potential impacts in the operation phase.

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Electricity generation	Increased noise levels	Physical	Sound Pressure Levels	The noise produced by the operation of wind turbines can affect sound-sensitive marine fauna.
	Alteration of marine habitats	Biotic	Marine fauna	Noise and vibrations from turbines can disturb fish and marine mammals.
	Mortality or injury to marine species due to collision	Biotic	Marine fauna	Marine species may collide with turbine structures.
	Bird mortality or injuries from collision	Biotic	Seabirds	Turbines pose collision risks, especially to migratory birds.
	Vibration disturbance	Physical	Sound Pressure Levels	Vibrations from turbines can affect sensitive marine fauna.
	Impact by electromagnetic fields	Physical	Water temperature	EM fields from cables can increase water temperatures.
	Formation of a new ecosystem	Biotic	Marine fauna and flora	Structures can act as artificial reefs, altering ecosystems.
	Alteration of the landscape	Anthropic	Landscape	Depending on proximity, visual impacts may occur.
	Impact on fishing activities	Anthropic	Fishing	Wind farms may interfere with fishing routes and areas.

Table A3. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
Electricity transmission to substations	Temperature rise	Physical	Water temperature	Heat dissipation from cables may raise local water temperature.
	Impact on water quality	Physical	Water quality	Cable damage may lead to pollutant leaks.
	Impact of electromagnetic fields	Physical	Water temperature	EM fields may raise water temperature, affecting fauna.
	Mortality or injury to marine species due to collision	Biotic	Marine fauna	Unburied cables may lead to entanglements or electric field exposure.
	Alteration of the landscape	Anthropic	Landscape	Cable landfalls may restrict beach access.
	Formation of a new ecosystem	Biotic	Marine fauna and flora	Cables can foster artificial reef development.
	Impact on fishing activities	Anthropic	Fishing	Cables may restrict or pose hazards to bottom trawling.
Planned and unplanned maintenance	Disturbance to marine fauna	Biotic	Marine fauna	Vessel traffic and maintenance activities may alter marine behavior.
	Solid waste generation	Physical	Water quality	Waste from operations must be managed to prevent contamination.
	Increased maritime traffic	Anthropic	Navigation	More vessels increase collision and navigational risks.
	Effect on air quality	Physical	Air quality	Emissions from service vessels impact air quality.
	Mortality or injury to marine species due to collision	Biotic	Marine fauna	Collisions with maintenance vessels may injure or kill marine species.
	Logistics service congestion	Anthropic	Traffic	Port congestion may impact other port users.
	Impact on fishing activities	Anthropic	Fishing	Maintenance zones may restrict fishing, affecting livelihoods.
Continuous operation of electrolyzers	Possible pressure on natural resources due to water consumption	Physical	Water quality	PEM electrolyzers require highly purified water, putting pressure on water resources.
	Alteration of costs	Anthropic	Landscape	Onshore H_2 plants may impact coastal zones previously used for tourism or recreation.
	O_2 emissions	Physical	Air quality	High oxygen concentrations may pose fire or explosion hazards without proper ventilation.
	Effect on air quality	Physical	Air quality	H_2 emissions can indirectly increase the methane lifetime by depleting atmospheric OH radicals [43].

Table A3. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
	Temperature rise	Physical	Water temperature	PEM electrolyzers operate between 20 and 80°C and may increase the local water temperature.
	Increased noise levels	Physical	Sound Pressure Levels	High-pressure equipment generates noise that may disturb wildlife and nearby communities.
	Impact of electromagnetic fields	Physical	Water temperature	EM fields from power cables may influence water temperature and marine life.
	Solid waste generation	Physical	Water quality	Maintenance chemicals must be carefully handled to avoid pollution.
	Formation of a new ecosystem	Biotic	Marine fauna and flora	Electrolyzer structures can act as artificial reefs, altering local ecosystems.
	Security risks and leaks	Anthropic	Air quality	H_2 is flammable and explosive; leaks during compression can be hazardous.
	Vibration disturbance	Physical	Sound Pressure Levels	Equipment operation may generate vibrations affecting marine fauna and the acoustic environment.
Continuous desalination plant operation	Possible pressure on natural resources due to water consumption	Physical	Water quality	The desalination plant consumes large amounts of water, which can affect local water resources.
	Alteration of the landscape	Anthropic	Landscape	Onshore desalination plants may impact coastal areas used for tourism or recreation.
	Groundwater contamination	Physical	Water quality	Underground brine pipes can leak and affect coastal aquifers.
	Alteration of marine habitats	Biotic	Marine fauna	Dense brine return may alter salinity and oxygen levels, affecting seabed organisms.
	Impact on water quality	Physical	Water quality	Brine discharge may introduce harmful chemical residues from desalination processes.
	Increased noise levels	Physical	Sound Pressure Levels	High-pressure pumps and turbines generate significant noise that may affect marine and human environments.
	Mortality or injury to marine species due to collision	Biotic	Marine fauna	Marine organisms may be unintentionally captured or harmed by the pumping system.
	Increased concentration of metals in water	Physical	Water quality	Corrosion-resistant metals like copper can accumulate and become toxic to marine life.

Table A3. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
	Formation of a new ecosystem	Biotic	Marine fauna and flora	Submerged structures may act as artificial reefs, promoting colonization.
	Liquid waste generation	Physical	Water quality	Pretreatment chemicals may be present in discharged wastewater.
	Vibration disturbance	Physical	Sound Pressure Levels	Equipment operation may produce vibrations affecting marine fauna.
Compression system	Increased noise levels	Physical	Sound Pressure Levels	Compression systems emit high noise levels that can impact the environment.
	Vibration disturbance	Physical	Sound Pressure Levels	Generated vibrations may disturb marine fauna and the acoustic environment.
	Security risks and leaks	Anthropic	Air quality	Hydrogen is highly flammable and explosive; compression leaks are hazardous.
	Effect on air quality	Physical	Air quality	H_2 emissions can contribute to greenhouse effects [43].
H_2 storage	Security risks and leaks	Anthropic	Air quality	Hydrogen is highly flammable and explosive; leaks during compression can be hazardous.
	Increased maritime traffic	Anthropic	Navigation	Offshore H_2 storage may require frequent transfers to vessels, increasing ship traffic.
	Formation of a new ecosystem	Biotic	Marine fauna and flora	Submerged storage structures may act as artificial reefs, facilitating marine colonization.
	Impact on fishing activities	Anthropic	Fishing	Project areas may restrict fishing zones, potentially affecting fishers' livelihoods.
Preventive and corrective maintenance of equipment	Solid waste generation	Physical	Water quality	Discarded membranes and waste like lubricants or packaging can release pollutants.
	Disturbance to marine fauna	Biotic	Marine fauna	Increased vessel activity during maintenance can disturb and displace marine species.
	Increased maritime traffic	Anthropic	Navigation	Maintenance vessels increase collision risks and affect navigational routes.
	Effect on air quality	Physical	Air quality	Emissions from service vessels may degrade air quality in nearby areas.

Table A3. *Cont.*

Activity	Environmental Impact	Component	Environmental Factor	Outreach
	Mortality or injury to marine species due to collision	Biotic	Marine fauna	Collisions with maintenance vessels can result in injury or death of marine life.
	Impact on fishing activities	Anthropic	Fishing	Maintenance areas may restrict fishing access and impact incomes.

References

1. Vásquez, R.; Salinas, F. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Hydrogen Technologies and Perspectives for Chile. Prepared by the Project "Promotion of Solar Energy in Chile" Implemented by the Chilean Ministry of Energy and GIZ, as Part of the Bilateral Cooperation Between Chile and Germany, Santiago, Chile. 2018. Available online: https://4echile.cl/wp-content/uploads/2020/07/LIBRO-TECNOLOGIAS-H2-Y-PERSPECTIVAS-CHILE.pdf (accessed on 5 July 2024).
2. Calado, G.; Castro, R. Hydrogen production from offshore wind parks: Current situation and future perspectives. *Appl. Sci.* **2021**, *11*, 5561. [CrossRef]
3. TGS New Energy. Tgs New Energy. 2024. Available online: https://www.4coffshore.com/ (accessed on 14 March 2024).
4. Letcher, T.M. *Wind Energy Engineering: A Handbook for Onshore and Offshore Wind Turbines*; Academic Press: London, UK, 2017; ISBN 9780128094518.
5. Barreiro, M. Física del Sistema Climático. 2023. Available online: http://www.meteorologia.edu.uy/wp-content/uploads/2019/Fisica_del_sistema_climatico/Clase4.pdf (accessed on 29 December 2023).
6. Rivas, L. Identificación de los Posibles Impactos Ambientales de la Producción de Hidrógeno Verde a Partir de Proyectos eólicos Offshore. Caso de Estudio: Zona Económica Exclusiva de Uruguay. Repositorio Institucional de la Universidad de la República. 2024. Available online: https://hdl.handle.net/20.500.12008/48564 (accessed on 5 April 2025).
7. BVG Associates. Guide to an Offshore Wind Farm. Published on Behalf of The Crown Estate and the Offshore Renewable Energy Catapult. 2019. Available online: https://bvgassociates.com/wp-content/uploads/2019/04/BVGA-Guide-to-an-offshore-wind-farm-r2.pdf (accessed on 5 July 2024).
8. República Oriental del Uruguay. Ley n° 16.466. Ley de Evaluación de Impacto Ambiental. Montevideo, Publicado por la República Oriental del Uruguay. 1994. Available online: https://www.impo.com.uy/bases/leyes/16466-1994 (accessed on 21 April 2024).
9. República Oriental del Uruguay Decreto n° 349/005. Reglamento de Evaluación de Impacto Ambiental y Autorizaciones Ambientales. Publicado por la República Oriental del Uruguay. Montevideo. 2005. Available online: https://www.impo.com.uy/bases/decretos/349-2005 (accessed on 21 April 2024).
10. Fan, Q.; Wang, X.; Yuan, J.; Liu, X.; Hu, H.; Lin, P. A review of the development of key technologies for offshore wind power in China. *J. Mar. Sci. Eng.* **2022**, *10*, 929. [CrossRef]
11. Thomsen, K.E. *Offshore Wind: A Comprehensive Guide to Successful Offshore Wind Farm Installation*; Elsevier: Amsterdam, The Netherlands; Academic Press: Cambridge, MA, USA, 2011; ISBN 978-0123859365.
12. Rodríguez Masnou, O. Caracterización y Estudio de Parques eólicos Offshore. Barcelona. 2020. Available online: https://upcommons.upc.edu/handle/2117/180315 (accessed on 29 December 2023).
13. Armstrong, I.d.l.R. Criterios de Instalación de un Parque eólico Marino. Madrid. 2018. Available online: https://core.ac.uk/download/pdf/288502023.pdf (accessed on 30 December 2023).
14. Goldman Sachs Global Investment Research. Carbonomics: The Clean Hydrogen Revolution. New York. 2022. Available online: https://www.goldmansachs.com/pdfs/insights/pages/gs-research/carbonomics-the-clean-hydrogen-revolution/carbonomics-the-clean-hydrogen-revolution.pdf (accessed on 30 December 2023).
15. Sampangi, D.; Vurimindi, H. Hydrogen production by pem water electrolysis—A review. *Mater. Sci. Energy Technol.* **2019**, *2*, 442–454. [CrossRef]
16. Administración Nacional de Combustibles, Alcohol y Portland (ANCAP). H2U Offshore Round. 2024. Available online: https://www.ancap.com.uy/17068/6/h2u-offshore-round.html (accessed on 5 April 2025).
17. Administración Nacional de Combustibles, Alcohol y Portland (ANCAP); Facultad de Ciencias, Universidad de la República. *Uruguay: Margen Continental. Programa Oceanográfico de Caracterización del Margen Continental Uruguayo. Zona Económica Exclusiva*; Zona Editorial: Montevideo, Uruguay, 2014; ISBN 978-9974-8465-1-7.

18. Zaror, C.A. *Introducción a la Ingeniería Ambiental para la Industria de Procesos*; Universidad de Concepción: Concepción, Chile, 2000. Available online: https://eva.fing.edu.uy/pluginfile.php/306131/mod_resource/content/1/Zaror%20-%20Aspectos%20ambientales%20de%20la%20industria%20de%20procesos.pdf (accessed on 14 March 2024).
19. República Oriental del Uruguay. Ley N° 17033. Bienes del Estado. Recursos Naturales. Normas referentes a mar territorial, zona económica exclusiva y plataforma continental de la República. Montevideo, Uruguay, 1998. Available online: https://www.impo.com.uy/bases/leyes/17033-1998 (accessed on 21 April 2024).
20. Sistema Nacional de Áreas Protegidas (SNAP). Visualizador de Áreas Protegidas. 2025. Available online: https://www.ambiente.gub.uy/visualizador/index.php?vis=sig (accessed on 21 April 2025).
21. Bureau of Ocean Energy Management (BOEM). Geological and Geophysical Surveys. 2018. Available online: https://www.boem.gov/sites/default/files/about-boem/BOEM-Regions/Atlantic-Region/GandG-Overview.pdf (accessed on 10 May 2024).
22. Bureau of Ocean Energy Management (BOEM). Regulatory Framework and Guidelines. 2024. Available online: https://www.boem.gov/ (accessed on 20 November 2024).
23. Mooney, T.A.; Andersson, M.H.; Stanley, J. Acoustic impacts of offshore wind energy on fishery resources: An evolving source and varied effects across a wind farm's lifetime. *Oceanography* **2020** . [CrossRef]
24. Galparsoro, I.; Menchaca, I.; Garmendia, J.M.; Borja, Á.; Maldonado, A.D.; Iglesias, G.; Bald, J. Reviewing the ecological impacts of offshore wind farms. *NPJ Ocean Sustain.* **2022**, *1*, 1. [CrossRef]
25. Hoey, G.V.; Bastardie, F.; Birchenough, S.; Backer, A.D.; Gill, A.; de Koning, S.; Hodgson, S.; Chai, S.M.; Steenbergen, J.; Termeer, E.; et al. *Overview of the Effects of Offshore Wind Farms on Fisheries and Aquaculture—Final Report*; Publications Office of the European Union: Luxembourg, 2021.
26. Byrnes, T.A.; Dunn, R.J.K. Boating- and shipping-related environmental impacts and example management measures: A review. *J. Mar. Sci. Eng.* **2020**, *8*, 908. [CrossRef]
27. Exo, K.-M.; Huppop, O.; Garthe, S. Birds and offshore wind farms: A hot topic in marine ecology. *Wader Study Group Bull.* **2003**, *100*, 50–53.
28. Missimer, T.M.; Maliva, R.G. Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. *Desalination* **2018**, *434*, 198–215. [CrossRef]
29. Köller, J. *Offshore Wind Energy. Research on Environmental Impacts*; Institute of Landscape Architecture and Environmental Planning, Department for Landscape Planning, and Environmental Impact Assessment, Berlin University of Technology: Berlin, Germany, 2006. [CrossRef]
30. Congressional Research Service. Potential Impacts of Offshore Wind on the Marine Ecosystem and Associated Species: Background and Issues for Congress. 2024. Available online: https://crsreports.congress.gov (accessed on 12 December 2024).
31. Oisín, D.; Rogério, C.; Coca, I. Impact of Geophysical and Geotechnical Site Investigation Surveys on Fish and Shellfish. Wind Energy Ireland (WEI): Blue Wise Marine. 2023. Available online: https://windenergyireland.com/images/files/november-23-impact-of-surveys-on-fisheries-corrected.pdf (accessed on 12 December 2024).
32. Tougaard, J.; Hermannsen, L.; Madsen, P.T. How loud is the underwater noise from operating offshore wind turbines. *J. Acoust. Soc. Am.* **2022**, *148*, 2885. [CrossRef] [PubMed]
33. Stocker, M. Potential biological impacts of very low frequency acoustical energy produced by offshore wind turbine energy generation. *J. Acoust. Soc. Am.* **2023**, *153*, A185. [CrossRef]
34. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH; Inodú; Ministerio de Energía de Chile; Servicio de Evaluación Ambiental. *Identificación de aspectos ambientales, sectoriales y territoriales para el desarrollo de proyectos de hidrógeno verde en toda su cadena de valor*; Primera edición digital; GIZ: Santiago de Chile, Chile, 2020; ISBN 978-956-8066-19-2.
35. Nuevo, D. La Salmuera en el Vertido de Desaladoras. November 2020. Available online: https://www.tecpa.es/salmuera-desaladora/ (accessed on 20 November 2024).
36. LaFleur, C.; Hecht, E.; Ehrhart, B.; Ronevich, J.; Marchi, C.S. *Chapter 16—Safety of Hydrogen for Large-Scale Energy Deployment in a Decarbonized Economy*; Academic Press: Cambridge, MA, USA; Elsevier: Amsterdam, The Netherlands, 2023. [CrossRef]
37. IRENA and Bluerisk. *Water for Hydrogen Production*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2023. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Dec/IRENA_Bluerisk_Water_for_hydrogen_production_2023.pdf (accessed on 6 August 2024).
38. UK Government. Offshore Wind Sector Deal. Department for Business, Energy & Industrial Strategy. 2020. Available online: https://www.gov.uk/government/publications/offshore-wind-sector-deal/offshore-wind-sector-deal (accessed on 20 September 2024).
39. Global Wind Energy Council (GWEC) and International Renewable Energy Agency (IRENA). Enabling Frameworks for Offshore Wind Scale Up: Innovations in Permitting. IRENA. 2023. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Sep/IRENA_GWEC_Enabling_frameworks_offshore_wind_2023.pdf (accessed on 20 September 2024).

40. Al-Hashimi, T. Key Lessons from the UK Offshore Wind Experience for Australia and New Zealand. RPS Group. 2022. Available online: https://rpsgroup.com/insights/aap/key-lessons-australia-can-take-from-the-uk-offshore-wind-experience/ (accessed on 20 September 2024).
41. WindEurope. A 2030 Vision for European Offshore Wind Ports: Trends and Opportunities. 2021. Available online: https://windeurope.org/intelligence-platform/product/a-2030-vision-for-european-offshore-wind-ports-trends-and-opportunities/ (accessed on 20 September 2024).
42. Subsea Working Group. Guidance Notes on Geotechnical Investigations for Subsea Structures. Offshore Soil Investigation Forum. 2000. Available online: https://sut.org/wp-content/uploads/2014/03/subseaguidancenotes.pdf (accessed on 21 April 2024).
43. Shaddix, C.R. *An Assessment of Current Understanding of the Greenhouse Gas Impacts from H_2 Emissions*; OSTI.GOV, Technical Report OSTI ID:1884932; Sandia National Laboratories: Albuquerque, NM, USA; Livermore, CA, USA, 2022. [CrossRef]