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Sustainability Assessment of an Oscillating Water Column During the Design, Installation, Operation, and Disassembly Phases

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Abstract: The increasing global demand for renewable energy sources for electricity generation, coupled with the urgent need to reduce reliance on fossil fuels, has made the transition to cleaner alternatives more critical in recent years due to the environmental degradation caused by fossil fuel consumption. Among renewable energy sources, wave energy stands out as one of the most promising options because its resource, ocean waves, is inexhaustible. To harness wave energy, one effective device is the oscillating water column (OWC), which converts the kinetic energy of waves into electrical power. Despite the significant capacity of wave energy, particularly through the implementation of OWCs, the environmental and socio-economic impacts remain insufficiently studied. This research addresses this gap by analyzing the potential impacts associated with the deployment of wave energy systems, such as OWCs. Specifically, a sustainability assessment of OWCs was conducted, and a cause-and-effect matrix was developed using Conesa's methodology to evaluate the impacts linked to their design, installation, operation, maintenance, and disassembly phases. The results obtained revealed that the majority of impacts caused by an OWC are moderate. Notably, the most significant positive effects are related to improvements in the quality of life of communities benefiting from the technology studied. The findings underscore the sustainability of OWCs in harnessing wave energy to generate electricity.

Keywords: non-conventional sources of renewable energy; oscillating water column; sustainability assessment; wave energy

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1. Introduction

Environmental degradation has intensified in recent years due to rapid economic expansion, industrialization, and population growth, posing a significant threat to sustainable development [1]. Natural phenomena such as droughts, wildfires, floods, biodiversity loss within ecosystems, and even the complete destruction of certain habitats are largely driven by anthropogenic activities. These activities exacerbate climate change and environmental deterioration, leading to substantial impacts on living organisms [2]. Inefficient energy management and the overexploitation of natural resources have emerged as critical barriers to achieving sustainable development and mitigating climate change [3]. The reliance on fossil fuels, including natural gas, coal, petroleum, and biofuels, for energy generation is among the most significant anthropogenic contributors to climate change [1,4,5]. The combustion of fossil fuels releases greenhouse gases (GHGs), particulate matter (PM), and toxic gases such as tropospheric ozone (O_3), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). These emissions are major drivers of global warming due to their capacity to absorb infrared radiation, thereby intensifying the greenhouse effect [6]. To address the environmental impacts associated with fossil fuel-based energy generation, alternative energy solutions with lower environmental footprints are being explored. These alternatives aim to reduce the dependency on fossil fuels, mitigate climate change, and minimize environmental degradation.

The development of renewable energy has become a global necessity to ensure the long-term preservation of natural resources. Developing nations, such as Colombia, have committed to ambitious climate goals, exemplified by their adoption of the Paris Agreement. Colombia has pledged to reduce GHG emissions by 51% by 2030 and achieve net-zero emissions by 2050. Reaching these targets requires the integration of renewable energy sources into the energy matrix, as renewable energy has been demonstrated to play a crucial role in achieving long-term emission reductions. The adoption of renewable energy not only reduces GHG emissions but also addresses energy security and pollution challenges ascribed to conventional energy sources. By decreasing dependency on fossil fuels, renewable energy contributes to mitigating climate change while simultaneously supporting global economic stability, social development, and environmental sustainability [5,7]. This makes the transition from conventional to renewable energy sources an essential step [8]. In Colombia, government initiatives and regulatory frameworks have facilitated the integration of renewable energy into the national energy sector. A notable example is Law 1715 of 2014, which marked a foundational step in promoting the development and implementation of renewable energy technologies [9]. These efforts underscore the country's commitment to fostering a cleaner and more sustainable energy future.

Renewable energy sources rely on natural resources as a foundation for energy generation, aiming to minimize the environmental impact associated with traditional energy systems. Examples of renewable energy include solar radiation, wind energy, tidal energy, wave energy, biomass energy, and geothermal energy, among others [7,10]. These energy sources can be harnessed through various technologies and devices specifically designed to optimize their use. For instance, wind turbines are widely used to convert wind energy into electricity [11,12]. Similarly, solar energy is harnessed using photovoltaic panels or concentrated solar power systems. Another example is geothermal energy, which utilizes heat pumps to extract steam or hot water from beneath the Earth's surface [11]. In turn, energy from water sources can be harnessed in several forms, including conventional hydroelectric power, tidal energy, and wave energy. Conventional hydroelectricity captures energy from the gravitational force of moving water, typically through the construction of dams and power plants [13]. Tidal energy, on the other hand, takes advantage of the power generated by ocean tides, using submerged or bridge-mounted turbines to harness energy from tidal movements [11,13]. Wave energy captures the kinetic energy produced by ocean waves, which are primarily driven by wind. This energy is converted into electricity using specialized systems designed to capture the motion of waves at the sea's surface. As an inexhaustible resource, wave energy is crucial for achieving sustainable energy goals and economically viable renewable energy production [14]. Although wave energy is still in its early stages of development and requires further technological advancements for large-scale commercial deployment, it is regarded as a promising renewable energy source. Wave energy represents one of the most promising renewable energy sources for the future, especially for coastal communities. The global potential of wave energy is estimated at around 32×10^{12} kWh per year, nearly double the total global electricity generation in 2008 [15]. This potential highlights wave energy's capacity to become a key player in meeting the world's growing energy demands sustainably. What makes wave energy particularly attractive is its predictability and consistency. Unlike solar or wind energy, wave patterns are relatively stable and can provide a constant and reliable source of power, especially for coastal areas. This reliability is crucial for regions that depend on stable energy supplies for economic development, industrial growth, and the well-being of their populations. By harnessing wave energy, coastal communities can reduce their dependence on fossil fuels and contribute to global efforts to combat climate change [16]. Furthermore, the ability of wave energy to be harnessed close to shore reduces energy transmission losses, making it an efficient solution for powering nearby communities. Many coastal areas are remote and often face challenges in accessing centralized power grids. Wave energy can offer a decentralized and locally available energy source, creating more energy autonomy for these regions [17].

Wave energy can be harnessed through a variety of converters, each designed to capture the kinetic energy of ocean waves. There are several types of wave energy converters (WECs), including point absorbers, attenuators, overtopping devices, and oscillating water columns (OWCs) [18–21]. Point absorbers capture energy from the motion of waves at a single point, while attenuators are long, floating structures that move with the direction of the wave. In turn, overtopping devices capture water as it moves over a barrier and convert its potential energy. Among these options, the OWCs are considered one of the most widely used systems for generating energy from sea waves [14].

The OWC system works by utilizing the periodic rise and fall of ocean waves to create variations in air volume within its air chamber, resulting in a bidirectional airflow [22,23]. This airflow drives a turbine, converting the kinetic energy of the waves into mechanical energy. What makes OWC particularly advantageous compared to other wave energy technologies is its simplicity, scalability, and low maintenance requirements. The OWC's turbine is specifically designed to be adapted to bidirectional airflow, enabling continuous operation with a consistent rotational direction [24,25]. In addition, OWC systems have a relatively simple design and operation, making them more reliable and easier to maintain compared to more complex wave energy technologies, reducing the likelihood of mechanical failure. Furthermore, OWC systems typically have a smaller environmental footprint than other wave energy technologies, such as those involving large-scale installations or underwater turbines, making them less intrusive to marine ecosystems [26]. In terms of efficiency, OWC systems can operate effectively across a wide range of wave conditions, allowing for efficient energy conversion from ocean waves to electrical power. Moreover, the scalability of OWC technology provides flexibility, as it can be adjusted to both small- and large-scale applications depending on the specific energy needs of a location. Finally, OWC is considered a more mature technology compared to some other wave energy alternatives since it has been extensively tested and deployed in various locations worldwide, demonstrating its feasibility and reliability [15,27].

Although renewable energy sources produce less pollution than conventional energy, they can still have various negative environmental impacts [13,28,29]. In fact, one of the major challenges facing the scaling-up of OWC devices is the uncertainty about the environmental impacts that these devices may have on the components of coastal and marine ecosystems [22]. These impacts can arise during different stages such as the design, construction, operation, maintenance, and disassembly of the devices used to harness energy and facilitate their operation. As a matter of fact, OWCs may cause damage to coastal areas and contribute to noise pollution. However, they also offer significant benefits, including the generation of renewable energy. Therefore, it is essential to evaluate the environmental and socio-economic impacts ascribed to determine whether this technology is environmentally safe and sustainable [12] and, consequently, fill the knowledge gaps regarding the impacts that this type of device can cause on the environment and society.

To assess and analyze potential impacts, an environmental impact assessment (EIA) should be conducted. EIAs are recognized as an effective tool for environmental planning and management. The primary objective of an EIA is to ensure sustainable development and ecosystem conservation while also incorporating the precautionary principle to prevent the loss of natural resources [30]. An EIA allows for the identification of direct and indirect impacts on humans, wildlife, flora, water, soil, air, and climate [31]. The EIA process can be carried out using interaction matrices to determine the impacts resulting from a project's interaction with the environment. These matrices are commonly used in EIAs due to their simplicity, low cost, and minimal time requirements [30].

One matrix used to assess the environmental impact of a project is Conesa's matrix. This cause-and-effect matrix characterizes activities based on the significance of their respective impacts to identify the interactions between a project and the environment [32]. Conesa's methodology employs a qualitative EIA by assigning numerical values to attributes that characterize environmental impacts in detail using qualitative scales or descriptors (e.g., low, medium, high, moderate, severe). This EIA approach provides flexibility in incorporating attributes based on the specific characteristics of the project [33]. The use of Conesa's matrix can help us understand the risks associated with a specific project and establish the basis for adopting responsible and sustainable practices. It also integrates the economic and social aspects of a project with the environmental challenges that may arise [34]. Although this matrix has been widely used to conduct EIAs, to the best of the authors' knowledge, to date, there are no studies reported in the literature that analyze the sustainability of an OWC device during its different phases (i.e., design, installation, operation, maintenance, and decommissioning) using this cause–effect matrix.

Based on the aforementioned considerations, this study aims to determine the environmental and socio-economic impacts of an OWC, taking into account the design, installation, operation, maintenance, and decommissioning phases. The EIA of the OWC is conducted using Conesa's matrix for each stage, with the goal of identifying and classifying the impacts caused by the interactions between these different phases and the environment and society.

2. Materials and Methods

2.1. Environmental Impact Assessment

There are several methodologies used for sustainability assessment of energy generation technologies, each with its own characteristics and approaches. Leopold's matrix, Ishikawa's diagram, McAllister's energy analysis, and Conesa's matrix are named among the most well-known methodologies. Leopold's matrix is widely used for its simple and effective structure, allowing for the identification and evaluation of direct environmental impacts of a project. Nevertheless, its approach can be limited when it comes to indirect or cumulative impacts, which are not always addressed in depth [35]. Ishikawa's diagram, on the other hand, is very useful for identifying root causes of problems, but it focuses more on solving specific issues and may not be suitable for evaluating large-scale or complex projects like the OWC [36]. In turn, McAllister's energy analysis focuses on the efficiency of energy consumption and reducing impacts related to resource use, but it lacks a comprehensive evaluation of environmental and social effects, which is crucial for technologies that directly interact with the marine environment and nearby communities [37].

In this context, Conesa's matrix emerges as an ideal option for the sustainability assessment of technologies like OWC. This methodology is highly flexible and adapts to the complexity and diversity of energy generation projects, addressing both direct and indirect, as well as cumulative, impacts [38]. Unlike other methodologies, Conesa's approach offers an integrated framework that evaluates not only environmental effects but also social, economic, and cultural impacts, which is crucial when dealing with projects located near coastal communities. Furthermore, its ability to combine qualitative and quantitative assessments provides a more comprehensive view of short-, medium-, and long-term effects, which is essential for emerging technologies like OWCs, whose implementation can have implications for both marine life and local human activities [39]. By integrating a multidimensional and preventive analysis, Conesa's methodology facilitates the early identification of potential impacts, allowing for mitigation measures to be implemented before project execution. This makes it an ideal tool to ensure that the development of OWC technology is sustainable, environmentally respectful, and beneficial to nearby communities.

In this work, the cause-and-effect matrix proposed by Conesa [40] was employed. The significance of each impact was assessed based on the extent and intensity of the environmental alteration caused, as well as the characterization of the effects produced by each activity required during the design, installation, operation, maintenance, and decommissioning phases of an OWC system Additionally, parameters such as coastal erosion, fisheries, job creation, reductions in tourism, navigability, population growth, and improved access to energy services were considered.

For this purpose, a panel of 15 highly qualified experts, each with extensive experience in their respective fields, was carefully assembled. These experts represented a diverse range of disciplines, including civil engineering, mechanical engineering, environmental engineering, oceanographic engineering, economics, social work, biology, and anthropology, ensuring a holistic and interdisciplinary approach to the assessment. Their varied backgrounds allowed for a comprehensive evaluation, drawing on specialized knowledge from each area to thoroughly assess the potential environmental impacts. Each expert individually evaluated the significance of the identified impacts, applying their specialized knowledge to consider environmental, technical, and socio-economic aspects of the technology. To further enhance the rigor of the process, the experts assigned scores to each impact based on its perceived relevance and magnitude. These individual assessments were then aggregated to calculate the average significance values for each impact, providing a clear and quantitative measurement of their overall importance.

This method ensured a high level of objectivity in the evaluation by mitigating potential biases. By incorporating diverse perspectives and drawing on the expertise of professionals from various disciplines, the process minimized the risk of overlooking key factors or giving undue weight to one specific aspect. The result was a balanced and well-rounded evaluation that offered a nuanced understanding of the consequences of the technology under study, ensuring that all potential impacts, whether environmental, social, or economic, were thoroughly considered in the decision-making process. On the other hand, this approach provides a systematic evaluation of the OWC lifecycle, facilitating the identification of critical impacts, informing mitigation strategies to reduce adverse effects, and promoting the sustainability of the studied technology.

2.1.1. Identification of Aspects and Impacts

In accordance with Conesa's methodology [40], environmental aspects were defined for each activity susceptible to generating an impact (ASPI). These aspects refer to activities that may interfere with or affect the natural and socio-economic environment. These activities can range from construction and resource extraction to emissions and waste generation; all of which have the potential to alter natural or socio-economic conditions.

Once these activities are identified, the next step is the identification of environmental factors susceptible to being impacted (FARI), which categorizes the affected components into biotic (living organisms such as terrestrial and aquatic flora and fauna), abiotic (non-living environmental elements like air, water, soil, and landscape), and socio-economic (human-related aspects such as local communities, economy, demography, and cultural heritage). This step establishes a direct link between project activities and their potential environmental consequences.

Following this, the identification of components allows for a deeper analysis of each environmental factor, breaking them down into specific elements that define their structure and are vulnerable to pollutants or degradation agents. For instance, water quality, biodiversity, and economic stability are distinct components that can be affected in different ways. This level of detail helps refine the assessment by focusing on particular vulnerabilities within each category. The process then moves to the identification of environmental aspects, where specific elements or activities stemming from ASPI are analyzed in terms of their direct interaction with the environment. For example, GHG emissions from industrial operations or noise pollution from construction work are considered environmental aspects that contribute to broader environmental changes. Clearly, defining these aspects is crucial for assessing their magnitude and developing mitigation strategies.

Afterward, environmental impact identification is conducted, which determines the actual alterations in the environment resulting from the project's implementation. An environmental impact occurs when an identified environmental aspect triggers changes that affect ecosystem health, natural resources, or living organisms.

2.1.2. Evaluation and Classification of Impacts

Once the impacts have been identified, they are evaluated and classified. These impacts can be considered positive or negative, direct or indirect, reversible or irreversible, and short-term or long-term, depending on their nature and duration.

The significance of the impacts was determined in terms of both their intensity and their characterization, taking into account a range of qualitative attributes. A score was assigned to each attribute according to its characteristics, following the criteria outlined in Table 1. The evaluation of these attributes was standardized using Equation (1) to calculate the significance (I) of each impact [30,32,40,41]. The variables in Equation (1) represent the attributes considered for calculating impact significance. Their definitions are provided in Table 1. In the table, for the attribute related to intensity, an impact is classified as "total" if the modification of the environment caused by a specific activity costs the total destruction of the factor (i.e., water, air, soil, fauna, flora, and socio-economic factors). For the spreading attribute, an impact classified as "total" means that the impact is manifested in all the environments considered, and "critical" represents the impacts occurring in critical situations that may lead to the degradation of the environment and may create a hazard to living organisms.

$$I = \pm\,[3i + 2EX + MO + PE + RV + SI + AC + EF + PR + MC] \quad (1)$$

Table 1. Attributes for impact significance determination and their respective scores. Adapted from [40].

± = Nature of the impact Impacts can be beneficial or positive if the action leads to an improvement in environmental quality, and negative if the action results in a deterioration of environmental quality.	
Positive or beneficial Negative	+ −
i = Intensity Influence of the action on the affected factor in the area where the effect occurs (destruction degree).	EX = Spreading Area affected compared to the total area.

Table 1. *Cont.*

Low Medium High Very high Total	1 2 4 8 12	Isolated or punctual Partial Large Total Critical	1 2 4 8 12
MO = Moment The time between the start of the action and the time it takes for the effect to appear.		PE = Persistence Permanence of the impact from the moment it occurs until the environment can return to its original state by itself or through the corrective action.	
Long term (>5 years) Medium term (1–5 years) Immediate (<1 year) Critical	1 2 4 8	Brief (<1 year) Temporary (1–10 years) Permanent (>10 years)	1 2 4
RV = Reversibility Natural restoration of the environmental factor to its original state before the impact.		SI = Synergy Mutual reinforcement of two or more individual impacts.	
Short term (<1 year) Medium term (1–5 years) Irreversible	1 2 4	Non synergistic Synergistic Highly synergistic	1 2 4
AC = Accumulation Reinforcement of the effect with the persistence of the cause.		EF = Effect Cause–effect relationship of the impact on the environmental factor.	
Simple Accumulative	1 4	Indirect Direct	1 4
PR = Regularity Impact occurrence rate.		MC = Recoverability Ability of the environmental factor to recover the initial environmental conditions through the application of corrective measures.	
Irregular Periodic or regular Constant or continuous	1 2 4	Total or immediate (0 years) Recoverable (<1 year) Mitigable (10–15 years) Irrecoverable (>15 years)	1 2 4 8

The significance of the impact, which was calculated using Equation (1), was expected to fall within the range of from 13 to 100. Based on the magnitude and the sign of this value, impacts were classified according to the criteria outlined in Table 2 [32,40].

Table 2. Impact classification according to their significance.

Negative	Significance	Positive
Low or irrelevant	13–25	Limited
Moderate	26–50	Moderate
Severe	51–75	High
Critical	76–100	Very high

A structured evaluation at this stage enables prioritization of impacts that require mitigation or monitoring efforts. The entire process can be visually represented through a flow diagram (Figure 1), illustrating how each stage refines the analysis and contributes to a comprehensive assessment.

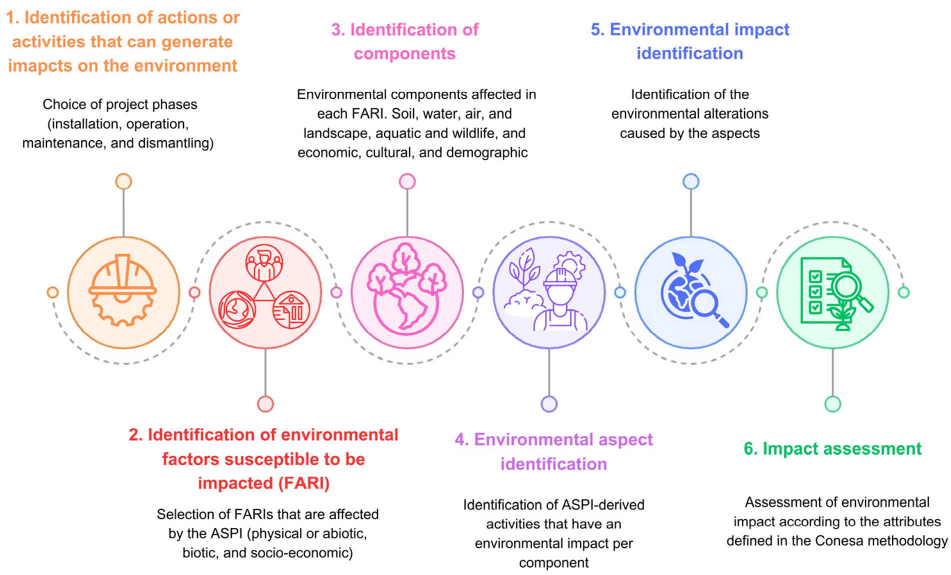

Figure 1. Stages involved during the assessment of environmental impacts.

This procedure was carried out for all the phases of the OWC lifecycle, including the design and installation, operation, maintenance, and decommissioning stages. The effects of the activities required for the design, installation, operation, maintenance, and decommissioning phases of an OWC were characterized based on the significance of each impact generated by these specific activities.

By following this systematic methodology, decision-makers can enhance the accuracy of impact evaluations, implement effective mitigation strategies, and ensure that energy projects, such as OWC technologies, align with sustainability principles and environmental regulations.

3. Results and Discussion

3.1. Identification of Aspects and Impacts of an OWC

Various environmental impacts have been identified throughout the design, installation, operation, maintenance, and decommissioning phases of an OWC, which can alter the natural dynamics of the surrounding environment. The effects associated with wave energy devices include noise, vibrations, potential collisions of marine animals with equipment components, habitat changes or removal, alterations in hydro sedimentary dynamics, changes in electric and electromagnetic fields, and wave modifications [42,43].

OWCs can also affect water quality in the installation area due to the release of oils and other chemicals required for the proper functioning of their components [44]. Beyond the impacts on water, fauna, and flora, OWCs can generate socio-economic and landscape effects. Socio-economic impacts, aside from job creation, may include disruptions to fishing, tourism, and navigation activities potentially affecting the economic development of communities reliant on these sectors [45].

Landscape impacts are primarily attributed to the introduction of non-natural elements into the environment, causing significant visual intrusions that alter the natural aesthetic of the area [44]. Based on the various environmental components potentially affected and the impacts identified in the literature, specific aspects and environmental impacts were defined for each phase of the OWC lifecycle: design and installation, operation, maintenance, and decommissioning. This ensures a comprehensive understanding of the potential consequences of OWC deployment and guides the development of strategies to mitigate adverse effects and promote the sustainability of the target technology.

3.2. Impact Assessment of an OWC

The significance of each impact was determined by assigning scores to the attributes considered in the calculation of its importance. A panel of multiple evaluators with expertise in the field was assembled to assess the matrix, ensuring a well-rounded and informed evaluation of each impact. By incorporating diverse perspectives and specialized knowledge, this approach minimizes the influence of individual biases and subjective interpretations. Each evaluator independently analyzed and assigned significance values to the identified impacts, and an average significance value was then calculated. This methodological approach not only enhanced the reliability and consistency of the assessment but also mitigated uncertainties and subjectivity that often arise in the implementation of cause–effect matrices. Furthermore, by leveraging a collective evaluation process, the methodology strengthened the validity of the results, providing a more objective and comprehensive assessment of environmental impacts [41,46,47].

The evaluated matrix, along with the classification of each impact, is provided in the Supplementary Materials. This methodology ensures an interdisciplinary, robust, and transparent evaluation process, facilitating informed decision-making for mitigating the impacts associated with the implementation of the OWC system.

3.2.1. Design and Installation Phase of an OWC

The process of installing an OWC leads to environmental consequences that mainly influence physical, biotic, and socio-economic aspects. Tasks like excavation and the removal of materials change the land's structure and contribute to moderate levels of erosion. Furthermore, spills from machinery and the use of water resources negatively impact soil conditions and aquatic ecosystems. The outcomes of the EIA for this stage are detailed in Table 3.

The assessment of the environmental impacts associated with the design and installation of an OWC reveals a complex balance between environmental challenges and socio-economic benefits. The analysis highlights that, while the implementation of this wave energy technology introduces moderate environmental impacts, particularly in terms of soil degradation, pollution, and ecosystem disturbances, it also presents significant opportunities for economic growth, job creation, and local development.

From a physical (abiotic) perspective, the most concerning impacts stem from soil excavation (−25), erosion (−30), removal of land material (−33), and morphological changes (−34), all of which are classified as moderate in significance. These effects emphasize the need for sustainable land management practices to minimize habitat disruption. Additionally, machinery waste spillage contributes to increased soil (−33) and ocean (−28) pollution, underscoring the necessity of pollution control measures during installation. In terms of water resources, water consumption (−22), changes in wave intensity (−23), velocity (−25), and energy (−24), the OWC presence alters local hydrodynamics, though at a low to moderate significance level. A more pressing concern is the potential for oil spillage from turbine installation (−35), which could cause lasting damage to marine ecosystems, reinforcing the importance of preventive maintenance and spill-response plans. Furthermore, air quality deterioration due to increased CO_2 emissions (−29), PM (−28), and noise pollution (−35) highlights additional environmental burdens that require mitigation strategies, including emission control technologies and noise reduction measures.

Table 3. Impacts ascribed to the design and installation stages of an OWC.

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Desing and installation of an OWC	Physical or abiotic	Soil	Site preparation for the OWC construction	Changes in land morphology	−34	Moderate
				Soil excavation	−25	Moderate
				Ground coupling	6	Low
				Soil erosion	−30	Moderate
				Removal of land material	−33	Moderate
			Machinery waste spillage	Increase in soil pollution	−33	Moderate
		Water	Water consumption	Water depletion	−22	Low
			Machinery waste spillage	Increase in ocean pollution	−28	Moderate
			Infrastructure construction	Changes in wave intensity	−23	Low
				Changes in wave velocity	−25	Moderate
				Changes in wave energy	−24	Low
			Installation of Wells turbine	Oil spillage	−35	Moderate
		Air	Noise generation	Increase in sound pressure levels in the area due to machinery	−35	Moderate
				Increase in sound pressure levels in the area due to entirely human activities	−27	Moderate
			Atmospheric damage	Increase in particle matter emissions	−28	Moderate
				Increase in CO_2 emissions	−29	Moderate
		Landscape	Location/sitting of the OWC	Imperceptible landscape alteration	−27	Moderate
				Decrease in wild fauna	−29	Moderate
				Decrease in marine flora	−27	Moderate
				Removal of wild flora in the surroundings of the installation area	−28	Moderate

Table 3. *Cont.*

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Desing and installation of an OWC	Biotic	Aquatic biota	Construction and installation of the OWC	Migratory process alteration	−27	Moderate
				Alteration in the development of nearshore autotrophic species	−25	Moderate
				Disruption of marine fauna feeding processes	−25	Moderate
				Disruption of marine fauna reproduction process	−24	Low
				Reduction in zones for fish aggregation	−27	Moderate
				Landscape alteration	−32	Moderate
				Reduction in photosynthesis process (reduction in radiation)	−21	Low
				Seabed alteration	−27	Moderate
		Wild biota	Construction and installation of the OWC	Disruption of wild fauna feeding process	−28	Moderate
				Disruption of wild fauna reproduction process	−27	Moderate
	Socio-economic	Economic	Alteration of coastal activities	Tourism alteration	−38	Moderate
				Landscape alteration	−34	Moderate
				Reduction in zones for recreative use	−31	Moderate
				Alteration of fishing zones	−35	Moderate
				Decrease in the areas for extraction of aggregates	−27	Moderate
				Increase in the risk of collision and accidents	−28	Moderate
				Affectation of the navigable area	−18	Low

Table 3. *Cont.*

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Desing and installation of an OWC	Socio-economic	Economic	Job creation	Increase in zone development	50	Moderate
				Increase in quality of life	46	Moderate
				Job creation for device structure designers	42	Moderate
				Increased demand in the material transport sector	32	Moderate
				Job creation for staff for the construction of the OWC	47	Moderate
				Creating jobs for oceanographers to better assess the environmental impacts caused by the OWC	45	Moderate
				Increase in economic conditions of the zone	49	Moderate
		Cultural	Job creation	Improvement of social relationships	37	Moderate
				Increase in educational levels	38	Moderate
		Demographic		Increase in population	36	Moderate

Regarding biotic factors, this study indicates moderate disturbances to marine and terrestrial ecosystems, particularly concerning the alteration of the migratory patterns (−27), feeding (−25 for marine fauna, −28 for terrestrial fauna), and reproduction processes (−24 for marine fauna, −27 for terrestrial fauna) of various species. Furthermore, the disruption of nearshore autotrophic species (−25), seabed alterations (−27), and reductions in photosynthesis due to lower radiation levels (−21) suggest that the OWC construction and operation may lead to ecological shifts in coastal habitats. Although these impacts are generally moderate, their cumulative effects over time could become significant, requiring continuous ecosystem monitoring and adaptive management strategies.

On the socio-economic front, the results reveal a dual impact, with both challenges and opportunities emerging from the OWC implementation. One of the primary concerns is the disruption of economic activities, particularly in tourism (−38), fishing (−35), recreational areas (−31), and aggregate extraction (−27). The risk of collisions and accidents (−28) and limitations in navigable areas (−18) further complicate the integration of the OWC into existing maritime industries. These factors underscore the importance of coastal planning and stakeholder engagement to mitigate conflicts and develop coexistence strategies with local communities.

However, this study also highlights significant socio-economic benefits, particularly in job creation and regional economic development. The increase in employment opportunities for construction workers (+47), engineers (+42), material transport (+32), and oceanographers (+45) contributes to the overall economic improvement of the region (+49). Additionally, enhancements in social relationships (+37), education levels (+38), and population growth (+36) indicate that wave energy projects can serve as catalysts for community development and long-term prosperity.

Site Preparation

The site preparation process for the installation of an OWC involves activities that can result in environmental impacts, such as land clearing, excavation, and modifications to coastal areas. These activities can disturb existing ecosystems, alter hydrodynamic conditions, and potentially impact local biodiversity. For example, construction activities may increase soil erosion, sedimentation in nearby aquatic systems, and emissions of noise and dust, all of which can affect both terrestrial and aquatic species.

The potential impacts generated during the site preparation were classified as ranging from low to moderate in significance. OWCs can be installed in various configurations, including floating or fixed systems located offshore, nearshore, or onshore, or integrated into breakwaters [48,49].

For onshore OWCs or those integrated into breakwaters, deep anchoring is typically not required, resulting in minimal land alteration [50]. Conversely, floating OWCs installed offshore require anchoring systems to ensure stability [51]. This anchoring process can lead to sediment suspension, increasing suspended solid concentrations in the water and potentially affecting benthic communities. However, this sediment suspension is generally considered a moderate impact, as sediments typically resettle over time [45]. When OWCs are installed onshore or integrated into breakwaters, the installation impacts mirror those observed during the construction of breakwater structures [52]. Integrating an OWC into existing coastal infrastructure, such as port breakwaters, can help reduce the additional environmental impacts associated with standalone OWC installations [53].

While the environmental impacts on terrain and coastal dynamics vary depending on the installation method, they are generally classified as from low to moderate. Proper planning and the integration of OWCs with existing coastal protection structures offer a strategic way to minimize these impacts while optimizing the benefits of renewable energy generation.

Machinery Waste Spillage

During the installation of an OWC, machinery waste spills, such as hydrocarbon leaks, may occur [54]. These spills can have detrimental effects on soil health, leading to a reduction in microbial abundance and density, thereby impairing soil functionality [55]. Heavy machinery used in construction typically operates with diesel fuel, and accidental fuel spills can contaminate soil and water resources.

While hydrocarbons have environmental detrimental effects, the rate of degradation depends on the ability of microorganisms to metabolize these substances and on environmental conditions that facilitate dispersion and evaporation. In coastal areas, natural processes, including evaporation, dispersion, and dilution, can support the degradation of hydrocarbons spilled during OWC installation. In this regard, to minimize the environmental impacts of machinery waste spills, it is essential to understand the specific environmental conditions at the installation site [56].

The environmental impacts resulting from machinery waste spills during the design and installation of an OWC are considered indirect, as they are secondary effects of construction activities involving heavy equipment [32]. These impacts are generally classified as moderate in significance, primarily because they are preventable through the careful and proper use of machinery.

Construction and Installation of the OWC

OWCs can influence the energy levels and the dynamics of the environments in which they are constructed. The impact on wave hydrodynamics decreases with distance from the device installation site. Studies have shown that the reduction in wave energy is generally no greater than 10% [45]. Nonetheless, alterations to wave-driven currents can affect marine habitats and the environmental quality of the installation area. Beyond altering natural flow patterns, wave energy extraction may also reduce wave heights [57].

During the construction and installation phase of an OWC, the impact on waves and current regimes is comparatively minor relative to the operational phase. Furthermore, it is one of the least significant impacts within the construction phase [47]. Installation activities, such as placing devices and laying cables for offshore OWCs, can disturb the seabed. Cables may rest on the seafloor and be shielded with rock or concrete armoring, or they may be buried. The burial process can suspend sediments, which later settle at the installation site. Although considered a localized effect, the extent of sediment disturbance can vary based on cable dimensions, potentially expanding the area impacted [58].

Anchoring offshore OWCs to the seabed may disrupt benthic communities and cause seabed erosion. Sediment dispersion associated with seabed erosion can affect ecosystem processes by altering biogeochemical cycles and reducing sunlight penetration into the water column. This disruption impacts photosynthetic organisms [59]. Reduced light penetration can hinder phytoplankton growth, subsequently affecting aquatic species that rely on phytoplankton as a food source. Such disturbances can propagate through the oceanic food chain [60]. Additionally, sediment dispersion can release toxic compounds that are adsorbed onto sediments, potentially affecting fish spawning in the area. The disruption or loss of benthic habitats due to the installation of anchoring lines may also impact coastal and pelagic species that depend on benthic zones for egg-laying [61].

Although the ecological impacts of OWC installation on local flora and fauna were considered from low to moderate, it is crucial to conduct studies on the potential effects of installation activities, particularly for offshore projects. These studies would provide a broader understanding and address existing knowledge gaps regarding the environmental consequences of OWC installations.

Noise Production

During the installation of OWC devices, high-frequency noise can be generated by activities such as ground drilling. Similarly, noise may also result from the engines and propellers of vessels used to transport machinery, as well as from the movement of heavy equipment [13]. Additionally, significant noise is produced during the installation of piles and anchoring systems [58].

Cetaceans are among the most affected animals during pile-driving activities. To mitigate this impact, it is recommended to schedule such activities during periods when conservation-sensitive species are less likely to be present in the installation area. Furthermore, hydroacoustic dampeners or bubble curtains are suggested as effective measures to reduce noise levels during these operations [29]. Among other impacts caused by noise during OWC installation, stress is named, as well as physical harm, such as temporary or permanent hearing loss, if sufficiently intense. In extreme cases, it may lead to barotrauma or even mortality [62]. On the other hand, noise can impact fish and marine mammals, tending to move away from construction sites during noisy activities but often return once the noise ceases [60,63]. However, despite its intensity, the noise produced during this phase is typically short-lived [13].

Therefore, the noise-related impacts of the OWC installation, given their temporary nature, were classified as moderate. It is important to note that for large-scale wave energy projects, the noise impact could become severe due to extended construction periods required for such installations [13].

Atmospheric Pollution

During the design and installation phase of an OWC, the impacts on air quality are primarily associated with the use of heavy machinery, such as transporting the required materials, increasing dust suspension, and raising the concentration of PM [64]. Additionally, air quality is affected by the transportation of personnel.

Dust suspension is the main source of PM_{10} (particles with a diameter of 10 μm). Fine ($PM_{2.5}$, particles with a diameter of 2.5 μm) and ultrafine particles ($PM_{0.1}$, particles with a diameter of 0.1 μm) are primarily generated through the combustion of fossil fuels [65]. Transportation activities also contribute to increased carbon dioxide (CO_2) levels during the installation of an OWC [66]. Elevated PM concentrations can reduce visibility and harm living organisms due to their carcinogenic effects. $PM_{2.5}$ and $PM_{0.1}$ pose greater health risks because they can penetrate deep into the lungs and bronchi [65]. Regarding CO_2, it is linked to global temperature rise, making it a key GHG contributing to climate change [67].

Given that the emissions of PM and CO_2 during the design and installation phase of an OWC occur over a relatively short period, the impact on the atmosphere is temporary and is, therefore, considered to have moderate significance [60].

Location of the OWC

The ocean is primarily composed of species that are highly sensitive to changes in the ecosystem. The establishment of WECs, such as OWCs, in the ocean can lead to alterations in parameters like temperature and dissolved oxygen. Consequently, during the installation of an OWC, species inhabiting the area where the device is placed will experience disturbances to their habitat. This disturbance often forces them to migrate to undisturbed zones, resulting in a decrease in the number of species previously present in the affected area [57].

Additionally, the installation of an OWC introduces a man-made structure into the natural environment, altering the landscape. While such structures may disrupt the existing ecosystem, they also create new habitats for colonization. This colonization, despite being undesirable due to its impact on the equipment's efficiency, can function as an "artificial reef", providing food and shelter for marine fauna [58]. Therefore, the impacts associated with the placement and location of an OWC were considered to have moderate significance.

Alteration of Coastal Activities

One of the coastal activities most affected by the installation of WECs is fishing, primarily due to the establishment of exclusion zones required for their proper operation. During the design and installation phases, disruptions to fishing areas have been described as temporary and low impact, which is why they are considered to have moderate significance [60]. During the installation of an OWC, the increased movement and number of vessels transporting equipment to the offshore construction site may pose navigation risks in the area, such as a higher likelihood of accidents or collisions. Nonetheless, since this activity is limited to a specific timeframe, its effects are generally deemed acceptable and have been categorized in this study as having from low to moderate significance.

OWCs are often installed on beaches or in remote coastal communities that may attract tourists. Consequently, tourism can be impacted during this phase, especially for onshore OWCs. Beaches designated for the installation may temporarily lose their recreational use as they are occupied by construction activities, machinery, and electrical cables. Despite this fact, the impact on tourism is considered moderate, as it is temporary, and the machinery and cables will be removed once construction is completed [60].

Job Generation

During the construction phase of such projects, there is a direct impact on job creation, as the installation of the OWC requires skilled labor, generating employment opportunities. Beyond the workforce needed for the physical construction of the OWC, various specialists are also required, including oceanographers and marine mammal observers, to ensure that the installation process minimizes harm to marine life. For offshore installations, marine mammal observers play a crucial role in maintaining safe distances between installation and marine mammals in the area. In addition, they ensure that installation sites are not located in regions critical to animal activities, such as molting areas [60].

The creation of these jobs contributes to an improvement in the quality of life for those employed and their families. This positive impact extends to enabling access to better education, thereby improving the overall educational level of the community.

3.2.2. Operation Phase of an OWC

Concerning the operational phase of an OWC, soil-related impacts involve changes in sediment movement and erosion, both of which are rated as moderate. In aquatic ecosystems, the device modifies wave energy and velocity, leading to shifts in water turbidity and potential contamination. Additionally, noise produced at both surface and seabed levels is assessed as having a moderate environmental effect. The impact assessment for the OWC's operational phase is summarized in Table 4.

Table 4. Impacts ascribed to the operation stage of an OWC.

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Operation of an OWC	Physical or abiotic	Soil	Sediment transport	Soil morphology alteration	−32	Moderate
				Changes in sediment transport patterns	−35	Moderate
				Soil erosion	−34	Moderate
		Air	Noise generation	Increase in sound pressure levels in ocean surface	−29	Moderate
				Increase in sound levels on the seabed	−36	Moderate
		Water	Operation of the OWC	Changes in wave energy	−35	Moderate
				Changes in wave velocity	−21	Low
				Changes in wave intensity	−21	Low
				Increase in suspended sediments	−27	Moderate
				Water turbidity alteration	−28	Moderate
				Increase in sea water pollution	−26	Moderate
				Air quality decrease	−25	Moderate
				Changes in nearshore depth	−35	Moderate
				Seabed alteration	−32	Moderate
				Changes in water flow velocity	−15	Low
				Alteration of marine sediment transport	−26	Moderate
				Radiation decrease	−23	Low
				Thermo-climatic alteration	−24	Low
				Dissolved oxygen increase	18	Low
				Temperature increase	−12	Low

Table 4. *Cont.*

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Operation of an OWC	Physical or abiotic	Landscape	Location/sitting of the OWC	Landscape alteration	−30	Moderate
				Extinction of some species of flora that inhabit the area	−29	Moderate
				Extinction of some species of marine flora in the area	−31	Moderate
				Reduction in wild flora growth in the area	−30	Moderate
				Alterations in marine habitat development	−29	Moderate
	Biotic	Aquatic biota	Operation of the OWC	Reduction in zones for fish aggregation	−31	Moderate
				Thermo-climatic alteration	−13	Low
				Alteration of marine fauna migratory processes	−30	Moderate
				Alteration of marine fauna feeding processes	−31	Moderate
				Alteration of marine fauna reproduction process	−30	Moderate
				Alteration of coral development process	−32	Moderate
				Mutilation of aquatic species if they encounter the most dangerous parts of the structure	−29	Moderate
				Death of aquatic species if they encounter the most dangerous parts of the structure	−31	Moderate
				Alteration in the development of nearshore autotrophic species	−32	Moderate
				Alteration in the development of underwater autotrophic species	−29	Moderate
				Landscape alteration	−31	Moderate
				Reduction in photosynthesis process (reduction in radiation)	−23	Low

Table 4. *Cont.*

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Operation of an OWC	Biotic	Wild biota	Operation of the OWC	Alteration of wild fauna reproduction process	−25	Low
				Relocation of flying animals living in the immediate area	−28	Moderate
				Relocation of terrestrial animals living in the immediate area	−26	Moderate
				Alteration of wild fauna feeding process	−29	Moderate
				Alteration of flying animals migratory process	−26	Moderate
	Socio-economic	Economic	Alteration of coastal activities	Tourism alteration	−37	Moderate
				Landscape alteration	−31	Moderate
				Fuel consumption for transport of materials	−33	Moderate
				Decrease in areas for recreational use	−31	Moderate
				Alteration of fishing zones	−34	Moderate
				Decrease in the areas for extraction of aggregates	−29	Moderate
				Increase in the risk of collision and accidents	−33	Moderate
				Affectation of the navigable area	−31	Moderate
			Job creation	Increase in the development of the zone	50	Severe
				Employment increase for Supervision Engineers	44	Moderate
				Job growth in the region's energy sector	48	Moderate
				Job creation for OWC operators	45	Moderate
				Increase in the quality of life	53	Severe
				Improvement of economic conditions in the region	49	Moderate

Table 4. *Cont.*

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Operation of an OWC	Socio-economic	Economic	Energy generation (service)	Improvement of accessibility to the service	59	Severe
				Increase in demand for the service (increase in customers)	52	Severe
				Increase in the quality of life	54	Severe
		Cultural	Energy generation (service)	Improvement of social relationships	46	Moderate
				Increase in educational levels	40	Moderate
		Demographic		Population increase	35	Moderate

The evaluation of environmental impacts during the operation phase of an OWC reveals a complex interaction between negative effects on ecosystems and socio-economic benefits associated with renewable energy generation. Environmentally, OWC operation primarily affects physical, biotic, and socio-economic factors, with most impacts classified as moderate, although some economic benefits and improvements in service accessibility reach severe significance.

From a physical and abiotic perspective, the soil undergoes morphological alterations (−32), changes in sediment transport patterns (−35), and erosion (−34), highlighting the infrastructure's influence on coastal sediment dynamics. Regarding air quality, there is an increase in noise levels at the ocean surface (−29) and the seabed (−36), which can negatively affect marine species sensitive to sound. In terms of water, OWC operation causes modifications in wave energy (−35), velocity (−21), and intensity (−21), along with an increase in turbidity (−28) and suspended sediments (−27). Additionally, changes in nearshore depth (−35), sediment transport (−26), and water flow velocity (−15) are observed. Despite these impacts, some changes, such as the increase in dissolved oxygen (+18), have a low-significance positive effect. Thermo-climatic alterations (−24) and decreased radiation (−23) suggest potential effects on biological processes in the water column.

The landscape also experiences moderate changes due to the presence of the OWC, leading to visual modifications (−30) and a reduction in wild flora growth (−30). Furthermore, the extinction of certain terrestrial flora species (−29) and marine flora species (−31) is noted, along with alterations in marine habitat development (−29). In addition, aquatic ecosystems are affected by the reduction in fish aggregation zones (−31) and alteration of marine fauna migratory (−30), feeding (−31), and reproduction processes (−30). The disruption of coral development (−32) is particularly concerning, along with the risk of mutilation (−29) or death (−31) of aquatic species encountering hazardous parts of the structure. Furthermore, negative effects on nearshore autotrophic species (−32) and underwater autotrophic organisms (−29) could impact trophic chains. Regarding terrestrial and airborne fauna, OWC operation causes relocation of flying (−28) and terrestrial animals (−26), as well as disruptions to feeding (−29) and migratory (−26) behaviors. While these impacts are classified as moderate, they could lead to cumulative effects on local biodiversity.

The socio-economic impacts reflect both adverse effects and significant benefits. On one hand, OWC operation affects tourism (−37), fishing (−34), recreational coastal areas (−31), and navigation (−31). It is also associated with an increase in fuel consumption for material transport (−33) and a higher risk of collisions and accidents (−33). Nevertheless, in contrast to these negative impacts, the analysis highlights important economic benefits, particularly in job creation and regional development. A rise in employment opportunities is evident, including jobs for supervision engineers (+44), OWC operators (+45), and personnel in the energy sector (+48). Consequently, a significant development of the region (+50) and an improvement in quality of life (+53), classified as positive severe impacts, are expected.

In terms of energy generation, OWC operation improves electricity access (+59), increases service demand (+52), and contributes to a higher quality of life (+54), all of which are classified with severe significance. Additionally, the cultural impact is moderately positive, as it is expected to enhance social relationships (+46) and increase educational levels (+40). A population increase (+35) is also projected, suggesting that the availability of a new energy source could attract more residents and stimulate economic activity.

Sediment Transportation

As highlighted by Mendoza et al. [63], the installation and operation of WECs can significantly alter sedimentation patterns and benthic habitats. The presence of physical structures on the seabed modifies water currents and sediment transport, potentially resulting in erosion or sediment accumulation in nearby areas. These changes directly affect benthic ecosystems, which host diverse organisms, such as crustaceans, mollusks, and other invertebrates, vital to marine ecological balance. Furthermore, alterations in sediment dynamics can indirectly impact biodiversity, affecting species that depend on these habitats for feeding, reproduction, or shelter. This disruption of essential habitats can trigger cascading effects throughout the marine food web, potentially compromising the long-term health and stability of local ecosystems [63].

Felix and coworkers [68] examine the potential impacts of WECs on marine sediments, emphasizing that the installation of these devices can modify sedimentation patterns and seabed morphology. These changes, primarily driven by the presence of physical structures altering marine currents and sediment transport, may lead to erosion or sediment accumulation in nearby areas. In tropical regions, where marine ecosystems are especially sensitive, these alterations could negatively impact benthic habitats and associated biodiversity, such as coral reefs and invertebrate communities. Although the study does not quantify the level of damage, it stresses the importance of addressing these impacts during the planning and assessment of wave energy projects, particularly in areas with high biodiversity and ecological fragility [68].

Similarly, Zburlea and Rusu [69] explore the potential environmental impacts of wave energy devices on the Black Sea coastal environment. This study underscores that the installation of these structures could alter sedimentation patterns by modifying marine currents and sediment transport, potentially causing erosion or sediment accumulation in surrounding areas. While the study lacks specific quantitative data on the magnitude of these changes, it highlights the need for more comprehensive studies, including in-situ measurements and numerical modeling, to assess the impacts on sediments and develop suitable mitigation strategies. The authors emphasize that these alterations could particularly affect benthic habitats and associated biodiversity, especially in the sensitive ecosystem of the Black Sea [69]. Together, these studies underline the importance of considering sediment transport and benthic habitat alterations when planning and evaluating wave energy projects. A more detailed and holistic understanding of these impacts is essential to mitigate potential ecological risks and ensure the sustainability of marine energy initiatives.

During the operation of an OWC, the presence of a new structure on the seabed causes changes in local hydrodynamics. When an OWC is installed on soft sediments, scouring may occur around the structure, potentially destabilizing it. To mitigate this risk in offshore installations, the structure is typically protected with rock layers or armor. However, these protective measures can lead to secondary scouring, whose extent depends on the sediment properties and local hydrodynamic conditions [58].

Changes in sediment dynamics may induce coastal erosion or sediment deposition, accelerating erosive processes on beaches and contributing to the loss of coastal dunes. Sediment dynamics are influenced by waves, tides, sediment type, and the morphology of the area, making the impacts of wave energy extraction highly site-specific. Therefore, prior to OWC installation, these factors must be evaluated to predict potential impacts caused by its operation [29].

Research has shown that sediment mobility increases in the vicinity of an OWC. Nonetheless, seabed changes are minor, with a magnitude of approximately 0.5%, which is considered insignificant given seabed elevations of up to 5 m [58]. On the other hand, OWCs extract energy from waves, reducing the energy of waves reaching the coast. This results in a decreased erosion rate and sediment transportation. Nonetheless, the reduction in erosion is a localized effect and may not significantly improve the coastal morphology [70].

Advancements in WEC design aim to develop devices that also serve to protect coasts from erosion. This is achieved by leveraging wave shadow zones created by the OWC, which reduces the energy of waves impacting the coastline [58,71]. Additionally, studies suggest that, under storm conditions, wave energy devices may influence sediment transportation both across and along the coast, altering erosion patterns as well as the extent of wet and dry beach zones. Consequently, beach profiles may change [72,73].

In this regard, the alteration of sediment dynamics is considered to have moderate significance, as the impacted area remains confined to the OWC installation site [60].

Noise Generation

The studies conducted by Buscaino et al. and Henriques and collaborators provide complementary insights into the acoustic impacts of WECs, highlighting both the sources of noise and their potential effects on marine ecosystems [74,75]. Buscaino et al. demonstrated that OWCs generate underwater noise, primarily in low frequencies (<1 kHz), which can propagate over long distances and potentially affect sound-sensitive marine species such as cetaceans and fish. While the noise levels from OWCs do not significantly exceed those of existing human activities, like maritime traffic, the study emphasizes that the impact could be more pronounced in quieter marine environments, where species are less adapted to high noise levels [75]. This underscores the importance of site selection and the need for mitigation strategies, such as designing quieter technologies and implementing continuous acoustic monitoring to assess and adapt to long-term impacts.

Henriques et al. further researched the noise generation mechanisms, focusing on the air turbines used in OWCs. They reported noise levels ranging between 90 and 110 dB at 1 m from the source, with higher rotational speeds and aerodynamic interactions (e.g., blade passing frequency and turbulence) being key contributors. Although these noise levels are moderate compared to some industrial sources, they could still pose risks to marine life, particularly in low-noise environments or for noise-sensitive species [74]. The study stresses the importance of optimizing turbine design to reduce noise emissions and calls for further research to better understand the ecological consequences of this noise.

In turn, Hutchison et al. evaluated the noise produced by an inertial seawater energy converter (ISWEC) during its operation [58]. Before the device was installed, the band sound pressure level (BSPL) was correlated with the height of the waves for from 4 to 8 kHz. After the installation of the ISWEC, the BSPL increased and was maintained up to 4 kHz. At a frequency of 63 kHz, the BSPL before the installation was 73 dB, increased to 106 dB after the installation, and, during the operation of the ISWEC, it rose to 126 dB. The increase in noise during the operation was attributed to the flywheel speed, the hydraulic pump, and the gyroscopic units in the device. Furthermore, it was detected that the operational sound was not constant [58]. In this study, the ISWEC sound frequency was found to not be able to overlap with the sound created by snapping shrimp *Alpheidae* sp. However, the sound created by the fish chorus overlapped at frequencies of from 600 to 1100 Hz at which the WEC emitted sound. At 800 Hz, which was the highest frequency at which WEC can emit sound, the fish chorus was masked by the operational sound of the ISWEC when the fishes were 40 m from the device. Therefore, although the noise produced by the ISWEC operation could interfere with the acoustic communication of the fishes present in the installation zone, at 1000 m from the device, the chorus of the fishes increased by 10 dB and was higher than the noise emitted by the ISWEC. Hence, the noise generated by the ISWC was considered to have negligible effects on fish [58].

The noise generated during the operation of an OWC predominantly affects marine mammals, fish, and other aquatic fauna, potentially causing injuries, behavioral changes, and even mortality. Additionally, underwater noise can serve as an orientation signal for pelagic larvae of reef fish and crustaceans [42].

Noise production in OWCs primarily arises from the interaction between waves and the device's chamber, which can induce stress in aquatic organisms and disrupt their behavior, orientation, reproduction, and predator–prey dynamics. In extreme cases, intense noise can cause physical injuries, such as temporary or permanent hearing loss, barotrauma, or death [13,74]. The extent to which marine animals detect and are affected by sound depends on its frequency, which varies by species group [76]. Cetaceans and pinnipeds are particularly sensitive, as they rely on sound for communication and navigation. The impact of increased sound pressure depends on proximity to the source, the type of device installed, and the duration of exposure [57]. On the other hand, studies on noise generated by OWCs suggest that operational noise is less intense compared to that from sonar or ships. However, the noise can still affect cetacean behavior, warranting further research to fully understand these effects [76]. Furthermore, WECs emit very low-frequency sounds, making the noise generated by OWCs barely audible to marine mammals, thereby minimizing the likelihood of significant negative impacts [77].

Loud noises associated with water-based energy devices are typically linked to moving components submerged in water, including hydrokinetic turbines [13]. Since OWCs are equipped with air turbines located above the water surface, their moving parts do not contribute to underwater noise [77]. Nevertheless, further investigation into the noise generated by OWCs is essential to better understand its impacts and to develop effective mitigation strategies. Noise remains one of the most concerning impacts of these devices, highlighting the need for detailed studies in this area [57].

Water Quality Deterioration

Wave energy extraction can change the elevation of water on the surface, the height, magnitude, direction, and frequency of the wave and turbulence, affecting the quality of water and sediment transportation. The zone that is most affected due to these changes is the immediate zone where the OWC operates; the generated effect vanishes with the increase in the distance from the OWC, and, when installed offshore, the effect decreases as the wave approaches the shore [29,58]. Contact with devices external to the natural environment causes the alteration of the flow pattern followed by the ocean currents when they collide with the structures of the OWC. Changes in hydrodynamics can affect the habitat of aquatic organisms and the quality of water [57]. Water quality is affected by the suspension of sediments due to the increase in turbidity and suspended solids, decreasing the dispersion of light in water. The suspension of sediments caused by the change in the flow patterns can release pollutants that were retained in the sediments generating a toxic hazard to living organisms [59,61]. When suspended sediments are easily dispersed, the associated effect is imperceptible provided that the species of the zone and the habitat do not present vulnerability, and the affected area is not large. Species like fish can distance from the zones where suspension of sediments occurs. Fish can temporarily relocate in places where sediments are not suspended or where the suspension is very low. When species are not able to avoid zones with the suspension of sediments, affected individuals can experience changes in their ability to search for food, obstruction, or gill damage and stress [58].

The change in the amount of sediment and the increase in seabed erosion caused by the change in flow patterns can affect organisms, such as corals, which are highly sensitive to changes in their sedimentary habitat. The change in the normal conditions for corals can lead to a decrease in coral cover and reduce the biodiversity of the affected area [57]. Changes in marine energy can influence the transportation of gas, nutrients, and food for some species and interfere with the distribution of other species that depend on the transportation by currents [45]. Additionally, changes in hydrodynamic conditions due to wave energy extraction generate effects on benthic zones, such as sandbanks, which are critical habitats for prey species like sand eels. These changes can trigger processes that cause changes at the population level of protected species with different types of vulnerability in the function of food search and prey characteristics [78].

To ensure the correct operation of an OWC, it is necessary to use hydraulic oils and lubricants in the moving parts of the device. The use of these substances is associated with water pollution due to the risk of oil spills in the ocean [13]. The introduction of hydraulic oils and lubricants into marine ecosystems can generate severe water pollution and negative impacts on aquatic organisms. It has been reported that hydraulic oils and lubricants can coat phytoplankton and algae, blocking the entrance of sunlight and affecting the ability to realize the photosynthesis process [57]. Alteration in photosynthesis can cause a collapse in the marine food chain since algae and phytoplankton are the primary producers and the alteration of their normal life cycle can generate impacts on the higher levels of the food chain.

Marine organisms can colonize OWC structures, causing biofouling that can affect the proper functioning and fluid dynamics of the equipment [58]. In order to reduce biological pollution on the OWC devices, anti-fouling paints are used. However, these paints are harmful to aquatic organisms [13,79]. To reduce the use of these paints and, therefore, their impact on aquatic organisms, it has been suggested that the colonization of the devices should be considered as artificial reefs. The artificial reefs generated by marine energy extraction devices can incorporate food provision and shelter into marine fauna by the creation of de facto marine protected areas (MAPs) [58,80]. Considering conventional mitigation measures, the alteration of water quality due to the spill of hydraulic substances and antifouling paints can be considered moderate and temporal [60].

Electromagnetic Field Generation

When OWCs are installed offshore, the electricity generated must be transported by submarine cables. These cables can generate electromagnetic fields, whose intensity depends on the amount of energy passing through the cable [63]. Some marine species can sense electromagnetic fields. These species use natural geomagnetic fields to orient themselves, navigate long and short distances, locate prey, predators, or conspecifics, and communicate [13,58]. Electromagnetic signals help marine animals navigate to areas with resources of ecological importance and are important for energy, survival, and reproduction success [58]. The generation of electromagnetic fields during the operation of an OWC can alter or hide natural electromagnetic fields and, therefore, interfere with the sensorial and navigation systems of species that use electroreception as rays and sharks. Furthermore, it has been suggested that exposure to electromagnetic fields can induce behavior changes and disturb the motion patterns of some species [57]. Electromagnetic fields associated with the transportation of energy from OWC devices are within the range of marine species' sensibility; hence, potential impacts must be considered [58]. The use of submarine cables is also associated with the increase in sediments and water temperature (mainly in the zones near the cable). It is estimated that the effect is minimal, as the temperature increase is small and only noticed within a few centimeters of the cable [81]. Risk levels associated with exposure to electromagnetic fields are determined by the proximity of the individuals to the source and the duration of the exposure. Rigorous studies are needed to determine the environmental impact and thus develop mitigation strategies to reduce the likelihood of marine species being affected by the generation of anthropogenic electromagnetic fields [57]. In the case of onshore OWCs, as the devices are installed on the coastline, underwater cables are not required and, subsequently, no electromagnetic field is generated during the operation of the OWC, reducing the impact on sensitive species [63].

Fauna Colliding Risk and Side Effects

Another impact associated with the operation of WECs is the risk of marine animals colliding with, becoming entangled with, or trapped in the structures of the devices. Since OWC has fewer mobile parts compared with other WECs, the probability of collision is low [62]. The risk of marine animal collision with OWC devices increases when installed offshore due to the anchoring of the OWC. Anchoring lines present a low risk associated with the collision of aquatic animals; therefore, they are not considered to represent a significant risk to marine fauna. In addition, the risk of entanglement in anchored lines is low due to the high tension needed to maintain the device in the right position. Nevertheless, abandoned fishing nets can entangled in anchored lines and create a hazard to species that get trapped in the nets [58].

Furthermore, offshore WECs have been reported to increase the risk of collision for flying species like birds. Nevertheless, since OWC has a lower profile compared to wind energy devices, the risk of birds colliding with OWC devices is low [82]. As mentioned before, OWCs can act as aggregation sites for fish or MPA, which increases the availability of food for birds. Regardless of the positive impact on marine birds, the formation of fish aggregates can cause the entanglement of birds in the anchoring lines causing injuries or even the death of birds [60]. The risk of collision and entanglement for birds increases as water turbidity around the device increases, reducing visibility. OWCs have air chambers that are partially exposed to the sea. This can pose a risk to marine birds as they may enter the chamber and become entangled. This effect depends on the type of device and can be mitigated by equipping the chamber with a net to prevent access by animals such as birds [82]. The presence of OWCs does not result in avoidance or extreme changes in the distribution of seabirds. The vulnerability of the species differs from the place where the device is operated and from the species that live in the operation zone [29]. When anthropogenic structures are operated in natural areas, contrary to native species, invasive species tend to rapidly colonize structures or zones near the structures. Invasive species colonization, besides affecting marine organisms, can also affect birds, since invasive species can surpass the population of birds. Despite that, it has been established that the presence of invasive species can be beneficial to birds if birds explode the created monocultures [82].

Moreover, the operation of large-scale marine energy devices poses a risk to the migration of mammal species such as dolphins and whales. By blocking migratory routes, marine energy converters can disrupt the natural movement patterns of migratory species, causing disruption to the ecosystem. Blocking migratory routes can reduce reproduction rates by preventing animals from accessing breeding grounds. In addition, blocking migratory routes can affect the search for food and the genetic diversity of populations [57]. These impacts are mainly attributed to tidal energy and offshore wind energy devices. OWCs are installed onshore or, when installed offshore, they are floating devices; consequently, the risk of blocking migratory routes is decreased [57,83]. Additionally, studies have shown that migratory species such as eels reduce their swimming speed when they encounter power cables (which can also affect migration) and continue their regular migration. Therefore, the disruption of migratory routes resulted in a moderate impact [58].

Disruption of Marine Habitat Integrity and Connectivity

During OWC operation, the integrity and connectivity of marine habitats can be disrupted, causing a decrease in nutrient availability and ecological interactions. OWC devices can act as small barriers affecting smaller organism connectivity and generating colonization by larger organisms like cetaceans, fishes, and aquatic birds. The colonization by larger organisms can affect the development of organisms located at lower levels in the marine food chain and cause an imbalance in the ecosystem [63]. When OWCs are installed and operated in zones where no life was present before, the establishment of these structures can become the support for some species transforming the place into a habitable zone. WECs can attract predators, increasing the mortality rate of species that lived in the zone prior to the installation and operation of the devices [13]. OWCs act as artificial reefs and fish aggregation sites, as stated above. This can attract predators higher up the food chain, such as mammals and seabirds, in search of food and can cause an imbalance in the ecosystem. Nevertheless, the creation of artificial reefs is temporary, while other studies have reported that the formation of artificial reefs is not evident during this stage. Hence, it is necessary to conduct specific research in the operation zone of OWC devices to identify the presence of this impact [29].

Even though the impacts generated on aquatic and wild fauna and on water during the operation of the OWC received moderate significance, it is important to consider that these impacts can exacerbate with time. For this reason, in the installation of an OWC, it is necessary to avoid areas with high biodiversity and monitor the arrival of invasive species that can pose a threat to native species life [42,63]. Additionally, it is important to promote specific studies on the zones where OWCs are planned to be installed and operated since the environmental conditions of the zone determine the receptors and the magnitude of the impact. Therefore, it is necessary to have precise reference data to understand the previous and following conditions of the zones where OWCs will be operated [42].

Location Impacts

As mentioned in section Noise Production, OWCs function as fish aggregation zones and are attractive to species like sharks, rays, porpoises, and dolphins due to the availability of food and shelter. For this reason, it has been defined that OWCs do not represent a reduction in the number of inhabitants in an area but serve as a refuge for various marine species such as fish, lobsters, crabs, and crustaceans. Particularly, OWCs mirror rocky reefs and offer habitable structures for marine animals [58]. When OWCs are installed offshore, the devices can provide unique habitats for species in the zone of installation and operation. This helps to increase the diversity of species that settle in the device structures and increase the biomass of benthic communities, contributing to the uniqueness and diversity of the settled communities [84]. An OWC can disrupt the seabed, affecting benthic communities (e.g., benthos, coral reefs, and seagrass). This disruption can promote the arrival of invasive species, resulting in an alteration or loss of biodiversity [42].

The habitat provided by the OWC can alter patterns of connectivity with the natural population adjacent to the device, resulting in changes in population size and genetic diversity, species biogeography, and the structure and functioning of larger ecological communities. In addition, the modification of marine habitats in response to the presence of OWC devices can affect the abundance, behavior, and distribution of some fishes, causing changes in the ecosystem and loss of biodiversity [58]. To reduce the impact generated by the location of OWC devices, it is necessary to conduct prior studies on the location. Those studies will help to avoid areas with high diversity, with the presence of protected or vulnerable species, and areas of migratory routes and zones or breeding. Once the OWC is installed and in operation, monitoring must be done to control the arrival of invasive species that can affect the biological diversity of the zone [42].

Changes in Coastal Activities

Coastal activities affected by the operation of OWC devices are mainly tourism, entertainment, navigation, fishing, and landscape. When OWC devices are installed and operated onshore, the amount of area that can be used for recreation and sports is reduced. WECs that are large and external to the natural environment can interrupt the continuity of the landscape. It has been reported that OWC devices reduce the available area for fishery and for the reproduction of species for human consumption. This creates zones where fishing is not allowed to protect the integrity of the device and the people who practice fishing [63]. Regardless, studies about WEC devices have presented evidence that their installation and operation can benefit local fishing. As a matter of fact, lobsters are species that migrate towards OWC structures, creating nests on the structures where fisheries can easily catch lobsters. To avoid the alteration of fishing and entertainment zones due to the operation of OWC, prior to the installation, consultations with the surrounding communities must be carried out. Hence, the project can be adjusted to the community requests avoiding the alteration of coastal activities derived from the presence of OWC devices [60].

Tourism activities in the zone of operation of OWC devices can also be affected. Studies have reported that communities express rejection towards the installation of energy-harvesting devices in antique towns. Communities consider that these devices can present a negative impact on the landscape and, therefore, affect tourism in the zone and the economy of the population when this relies on tourism. However, it has also been reported that the installation of energy-harvesting devices, like OWCs, is attractive to tourists and people gather in the zone to visit the devices [29]. Hence, impacts on coastal activities must be considered and plans that help in the reduction of the impacts must be created and implemented. Due to the different plans that must be applied to mitigate the impacts generated on coastal activities, the impacts received a moderate to low significance. In addition, it is important to note that impacts on coastal activities are sometimes a matter of the perception of communities surrounding the installation area.

Job Creation

As well as in projects of construction and operation, the operation of OWCs involves an increase in the generation of jobs due to the different specialists required to have a correct operation of the device. For example, specialists in the fields of engineering, maritime construction, biology or oceanography, electricity, electronics, and telecommunications are required. Hence, different job opportunities will be available and can benefit communities located near the installation and operation point of the OWC and communities from distant locations [60]. The increase in job opportunities can improve the quality of life of the people who access the offers and improve the economy of the region where the device is operated [29].

Energy Generation

For the socio-economic category and the energy production aspect, positive impacts of high significance were obtained. Wave energy is characterized by being more predictable than solar or wind energy and has a higher energy density. Therefore, the implementation of an OWC allows for higher energy production in smaller regions, providing access to energy for isolated regions and regions that do not have access to electrical energy services. Furthermore, the installation of OWC devices in remote locations such as islands can help local communities achieve energy independence [85]. Energy generation by the operation of OWC devices can improve the quality of life of populations due to a reduction in the dependence on imported energy resources and the instability of fossil energy prices, as well as a reduction in GHG emissions. Regardless of the socio-economic benefits associated with renewable energies, it has been reported that communities have expressed rejection of having energy-harvesting devices near their properties. Nevertheless, to avoid these kinds of reactions, it is important to involve the communities in the project by using community participation practices, previous consultations (as is needed when the location of a project has the presence of Indigenous communities), education about the type of energy and its benefits, and information exchange [63,86]. Involving the community in the project shows the population the different benefits that they can obtain from the installation and operation of the device, and it also helps to consider the community's ideas, making them active participants in the project [29].

3.2.3. OWC Maintenance

The primary environmental issues during the OWC's maintenance phase stem from soil and water contamination caused by spills of liquids and the release of wash water. Additionally, the impact on aquatic life is considered moderate, as there is a possibility of affecting marine plants and animals in the surrounding area. The assessment of environmental impacts linked to the OWC maintenance activities is detailed in Table 5.

The impacts associated with the maintenance stage of an OWC highlight a range of moderate effects on both the environment and the local economy. During this phase, soil pollution arises due to liquid spillage (−28), contributing to an increase in soil contamination. This reflects a potential risk to the surrounding terrestrial ecosystem, especially if proper containment and spill management protocols are not followed. Additionally, the water component is impacted by the discharge of wash water (−27), which can lead to water pollution through the presence of suspended solids, changes in pH, and contamination from fats and oils. This emphasizes the need for strict regulations to treat wastewater and prevent the degradation of water quality. The maintenance stage also involves water consumption (−24), which could result in water depletion, though its significance is considered low compared to other impacts.

In terms of biotic factors, liquid spillage during maintenance is particularly concerning for aquatic biota. It affects the development of nearshore autotrophic species (−25) and has an adverse impact on both aquatic flora (−28) and aquatic fauna (−28). This disruption could have cascading effects on marine food chains, affecting the overall health of the ecosystem and potentially harming local fisheries. These impacts emphasize the importance of adopting best practices for preventing and managing spills, as well as ensuring that maintenance activities do not introduce contaminants that could alter marine habitats.

From a socio-economic perspective, the maintenance stage is associated with positive impacts, such as job creation (+34) and an overall improvement in the region's economic conditions (+34). These benefits contribute to the economic development of the area, as the maintenance activities require a skilled workforce, which, in turn, can stimulate local employment and raise the quality of life (+35). Although these socio-economic benefits are classified as moderate, they highlight the potential for the OWC to contribute to sustainable regional development. However, it remains important to balance these economic advantages with effective environmental management practices to mitigate the negative effects on the surrounding ecosystems.

Table 5. Impacts ascribed to an OWC maintenance stage.

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Maintenance of an OWC	Physical or abiotic	Soil	Liquid spillage	Soil pollution increase	−28	Moderate
		Water	Wash water discharge	Increase in water pollution (suspended solids, pH, fats and oils)	−27	Moderate
			Water consumption	Water depletion	−24	Low
	Biotic	Aquatic biota	Liquid spillage	Alteration in the development of nearshore autotrophic species	−25	Moderate
				Aquatic flora affectation	−28	Moderate
				Aquatic fauna affectation	−28	Moderate
	Socio-economic	Economic	Job creation	Increase in the development of the zone	34	Moderate
				Increase in the quality of life	35	Moderate
				Improvement in economic conditions on the zone	34	Moderate

Liquid Spill and Job Creation

During OWC maintenance, there is an existing risk of hydraulic oil and lubricant spilling; these fluids are used to guarantee the right operation of the devices. Spilling can occur on the shores or in the water depending on the installation of the OWC (onshore or offshore). Lubricants and hydraulic oils are non-biodegradable substances and, once they are discharged into the environment, persist for longer periods, affecting living organisms that come into contact with the polluted area [87]. Water and soil pollution as a result of the spilling of substances during the maintenance of an OWC can decrease water and soil quality and generate mortality in species that live in the contaminated area [88]. Furthermore, lubricants create a film on the surface of water, blocking the entrance of light, causing the restriction of the photosynthesis process, and decreasing the dissolved oxygen concentration affecting the life of marine species [89]. Despite the impacts that can arise with the spilling of hydraulic substances, environmental impacts received low to moderate significance, since contingency plans must be followed to take immediate actions and reduce the impacts when these accidents occur [60].

On the other hand, during the maintenance of OWC devices, qualified staff must be present to guarantee the correct operation of the OWC. Therefore, as defined in the Job Creation section, the demand for qualified personnel will open vacancies that can be covered by people from the region to decrease the unemployment rate.

3.2.4. OWC Disassembly

Table 6 provides an overview of the EIA related to the OWC decommissioning stage.

The decommissioning stage of an OWC involves several moderate environmental impacts that need to be carefully managed to minimize long-term consequences. During the disposal of materials, there is a potential for soil pollution due to the transportation of materials (−28), and the decommissioning of the OWC itself could lead to permanent changes in soil morphology after the installation and operation of the structure (−43). These impacts reflect the difficulty in restoring the land to its original condition, highlighting the need for careful planning and mitigation measures during the decommissioning phase to reduce the alteration of the surrounding landscape.

In the air component, there is an increase in noise generation (−36) during dismantling, as well as an increase in PM and CO_2 emissions due to the transportation of materials (−34 and −32, respectively). These impacts indicate the environmental cost of the decommissioning process, which involves substantial vehicle use, increasing both air pollution and noise levels. Given that these impacts were classified as moderate, it is crucial to consider the implementation of technologies and strategies that can reduce emissions and noise pollution during the dismantling of the OWC.

The water component is also impacted during decommissioning. There is an increase in ocean water pollution due to wash water discharge (−29) and liquid spillage (−30), as well as the potential for oil spillage (−31) during the turbine deinstallation. These activities contribute to the deterioration of water quality, highlighting the need for stringent safeguards to prevent pollutants from contaminating marine ecosystems. In this context, proper handling, disposal, and containment systems are essential to mitigate these environmental risks.

The landscape is also affected, with lasting alterations remaining even after the OWC has been dismantled (−41). However, there is some potential for landscape recovery over time (+33), indicating that the environment may gradually return to its original state after decommissioning. This balance between alteration and recovery demonstrates the importance of planning for eventual restoration and ecological regeneration once the OWC is no longer in operation.

Table 6. Impacts ascribed to the decommissioning stage of an OWC.

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Desmantling of an OWC	Physical or abiotic	Soil	Disposal of materials	Transport of material	−28	Moderate
			Desmantling of the OWC	Permanent changes in soil morphology after installation and operation of the OWC	−43	Moderate
		Air	Noise generation	Increase in sound levels during desmantling	−36	Moderate
			Alteration of coastal activities	Increase in particulate emissions due to the increase in the number of vehicles used to transport materials during the desmantling process	−34	Moderate
				Increase in CO_2 emissions due to the increase in the number of vehicles in the area to transport materials during dismantling	−32	Moderate
		Water	Water consumption	Water depletion	−15	Low
			Wash water discharge	Increase in ocean water pollution	−29	Moderate
			Liquid spillage	Increase in ocean water pollution	−30	Moderate
			Turbine disassembly	Oil spillage	−31	Moderate
		Landscape	Location/sitting of the OWC	Lasting alterations that remain in the landscape after the installation and operation of the OWC	−41	Moderate
				Landscape recovery to some extent	33	Moderate

Table 6. *Cont.*

Activity Susceptible to Generating an Impact (ASPI)	Environmental Factor Susceptible to Be Impacted (FARI)	Component	Environmental Aspect	Environmental Impact	Average Score	Impact Significance (I)
Desmantling of an OWC	Biotic	Wild biota	Desmantling of the OWC	Persistent disturbance to the terrestrial biota remaining after the period of installation and operation of the OWC	−29	Moderate
				Wildlife recovery	31	Moderate
		Aquatic biota		Marine life recovery	32	Moderate
				Persistent disturbance to marine biota remaining after the period of installation and operation of the OWC	−29	Moderate
	Socio-economic	Economic	Desmantling of the OWC	Unemployment increase	−35	Moderate
				Fuel consumption for material transport	−39	Moderate
				Job creation	27	Moderate
				Growth in demand for materials handling equipment	26	Moderate
				Reduction in the accessibility of the service	−45	Moderate
				Reduction in economic conditions of the zone	−37	Moderate
		Demographic	Desmantling of the OWC	Population decrease	−30	Moderate

From a biotic perspective, the terrestrial biota may experience persistent disturbance after the OWC operation ends (−29), though there is potential for wildlife recovery (+31). Similarly, marine biota can face continued disturbance after the OWC decommissioning (−29), but marine life recovery is also possible (+32), reflecting the resilience of ecosystems in response to decommissioning activities. These impacts emphasize the need for careful management to allow for ecological recovery once the facility is decommissioned.

On the socio-economic part, the decommissioning phase may lead to an unemployment increase (−35) as workers in the OWC facility lose their jobs, while fuel consumption for material transport (−39) represents a notable economic and environmental cost. Nevertheless, there are also positive socio-economic impacts, including job creation (+27) and growth in demand for materials handling equipment (+26). Additionally, reduced accessibility to the service (−45) and a decline in economic conditions (−37) in the region are anticipated as the OWC ceases operation, which could lead to a downturn in the local economy. These impacts underscore the importance of planning for the socio-economic consequences of decommissioning, such as ensuring a transition strategy for workers and developing new economic opportunities in the region.

Finally, from a demographic standpoint, the population decrease (−30) associated with the decommissioning of the OWC may reflect the loss of local employment and reduced economic activity. As the region loses the OWC benefits, it could lead to population migration and shifts in local demographics.

Material Disposal

Due to the specificity of the parts, the recycling of the dismantled structures is a complicated process [13]. It has been reported that dismantled structures are stored in places where there is no landscape interest to have a minimal effect on the disposal of the structures. Impacts caused by the disposal of materials received moderate significance, since, among the different plans that must be elaborated during the planning of a project, plans to mitigate or reduce the impacts generated during the disposal should be considered [60].

Water Pollution

During the dismantling of the OWC device, water quality can be affected, and sediments can be suspended due to activities like the anchor line or submerged cable removal. Suspension of sediments can cause the release of toxic substances that were adsorbed into the sediments and reduce sunlight penetration. As defined in the section Construction and Installation of the OWC, dispersion of suspended sediments is a fast process; hence, the generated impact is moderate. Sediment suspension during the dismantling of energy transport cables causes disruptions in benthic communities. However, benthic communities recolonize the area in a rapid way, and no significant impacts are generated in the ecosystem [60]. In the dismantling activities, the spilling of lubricants and hydraulic oils can occur and affect the quality of water [13]. Contingency plans for hydraulic fluids during dismantling must be considered to reduce the risk associated with the spillage of toxic substances.

Noise Generation and Habitat Alteration

Due to the noise generated during the dismantling of OWC devices, fish and mammals distanced from the place to avoid being affected by the increased noise levels. Nevertheless, fish and mammals return to the place once the noise disappears as mentioned in the Noise Production section. The dismantling of OWCs is considered to be an activity with moderate impacts on the loss of habitat due to the mitigation plans that need to be elaborated. It is expected that the loss of habitat will be reduced once the devices are dismantled since environmental conditions return to their initial stage before the installation of the

OWC [82]. The dismantling of the devices causes the removal of the artificial reef generated in the structures. This can affect the species that arrive at the place to search for food. Moreover, the dismantling of the OWC can eliminate shelter zones. For these reasons, partial dismantling of the structures has been proposed to protect the artificial reefs created by the marine biota inside the devices [90].

Job Loss

The dismantling of the OWC and the finalization of its operation produce the elimination of jobs created for construction, operation, and maintenance. Increasing the unemployment rate and decreasing the accessibility to energy for the population that benefited from the operation of the energy device. Despite this, it is important to highlight the fact that well-structured dismantling plans provide sustainability to the deployment of energy-harvesting devices as they guarantee the restoration of the impacted area, provide compensation for the non-mitigable impacts generated, and pave the way for the installation of devices that allow the permanent connection to the energy service for the community [90].

Atmospheric Damage

As in the construction phase, impacts on the atmosphere are related to the use of transport. In the dismantling stage, the transportation of the OWC part to the disposal site and the transportation of the staff responsible for the dismantling of the device occurs. During dismantling, impacts on the air are temporary and with moderate significance [60].

Compared to the combustion of fossil fuels, wave energy harvesting generates lower impacts on climate change, ionizing radiation, environmental deterioration, and water depletion. Therefore, to achieve sustainable development, the application of renewable energy, like the use of OWCs, must be considered [91].

The design and installation, operation, maintenance, and dismantling of an OWC present an impact mainly with moderate significance due to the characteristics of this type of technology. Nevertheless, information about the impacts generated by large-scale OWC projects is still uncertain due to the current stage of research on these devices. Considering the potential of these types of energy-harvesting devices, it is imperative to evaluate these technologies, especially in zones with no interconnection. This can facilitate access to electricity for different communities and generate an impact on sustainable development and climate change.

It is important to carry out studies on the environmental impact generated by the operation of an OWC device to demonstrate the benefits to the community and accomplish the acquired obligations presented to the community. Communication, education, information exchange, public practices participation, and the avoidance of expensive economic projections can increase the acceptance of renewable energy by communities. Energy-harvesting devices, such as OWCs, compete for space with aquaculture, fisheries, platforms for the transportation of hydrocarbons and gas, and marine protected areas. Therefore, integral research must be elaborated to have a full understanding of the impacts generated by OWC projects. Advances in understanding the potential environmental impacts will be needed to enable the deployment of these technologies and make renewable energy production a reality around the world [58].

3.3. Mitigation Measures Across the Different Stages of an OWC Lifecycle

During the EIA of the OWC, critical parameters have been identified that exhibit varying degrees of sensitivity, influencing the environmental performance at each stage of the OWC lifecycle: design and installation, operation, maintenance, and decommissioning.

For instance, in the design and installation phase, parameters such as soil morphology changes, sediment transport, and machinery spills were identified as highly sensitive and capable of causing moderate impacts on the environment. The sensitivity of these parameters suggests that careful attention should be given to construction techniques that minimize excavation and avoid contamination from machinery spillage. Mitigation measures, like employing erosion control methods and implementing effective waste management practices, would significantly reduce the environmental impacts, particularly those related to soil disruption.

In the operation phase, the sensitivity of water quality parameters, such as suspended sediment levels, wave intensity, and water pollution, highlights the importance of mitigating measures to protect marine ecosystems. Since these parameters directly affect the OWC performance and long-term viability, mitigating water quality impacts through sediment management, water filtration, and resource extraction limitations is essential. These measures not only help maintain ecological balance but also ensure the system's operational efficiency over time.

During the maintenance stage, the sensitivity of parameters like liquid spills and water consumption further underlines the need for proper maintenance practices to minimize environmental damage. Appropriate management of waste discharges and spill prevention systems can significantly reduce the risk of long-term ecological harm, especially to aquatic biodiversity. The implementation of such mitigation strategies is essential to ensure that the OWC maintenance activities align with the broader environmental goals of the project.

Finally, in the decommissioning phase, impacts such as landscape alteration, wildlife recovery, and increased emissions from material transport were identified as sensitive parameters. Mitigating the long-term effects of these impacts involves strategies like controlling emissions, promoting the recovery of local ecosystems, and ensuring that material disposal practices minimize soil and water contamination. These mitigation efforts are crucial to avoid potential ecological and social disturbances during the decommissioning process, ultimately ensuring that the OWC lifecycle concludes with minimal adverse effects.

The following are some proposed mitigation measures to address the impacts identified at each stage of the OWC lifecycle, aiming to reduce negative effects and promote the sustainability of implementing an OWC system.

During the design and installation phase, proper site selection can significantly reduce the need for soil excavation and erosion, while the careful management of construction materials and equipment can prevent accidental spills that might lead to soil or water contamination. Furthermore, measures to reduce landscape alteration, such as careful consideration of the installation positioning to avoid sensitive ecosystems, are essential for preserving biodiversity and minimizing ecological disruption.

In the operation phase, the primary focus shifts to monitoring and controlling potential ongoing environmental impacts. Strategies to mitigate water pollution include the use of advanced filtration systems to prevent suspended solids, oils, and other pollutants from entering the marine environment. Additionally, minimizing alterations to wave intensity and velocity, which can impact coastal ecosystems, is crucial. Technologies that reduce noise pollution, like quieter machinery or noise barriers, should be implemented to protect marine fauna from harmful sound exposure. Another critical mitigation strategy is the protection of marine life, particularly through the creation of conservation areas around the OWC installations, which help to maintain biodiversity and allow for the natural regeneration of aquatic species.

During the maintenance phase, mitigation measures must focus on reducing the impacts of waste and water consumption. One effective strategy is the recycling of wastewater generated during maintenance activities, which can prevent further contamination of the surrounding water bodies. Moreover, implementing best practices for minimizing liquid spillage during maintenance work and ensuring the safe disposal of hazardous materials are crucial steps to safeguard both terrestrial and aquatic biota. Regular monitoring of water quality and the health of surrounding ecosystems also helps to identify and address potential issues before they become severe.

Finally, during the decommissioning stage, ensuring the recovery of the landscape and the minimization of lasting environmental effects is key. Restoration efforts should focus on returning the site to a condition as close to its original state as possible, with careful attention to soil recovery and the removal of any residual pollutants. Reducing the carbon footprint during the dismantling process is also essential, which can be achieved through optimized transportation methods to decrease emissions from vehicle use. Socially, the transition of the workforce to new opportunities is an important factor in minimizing the socio-economic impacts of decommissioning. Implementing job retraining programs and ensuring the continuation of local economic activity are integral strategies to support communities through the end of the project's operational life.

By incorporating these measures, each stage of the OWC lifecycle can be managed in a way that minimizes its environmental footprint and maximizes its positive contributions to renewable energy development. With effective mitigation strategies, the OWC can maintain its role as a sustainable energy technology, reducing its impacts while contributing to global energy goals.

4. Conclusions

The analysis of the impacts associated with the different stages of an OWC, from its design and installation to its maintenance, operation, and decommissioning, reveals a series of physical, biological, social, and economic consequences that require proper management to mitigate negative effects. In the design and installation phase, several impacts were identified, such as changes in soil morphology, machinery-related pollution, and changes in wave intensity and velocity. For example, in the case of site preparation for OWC construction, alterations to the land morphology received an average score of −34, indicating a moderate impact. This impact was due to soil excavation and erosion, which caused alterations to the local geography. However, the change in wave velocity and other effects from construction showed lower impacts, with scores of −23 and −25, respectively, suggesting that the effects, while present, are relatively minor.

In the operation phase, it is noteworthy that the most relevant impacts include alterations in sediment patterns and water pollution. The impact on sediments during operation, such as changes in sediment transport patterns, received an average score of −35, indicating a moderate impact. This change could alter both water quality and habitat for marine species. Additionally, increased water turbidity (−28) and marine pollution (−26) are key concerns that require control and monitoring measures. Nevertheless, impacts on marine species and aquatic fauna were moderate, with scores like the alteration of marine fauna migratory processes (−30) and disruption in the development of nearshore autotrophic species (−32).

The maintenance phase also presents several moderate impacts, such as the increase in pollution from liquid spills and water consumption. Liquid spillage during this phase caused an impact on aquatic species, with an average score of −28. Furthermore, the impact related to wash water discharge (−27) is significant in terms of water pollution due to suspended solids, fats, and oils. Water consumption during maintenance also represents a low impact, with a score of −24, which indicates a minor risk to water resources but is still important.

Finally, in the decommissioning phase, the impacts related to landscape alteration and permanent changes to soil morphology stand out as the most significant consequences. OWC decommissioning and permanent changes in soil morphology received a score of −43, indicating a moderate and long-lasting impact. Other important effects in this phase were the increase in CO_2 emissions due to material transport, with a score of −32, and increased noise pollution during the decommissioning process, with a score of −36. However, some effects were positive, such as landscape recovery (+33), suggesting that the negative impact of decommissioning is, to some extent, offset by the regeneration of the affected area.

On the other hand, the design, installation, operation, maintenance, and decommissioning of an OWC offer significant benefits to local communities. By deploying these energy-harnessing systems, electricity can be delivered to remote or off-grid areas that previously lacked access to electrical power. Furthermore, the implementation of an OWC system can mitigate the environmental impacts associated with fossil fuel use, such as GHG emissions and water resource depletion. Additionally, providing electricity to isolated or off-grid regions can have transformative effects, such as improving educational outcomes by enabling more children to attend school. These systems not only address energy access challenges but also contribute to broader social and environmental sustainability goals, particularly in underserved areas.

This study provides a holistic understanding of the direct and indirect effects of OWC implementation, enabling the development of strategies to mitigate negative impacts while maximizing benefits. The findings are intended to inform future decision-making and promote the sustainable integration of OWCs into coastal environments for electrical energy generation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17072996/su17072996/s1, File S1: Conesa's matrix applied to an OWC design, manufacture, operation, maintenance and disassembly phases is presented.

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