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Review

Marine Renewable Energy Resources in Peru: A Sustainable Blue Energy for Explore and Develop

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Abstract: The Peruvian coast covers more than 3000 km along the Pacific Ocean, being one of the richest seas in terms of biodiversity, productivity, fishing, and renewable energy potential. Marine renewable energy (MRE) in both offshore and coastal environments of Peru is, currently, a huge reserve of practically unused renewable energy, with inexhaustible potential. In this context, renewable energies from hydroelectric, biomass, wind, and solar sources have been applied in the country, but geothermal, waves, tidal currents, and tidal range sources are currently underdeveloped. This article presents the enormous source of sustainable blue energy for generating electrical energy that exists in Peru from waves and tidal resource potential. In addition, this article presents the main opportunities, gaps, and key issues for the implementation of marine renewable energy (MRE), with emphasis on: (i) showing the available potential in the northern, central, and southern Pacific Ocean territories of Peru, (ii) characterizing the marine energy best available technologies to implement, (iii) the environmental and socio-economic impacts of marine renewable energy, and (iv) discussion of challenges, opportunities, and future directions for developments in the marine energy sector. Finally, the article concludes that the greatest possibilities for exploiting the abundant marine renewable energy (MRE) resource in Peru are large spaces in both offshore and coastal environments on the Pacific Ocean that can be considered for harvesting energy. These issues will depend strongly on the implementation of regulations and policies for the strategic use for planning of marine resources, encouraging research and development (R&D) for creating sustainable innovations, incentives for project finance mechanisms, and developing specialized local human capital, considering the sustainability of livelihoods of coastal communities and ecosystems.

Keywords: marine renewable energy; sustainable blue energy; waves; tidal; Pacific Ocean; sustainability

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1. Introduction

1.1. Problem of Water Scarcity, Population Concentration and Need for Energy Supply in Coastal Areas

Peru has a very diverse geography, recognized worldwide, where three large areas can be classified: coast, sierra, and jungle. The majority of the population is concentrated in the coastal area, where the cities of Trujillo, Chiclayo, and the capital Lima stand out. Around 11 million inhabitants live in the latter, corresponding to a third of the total population. It is important to mention that Peru's ecosystems are diverse, with the desert in the coastal area, the Andes mountain range in the sierra area, and the Amazon in the jungle area [1]. It is in the coastal area, in the middle of the desert, where the inhabitants of the aforementioned cities carry out their daily activities, generating water stress in the watersheds. For example, Huanchaco Beach, located in a coastal environment close to Trujillo city, suffers the negative effects of climate change and water stress of watersheds (Figure 1).

Figure 1. Panoramic view of Huanchaco Beach, a coastal environment close to Trujillo city, Peru.

These inhabitants require water for various activities, including agriculture, livestock, mining, fishing industry, residential use, recreational use, and commercial use, among others. This fresh water is extracted mainly from surface water or groundwater from different rivers, for example, from the Chillón, Rímac, and Lurín rivers in the case of metropolitan Lima [2].

The key issue is that the water resource supply from river basins is being subjected to such stress that it will not be able to satisfy the entire population's demand in the coming decades [3]. More people are expected to migrate to the large coastal cities, increasing the urban population, and the demand for water for services will increase, thus generating periods of shortage of drinking water for people. It is known that the majority of people who migrate to the large coastal cities of Peru from the sierra or the jungle do so with scarce economic resources, and must build their homes informally and provide themselves with water in some way; in some cases, these people do not have drinking water or sewage services [4].

Another important aspect to mention that exacerbates the water stress of the hydrographic basins of the Pacific Ocean basin is climate change [5]. It is known from technical–scientific studies that the tropical glaciers in Peru's mountainous area are melting rapidly and are expected to disappear in the coming years [6]. The water from these glaciers feeds the aquifers and rivers of the hydrographic basins where different coastal cities of Peru satisfy their demands for water resources. Since the glaciers are located at the head of the hydrographic basins that supply the large coastal cities of Peru, it is expected that the supply of water resources will decrease substantially [7].

On the other hand, the ENSO phenomenon affects the weather conditions of these cities from time to time during the summer months, when rainfall occurs in the coastal area, which is a desert, causing mudslides or avalanches [8]. These avalanches cause the water in the rivers to increase its level of suspended solids and the flow to turn into mud, which prevents the drinking water treatment plants from being able to supply water to the population [9]. Suspensions in the supply of drinking water in the city of Lima due to this phenomenon have been recorded for several days, which are expected to happen again in the future [3,10].

1.2. Opportunities for Seawater Desalination and the Introduction of Marine Energy to Solve Current Difficulties

In this sense, alternatives must be explored and analyzed to solve the present and future context of water stress in the watersheds that supply coastal cities in Peru. An interesting alternative is the implementation of seawater desalination plants. Peru has a 3000 km coastline where it has the privilege of accessing different ecosystem services in the sea, and thus promotes a large number of activities such as fishing, sports (surfing and sailing), tourism, and gastronomy, among others. The use of desalinated seawater as a water resource for the inhabitants of coastal cities is an opportunity that can solve the current water stress [3].

Providing the implementation of infrastructure for seawater desalination plants requires designing seawater capture systems, providing pretreatment systems, installing reverse osmosis systems, designing hydraulic pumping systems, and designing a discharge system for the brine generated on the seabed.

These infrastructures also require the supply of energy, since the separation of water from sea salts through reverse osmosis and hydraulic pumping systems require it. Currently, in the coastal area of Peru, there are power generation plants using fossil fuels, such as thermal power plants using coal, oil, and natural gas [11,12]. This is where a great opportunity arises to provide clean, abundant, and always present energy to supply seawater desalination systems; we are talking about marine energy. Although Peru is known to have a green energy matrix, as it has a significant number of hydroelectric plants in the sierra region, the runoff flows of the rivers where these energy-generating infrastructures are located may be affected by the impacts of climate change; through modification of rainfall patterns, the presence of droughts, and considering the disappearance of glaciers. This can considerably alter the levels of energy supply for the different demands of human activities in the territory [13].

Peru can take advantage of the generation of electricity from renewable marine energy, both from waves and tides. If marine energy is supplied to seawater desalination plants, sustainability will be promoted, since: (i) the energy source will be renewable, (ii) the population will be supplied with drinking water for its services and different uses in the territory, (iii) water stress in the basins will decrease [14].

Implementing marine energy infrastructure at sea and on the coastline can promote the development of a blue economy that encourages the sustainability of the territory, helping different communities that inhabit the coast to develop different activities such as: (i) artisanal fishing, (ii) community-based experiential tourism, (iii) electrifying different towns and localities, (iv) reducing dependence on electric energy from fossil fuels, (v) construction of new ports that help the local economy and international exchange, (vi) promoting scientific and technological development for the study and testing of pilot systems for generating electric energy from marine energy sources, and (vii) transforming Peru into a world example of being a promoter of the insertion of marine energy [15].

According to a scientific study on global wave potential, the coasts of Peru have, on average, a renewable marine energy potential in the range of 20–25 kW/linear meter of wave in the 3000 km of coastal environments [16] (Figure 2). This represents an intermediate range of potential for the generation of electric energy through waves at a global level.

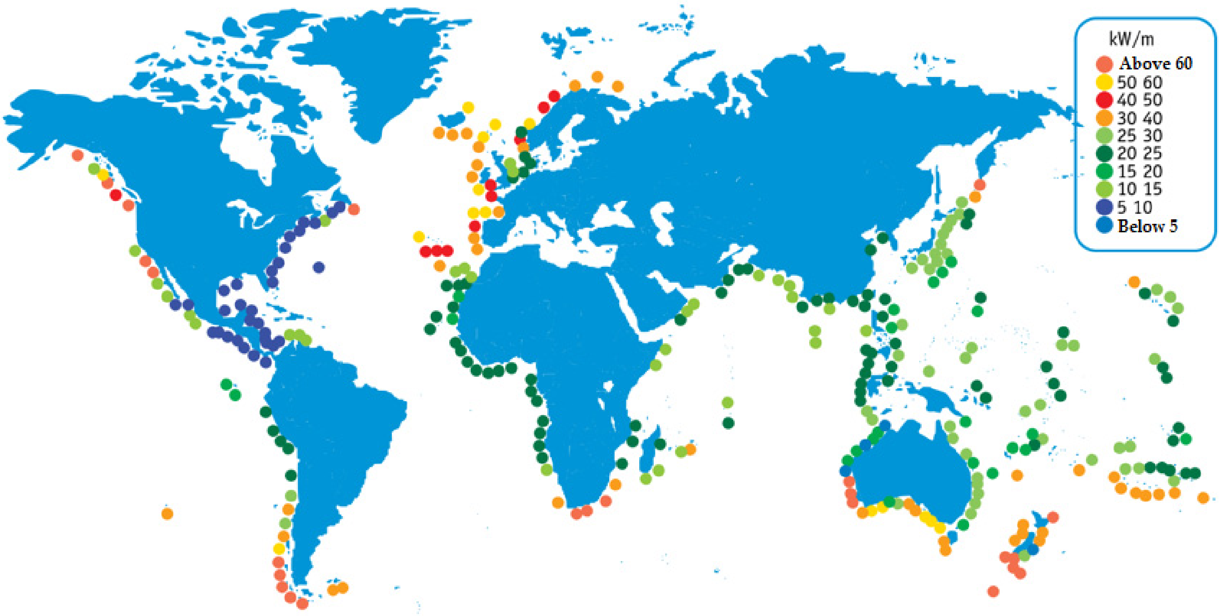

Figure 2. World map of density of waves, including the case of Peru.

Although the use of marine energy is promising, as of today in the year 2024 the implementation of marine energy infrastructures is still scarce worldwide [17]. Thus, hydroelectric energy is the most popular and cheapest renewable energy worldwide, followed by solar energy and wind energy, where efficient and increasingly economical technological systems have been developed in the last two decades. In intermediate places, we have renewable energy from biomass and geothermal energy (See Table 1). Finally, in last place is marine energy, where technological development stands out and the countries of Scotland and the United Kingdom are betting on this renewable energy source [18].

Table 1. Insertion of renewable energies worldwide in 2021.

Type of Power	Installed Capacity (GW)	Share of Total Installed Renewable Electricity Capacity (%)
Hydropower	1230.0	40.1
Solar Energy	849.5	27.7
Wind Energy	824.9	26.9
Bioenergy	143.4	4.7
Geothermal Energy	16.0	0.5
Marine Energy	0.5	0.02

The ongoing global energy transition seeks to establish a sustainable and secure global supply for human activities. While most attention has been directed towards inland systems, promising blue economy markets (BEMs) in coastal and offshore environments, ranging from offshore aquaculture to seawater desalination and green hydrogen production, will require increased energy supply to meet their projected growth [19–21]. Whether it is powering sensors or the electricity demand of electric ships, energy needs must be met with sustainable solutions, both from an economic and environmental perspective. To this end, several marine renewable energy (MRE) sources can provide suitable on-site options, at acceptable costs, while promoting energy independence for BEMs [22,23].

1.3. Aim of the Article

This article seeks to promote a sustainable alternative for the development of communities living in the coastal area of Peru. In this sense, the paradigm of a green economy based on the water and marine energy resources of the 3000 km of coastal environments that Peru has is presented to sustain markets with activities linked to the sea such as: artisanal fishing, industrial fishing, cultural and community development, port activity, tourism, urban activities, and rural activities, among others. For a correct understanding, the article is divided into the following sections: (i) Introduction, (ii) marine renewable energy potential in Peru, (iii) best available technologies for the insertion of marine renewable energy in Peru, (iv) evaluation of environmental and socioeconomic impacts of marine renewable energy in Peru, (v) discussion on challenges, opportunities, and future directions, and (vi) conclusions.

2. Potential of Marine Renewable Energy in Peru

2.1. Potential of Wave Energy

Peru's territory has 3000 km of open coasts facing the Pacific Ocean, with a high energy potential at an average range of 20–25 kW/m of linear waves. Peru's coastline is generally open to the Pacific Ocean, with some bays. Still, there are a few fjords or islands, and mainly small islands can be found in well-located places in the territory, such as the Ballestas Islands in the Ica region [24].

The movement of the waves in Peru is recognized worldwide for the sport of surfing. The country has outstanding athletes who are born and train in different places along its coast to compete at a global level. In the same way, many international championships are held in Peru as part of the world circuit and Pan American games.

Peru is also known for the magnitude and intensity of its waves, due to the presence of tidal waves or tsunamis from time to time every few years, where earthquakes occur due to being in a meeting zone of tectonic plates such as the Nazca tectonic plate and the South American tectonic plate. When earthquakes have their epicenter in the Pacific Ocean and have a magnitude greater than 7, tidal waves or tsunamis usually occur that flood and negatively impact the coastline with wave heights of 5 m, 10 m, and 15 m, inclusive. The presence of tsunamis is manifested through a high-rise wave train system that enters the bays with great amounts of energy and force, destroying everything around them. Even tsunami waves enter through river mouths against the current of the river upstream, managing to enter several kilometers into the river, flooding urban and rural areas [14].

Another important aspect to highlight in the characteristics of the Pacific Ocean waves on the coasts of Peru is regarding the marine currents of El Niño (ENSO) and Humboldt or Peruvian Current that interact in the marine waters of Peru. The current called El Niño (ENSO) is a marine current of warm waters that travels throughout the Pacific Ocean. When it reaches the coasts of Peru it does so in a north-to-south direction. In contrast, the current called Humboldt or Peruvian Current is a marine current of cold waters that moves from Antarctica and usually does so in a south-to-north direction. Considering this background, it is clear that the meeting of these two marine currents in the Pacific Ocean conditions the temperatures of its waters, in addition to regulating the climate of Peru [8,9].

The following thematic map, Figure 3, presents the potential of waves to generate electricity along the entire coast of Peru.

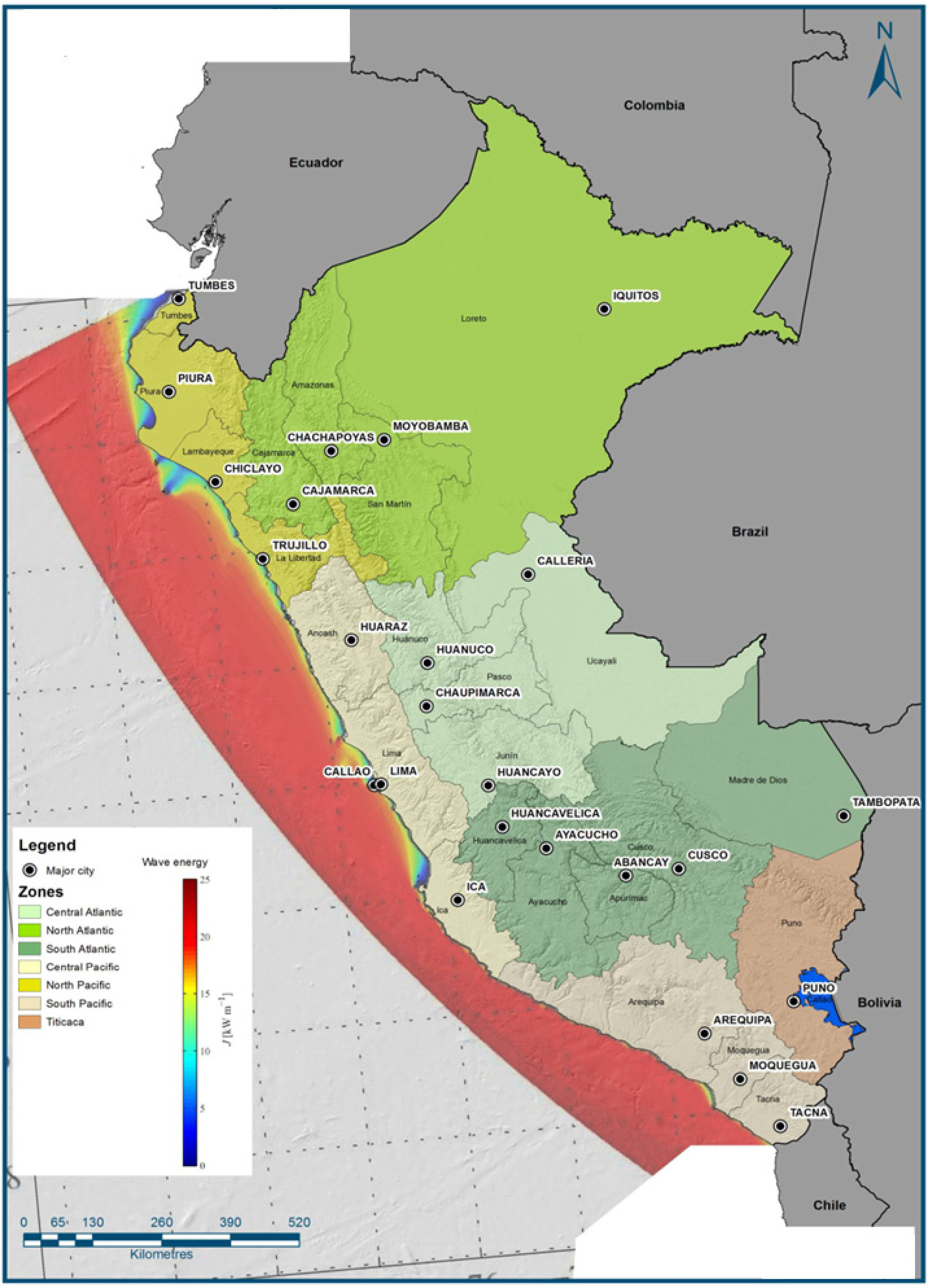

Figure 3. Potential of wave energy in Peru—offshore and coastal environment zones (kW/m).

In Figure 3, it can be seen in red that the potential for marine energy from waves is of the order of 25 kW/m along the entire Peruvian coast in the open sea [25]. A decrease in the potential for energy from waves can be seen in the Bay Area, such as the sectors of Paracas, Callao, Chiclayo, Piura, and Tumbes.

Figure 4 shows the potential for marine energy from waves in the northern Pacific Ocean area off the coast of Peru.

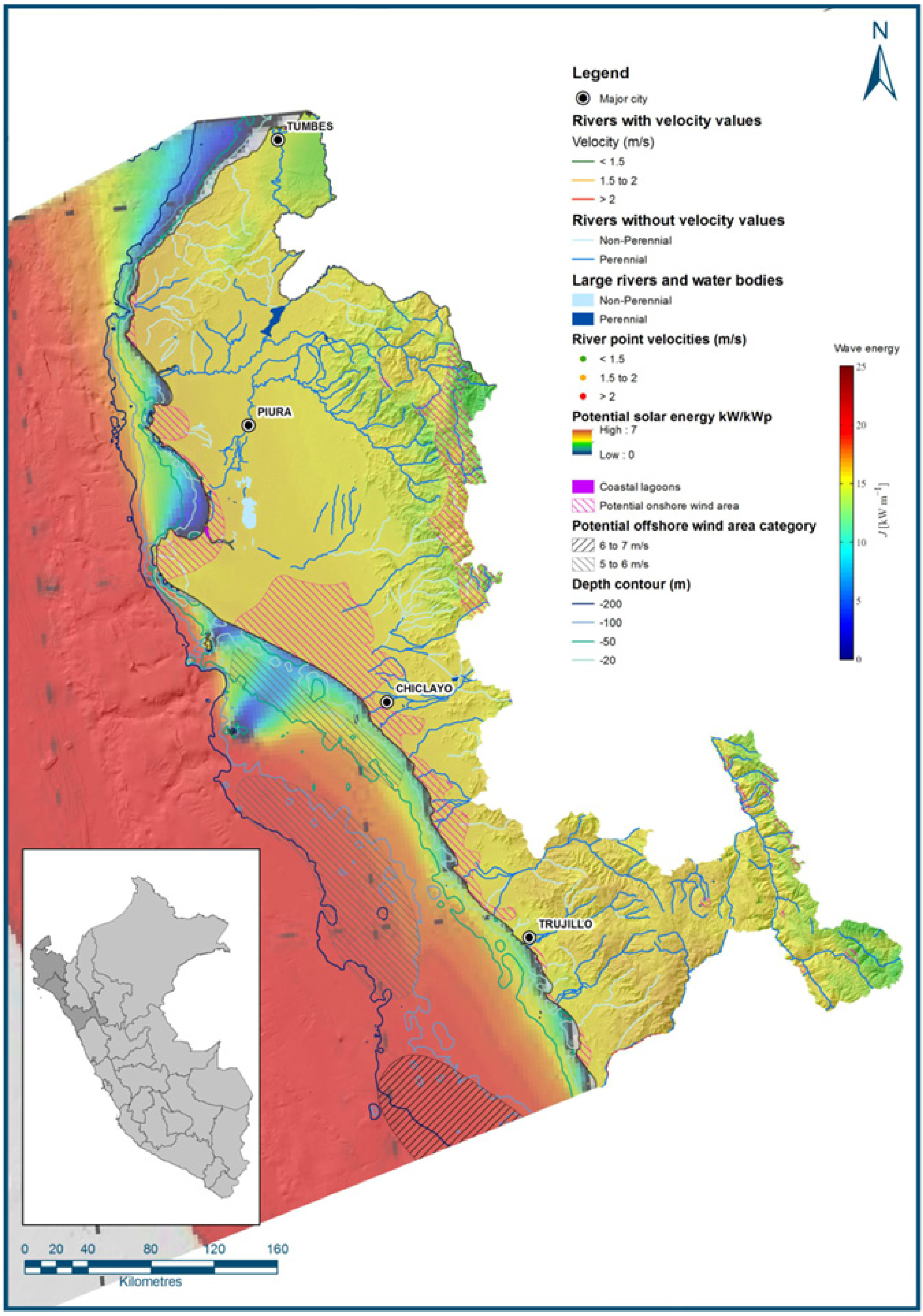

Figure 4. Potential of wave energy in Peru—north Pacific Ocean zone waves resource map (kW/m).

In Figure 4, it can be seen in red that the potential for marine energy from waves is of the order of 25 kW/m along the entire Peruvian coast in the open sea [25]. A decrease in the potential for energy from waves can be seen in the bay area, such as the sectors of Tumbes and Piura, but with high potential on the coasts of Chiclayo and Trujillo.

Figure 5 shows the potential for marine energy from waves in the central zone of the Pacific Ocean off the coast of Peru.

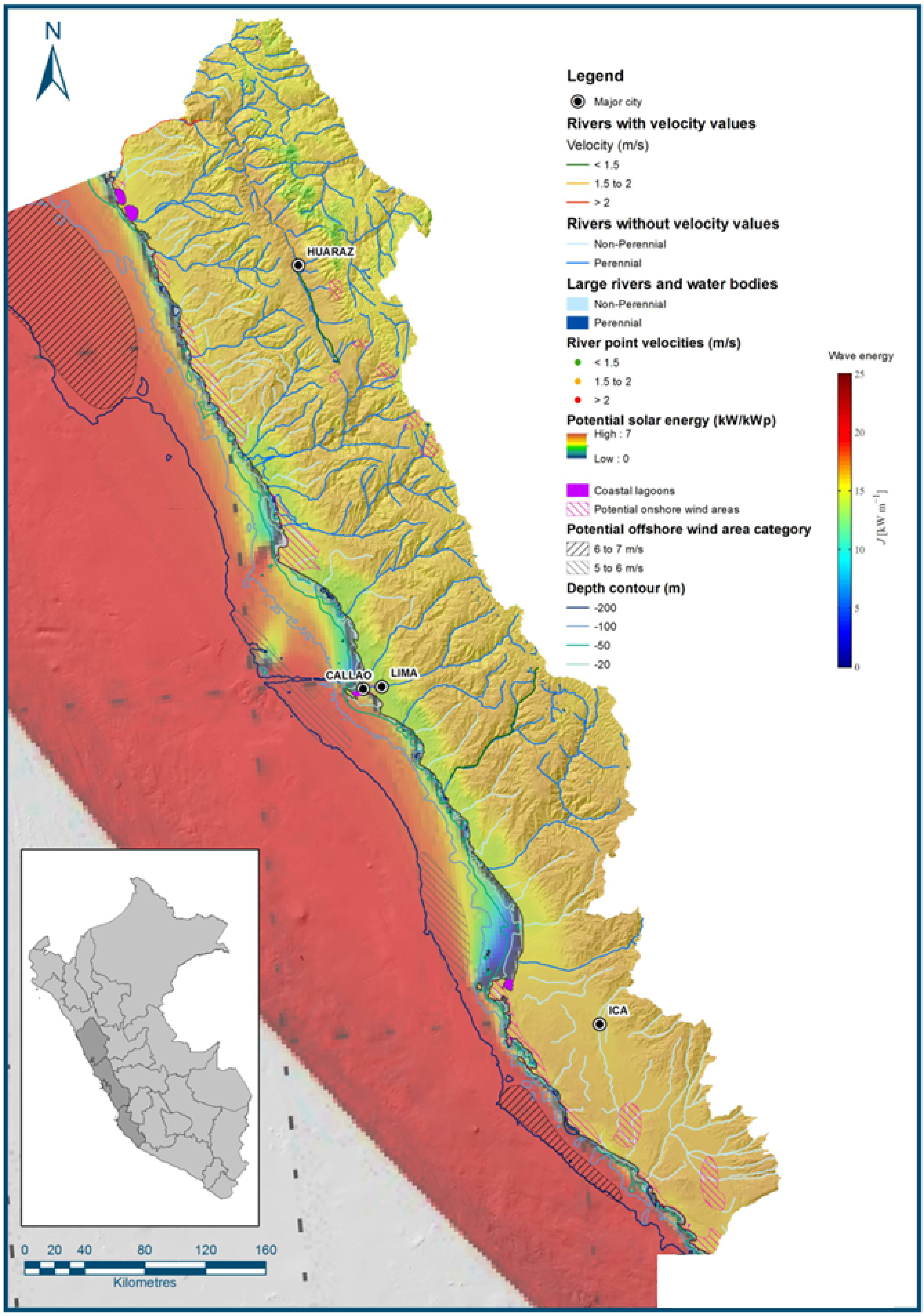

Figure 5. Potential of wave energy in Peru—central Pacific Ocean zone waves resource map.

In Figure 5, it can be seen in red that the potential for marine energy from waves is of the order of 25 kW/m along the entire Peruvian coast in the open sea [25]. A decrease in the potential for energy from waves can be seen in the bay area, such as in the Callao and Paracas sectors, but with high potential on the coasts in the rest of the territory.

Figure 6 shows the potential for marine energy from waves in the southern Pacific Ocean area off the coast of Peru.

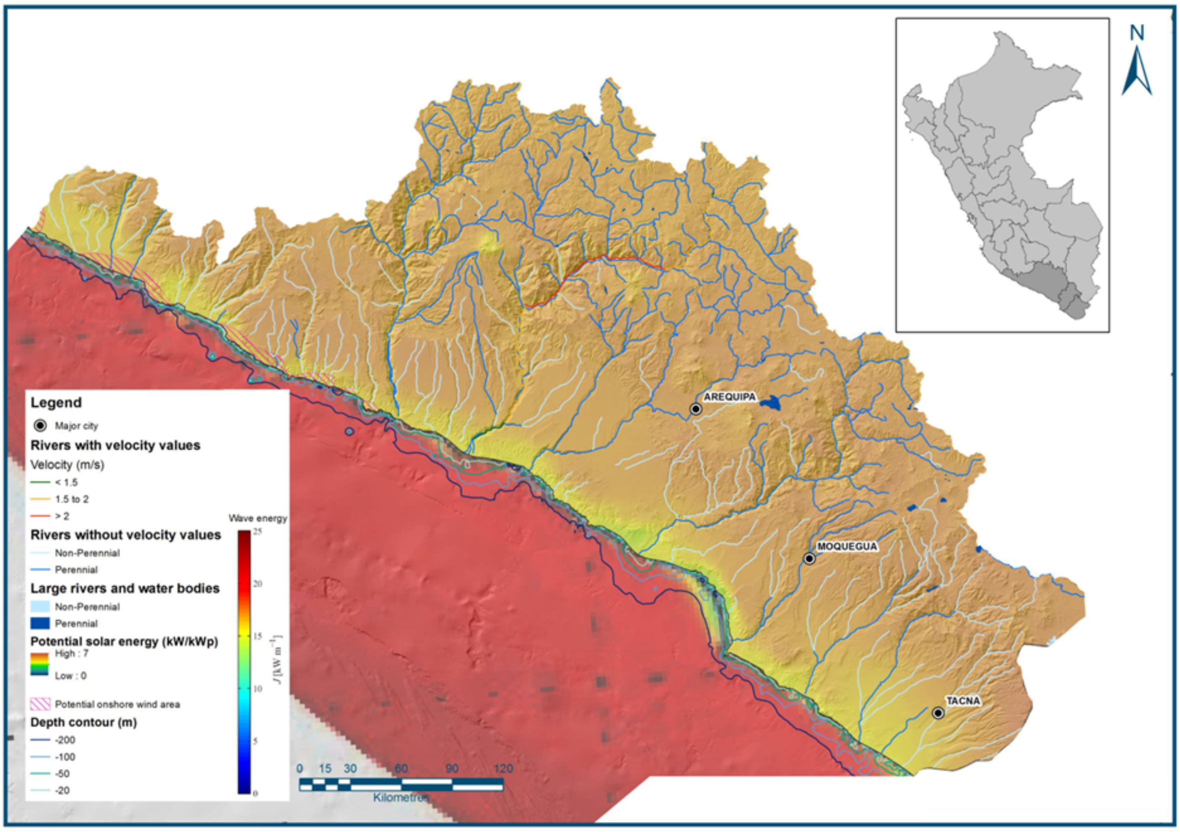

Figure 6. Potential of wave energy in Peru—south Pacific Ocean zone waves resource map.

In Figure 6, it can be seen in red that the potential for marine energy from waves is of the order of 25 kW/m along the entire open sea coast of Peru [25]. A decrease in the potential for energy from waves can be seen in the bay areas, such as the Mollendo Bay and Ilo Bay sectors, but with high potential on the coasts in the rest of the territory.

2.2. Potential of Tidal Energy

Tides are the regular and predictable change in ocean height, driven by gravitational and rotational forces between the Earth, moon, and sun, combined with centrifugal and inertial forces. Many coastal areas experience about two high tides and two low tides per day (called "semidiurnal"); in some places there is only one tide per day (called diurnal) [26].

Tidal periodicities can resonate with the natural oscillatory frequencies of estuaries and bays, resulting in a much larger tidal range. Consequently, the places with the largest tidal ranges are in resonant estuaries, such as the Bay of Fundy in Canada (tidal range 17 m), the Severn Estuary in the UK (15 m), and Mont Saint Michel Bay in France (13.5 m). In other places (e.g., the Mediterranean Sea), the tidal range is less than 1 m [18].

M2 is the largest tidal component (semidiurnal), whose amplitude is approximately 60% of the total tidal range. According to Figure 7 the white lines are cotidal lines, where the tides are at the same point of rise or fall, spaced in phase intervals of 30° (a little more than 1 h). According to Figure 7 the amphidromic points are the dark blue areas where the cotidal lines meet. The tides rotate around these points where little or no rise or fall of tide occurs, but where there can be strong tidal currents. In the case of Peru, the average value of M2 is a range equivalent to 20–30 cm. A typical example of the four tides in Peru per day are the following: 0.8 m, 0.2 m, 0.7 m and 0.4 m [27].

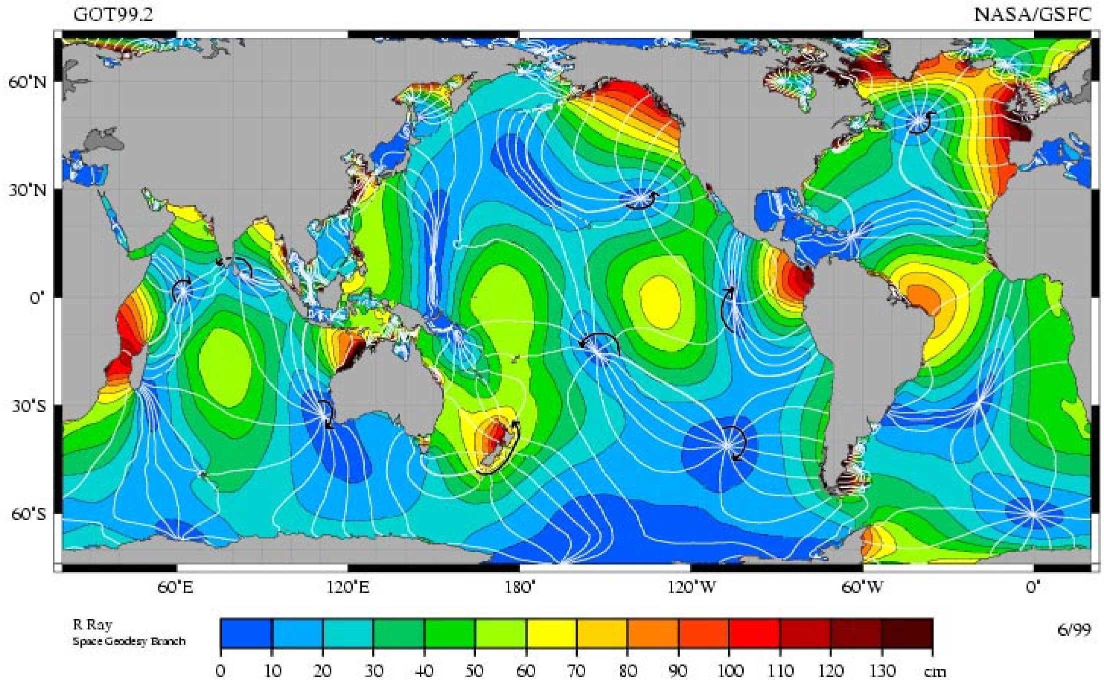

Figure 7. Tidal range world map: world map of M2 tidal amplitude.

This means that the potential for tidal energy in Peru is low compared to other countries. Peru's coast is open and has a shortage of fjords or channels where tidal changes in sea level can be more significant [26].

Peru currently has an information gap regarding its tidal resources, and therefore requires more detailed studies to be carried out in order to gain clarity on its specific potential.

2.3. Potential of Ocean Thermal Energy and Salinity Gradients Energy

Among the renewable energy sources of the future is the sea, with its immense potential: the most intuitive way of generating electricity is to use wave energy, but it is also possible to take advantage of tides, with the advantage that these can be predicted with precision. Other methods are based on the difference in temperature between surface and deep waters or on the difference in salinity between different bodies of water. The technologies for exploiting these energy sources are not yet sufficiently developed to allow their widespread commercial use, but some experimental plants and prototypes have already been built with good results, mainly regarding wave and tidal energy [28].

For OTEC (Ocean Thermal Energy in Celsius Degrees) to be operational, the temperature difference must be around 20 degrees Celsius (°C), which means that the surface temperature must be around 25 °C, as water temperatures tend to stabilize around 4 °C at 1000 m depth. However, OTEC is still in the R&D phase and its current implementation is limited to 100 kW demonstration plants in Hawaii (USA) and Japan [29].

Salinity gradient technologies harness energy through pressure-delayed osmosis or reverse electrodialysis, where energy is generated as a result of the difference in salt concentration between two fluids. This can be found in river beds where fresh water flows into the sea, as the difference in salt concentration is significant, thus having a higher potential for energy generation. Salinity gradient is the least mature ocean energy technology and globally only one project with a capacity of 50 kW was operational in 2020, in the Netherlands [30,31].

According to scientific studies, the potential of ocean thermal energy (44,000 TWh) is around 57% of total marine energy, followed by wave energy (29,500 TWh) with 38% of the total. Then, we have in third place the potential (1650 TWh) of the salinity gradient with 2.2% of the total, and finally we have tidal energy (1200 TWh) with 1.6% of the total. Peru currently has a gap or lack of information on its OTEC resource and salinity gradient, and therefore requires more detailed studies to be carried out in order to have clarity on its potential [32].

Considering the installed capacity of marine energy worldwide, the largest amount of infrastructure corresponds to tidal barrages with 97.5% (521.5 MW), followed in second place by tidal current facilities with 2.0% (10.6 MW). In third place are wave energy facilities with 0.4% (2.31 MW). In the last two places are ocean thermal energy facilities with 0.04% (0.23 MW) and salinity gradient energy facilities with 0.01% (0.05 MW). This shows that ocean thermal energy and salinity gradient energy facilities worldwide today are in an early stage of development. According to IRENA analysis, the cumulative global resource potential ranges from 45,000 terawatt-hours (TWh) to well over 130,000 TWh annually Ocean energy alone therefore has the potential to meet more than double the current global electricity demand [33].

3. Best Available Technologies to Develop Marine Renewable Energy in Peru

3.1. Coupling Marine Renewable Energy Sources to Power the Blue Economy

The implementation of marine renewable energy facilities and devices offers the opportunity to promote a blue economy around the potential offered by territories close to the sea. Today the sea is considered a passive resource, but under the blue economy paradigm, the sea becomes an active resource from which all citizens can benefit in different ways (see Figure 8).

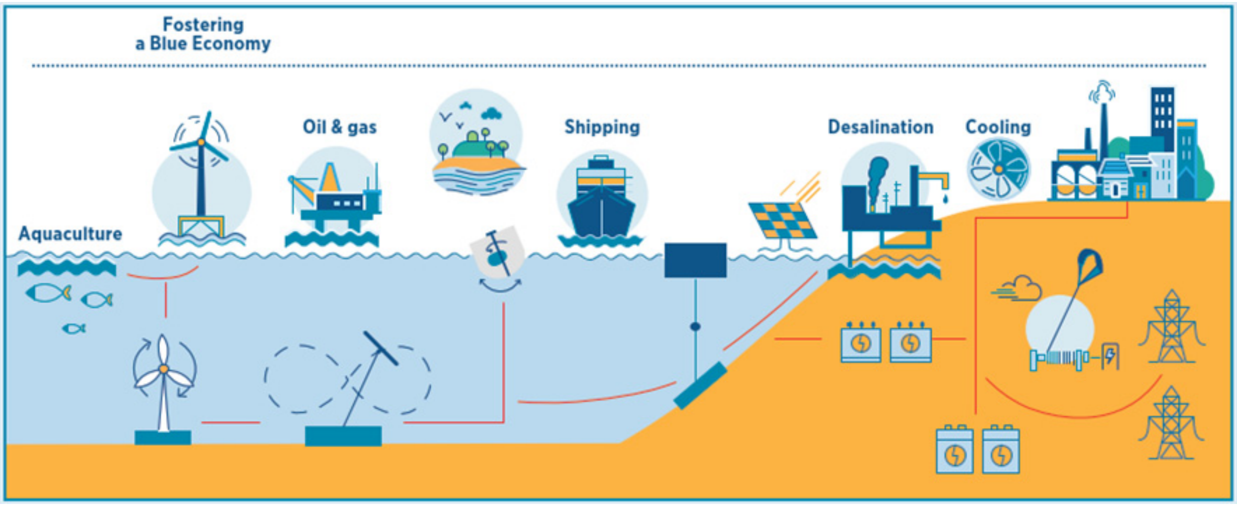

Figure 8. Conceptual model example of blue economy considering insertion of marine renewable energy.

Some of the benefits of marine renewable energy technologies are: (i) it is a predictable source of energy, (ii) it offers a high and constant capacity factor, (iii) it is socially acceptable, (iv) it is easily combinable with other renewable energy sources to form hybrid energy systems, (v) it can provide energy for continental systems, (vi) it generates new jobs for communities in coastal environments, (vii) it mitigates the impacts of climate change, and (viii) it combines electric power generation and seawater desalination to generate water for the population and industrial use [15].

In order to supply energy to the different terrestrial systems, it is possible to obtain energy from the ocean with different devices. For example, in the sea, but close to the coast, it is possible to install solar photovoltaic panels and buoy points, the latter to obtain energy from the waves that break on the coast. In deeper areas or offshore, it is feasible to install wave energy systems using highly efficient Pelamis or oscillatory devices. Then, in even deeper areas offshore, it is possible to install tidal energy harvesting systems such as turbine and pendulum devices. All these systems can be complemented with floating wind turbines [34,35].

Some of the activities that can be supplied with marine renewable energy are, for example: (i) fishing, (ii) oil and gas platforms, (iii) ship transport, (iv) seaports, (v) seawater desalination plants, (vi) cooling systems, (vii) urban areas, and (viii) interconnected electricity systems [36].

In order to achieve the insertion of marine renewable energy, it is necessary to develop eight pillars based on infrastructure (Figure 9). First, it is necessary to have the best available technologies (BATs), so that low-cost, safe, and efficient systems can be implemented. Second, it is necessary that the infrastructure and systems implemented are environmentally friendly and promote its conservation. Third, the engineering design stage of all marine energy systems and devices is key, ensuring high quality. Fourth, we have the manufacturing of parts of all infrastructure systems, which must ensure high factory quality of different components of the energy systems and devices so that they function properly and without problems. Then, fifth, we have the supply of the electrical system, where all marine systems are connected to land-based electrical systems to share clean energy. Sixth, we have the construction of infrastructure elements on the continent or land far from the sea, where interference must be minimized. Seventh is marine assembly, where the installation of marine energy electromechanical systems and devices is carried out at sea with the support of vessels. Finally, eighth is the operation and maintenance of marine renewable energy infrastructure, which will be necessary to ensure proper functioning during the useful life of the energy projects [15].

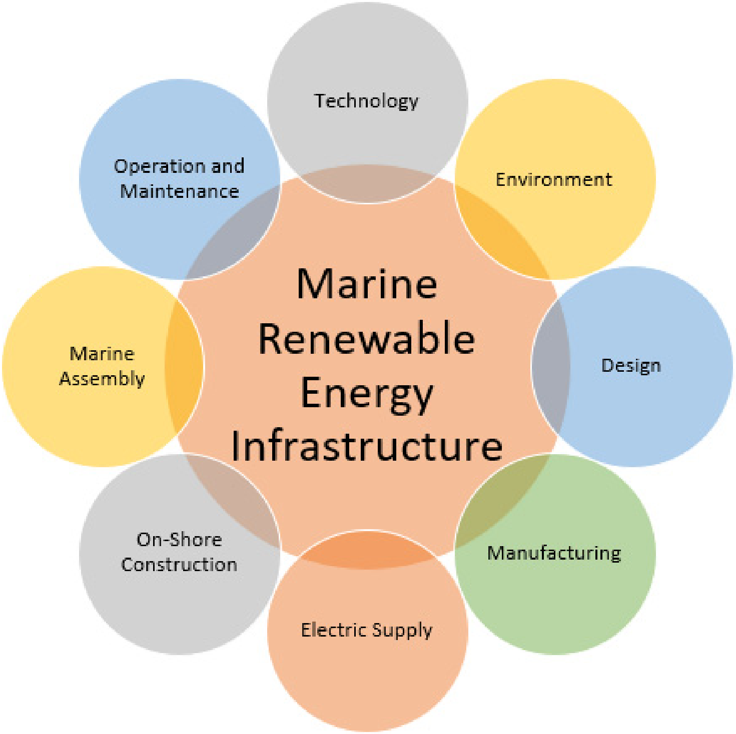

Figure 9. Pillars of development for marine renewable energy infrastructure.

3.2. Types of Waves Energy Technological Devices

The marine energy stored in waves, also known as wave energy, is due to the action of the wind on the sea surface, which generates ripples on the water surface itself. These ripples can be added together in sequence to produce the periodic surface movement characteristic of waves [32].

The formation of this phenomenon is greater on the surface and decreases as one descends towards the depths, until it disappears completely on the deep seabed. The called WEC (wave energy converter) systems take advantage of wave energy using different physical principles [33].

There are three main technologies that focus on three different physical principles with the aim of converting wave energy into electricity, a challenge that relies on intelligence and innovation: (i) wave-activated body, (ii) overtopping, and (iii) oscillating water column [32] (See Figure 10).

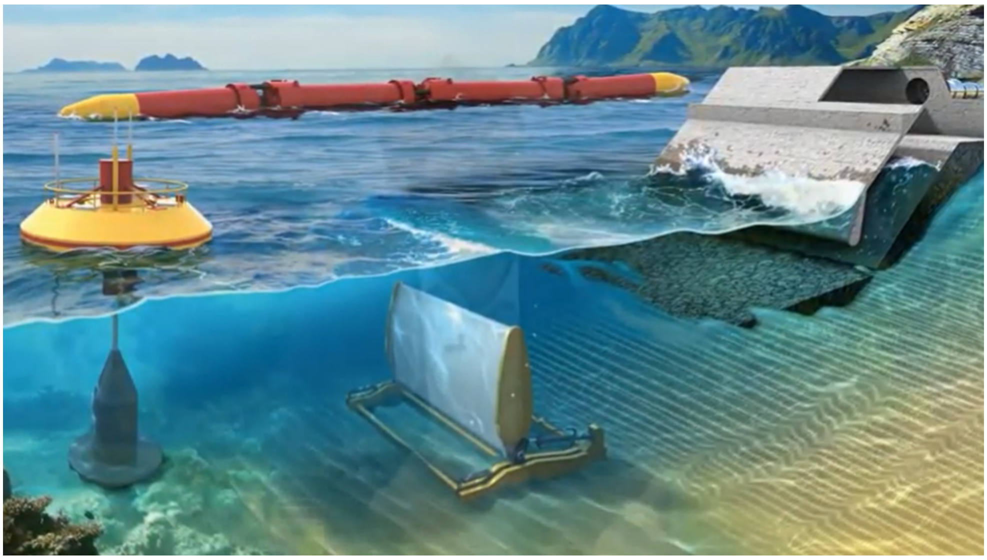

Figure 10. Example of different devices for wave energy harvesting.

WEC technologies are in the pre-commercial development phase, and it is not yet clear which technology will be the most cost-effective for widespread use in marine power generation in the future [33].

3.2.1. Attenuator Wave Energy Device

Attenuator devices are generally long floating structures aligned with the direction of the waves, which then absorb the motion. Their motion can be selectively damped to produce energy. They have a smaller area perpendicular to the waves compared to a terminator device, so the device can experience reduced forces. It uses the motion that waves confer on a body, which in turn is transmitted to a system capable of converting this mechanical energy into electrical energy (turbines or electrical converters). Figure 11 shows some representative images of this device, while Table 2 indicates the main technical specifications [33].

Figure 11 shows the attenuator, also known as the sea serpent, which consists of a system of multiple segments connected, with a flexible part that extracts energy from the waves following the parallel movement of the waves. Finally, Table 2 indicates the technology data and name of the manufacturer, as well as indicating that the development stage is currently commercially available, with a technological development level of TRL 8, 0.75 MW of installed capacity, and development in the UK with testing in the UK and Portugal [32].

Figure 11. Panoramic view of attenuator wave energy device.

Table 2. Attenuator specifications—wave energy device.

Parameter	**Value**	**Units**
Technology Name	Pelamis P2	-
Supplier Vendor Name	Pelamis Wave Power (Edinburgh, UK)	-
Development Stage	Commercially Available	-
TRLs	TRL 8	
Device Installed Capacity	0.75	MW
Country of Origin	Developed in UK and tested in UK and Portugal	-

3.2.2. Overtopping Wave Energy Device

Overtopping devices are wave concentration systems that operate by means of a ramp along which waves travel to an elevated storage reservoir. This creates a head of water in a reservoir which is then released through low-head hydroelectric turbines as the water flows back out to sea. An overtopping device can use concentration arms to concentrate wave energy. In short, this device uses the energy of a breakwater barrier, where the water that brushes the barrier is stored in a tank and then passed through a hydro turbine [32]. Figure 12 shows some representative images of this device, while Table 3 indicates the main technical specifications.

Table 3. Overtopping specifications—wave energy device.

Parameter	**Value**	**Units**
Technology Name	Wave Dragon	-
Supplier Vendor Name	Wave Dragon Ltd. (Copenhagen, Denmark)	-
Development Stage	Full-Scale Prototype	-
TRLs	TRL 5	-
Device Installed Capacity	11.0	MW
Country of Origin	Developed and tested in Denmark	-

Figure 12. Panoramic view of overtopping wave energy device.

Figure 12 shows the device where wave water is captured in a reservoir and released through a shaft system, where a turbine generates energy when seawater passes through it. Finally, Table 3 indicates the technology data and name of the manufacturer, as well as indicating that the development stage is currently a full-scale prototype, with a technological development level TRL 5, 11 MW installed capacity, and development and testing in Denmark [33].

3.2.3. Oscillating Water Column Wave Energy Device

An oscillating water column consists of a partially submerged, resonance-tuned collector that is open to the sea below the water surface and contains air trapped above a water column. This water column moves up and down with the movement of the waves, acting as a piston, compressing and decompressing the air. This air is channeled through an air turbine, which harnesses the airflow as it is expelled and sucked back into the collector. A significant advantage of this type of technology is that it can be integrated into the shoreline. It uses the periodic level variation of a water column that is created within a special chamber connected to the sea, which in turn compresses a mass of air that drives a turbogenerator [32]. Figure 13 shows some representative images of this device, while Table 4 points out the main technical specifications.

Table 4. Oscillating water column specifications—wave energy device.

Parameter	Value	Units
Technology Name	Limpet	-
Supplier Vendor Name	Voith Hydro Wavegen Ltd. (Inverness, Scotland)	-
Development Stage	Full Scale, grid connected prototype	-
TRLs	TRL 8	
Device Installed Capacity	500	kW
Country of Origin	Developed and tested in Scotland	-

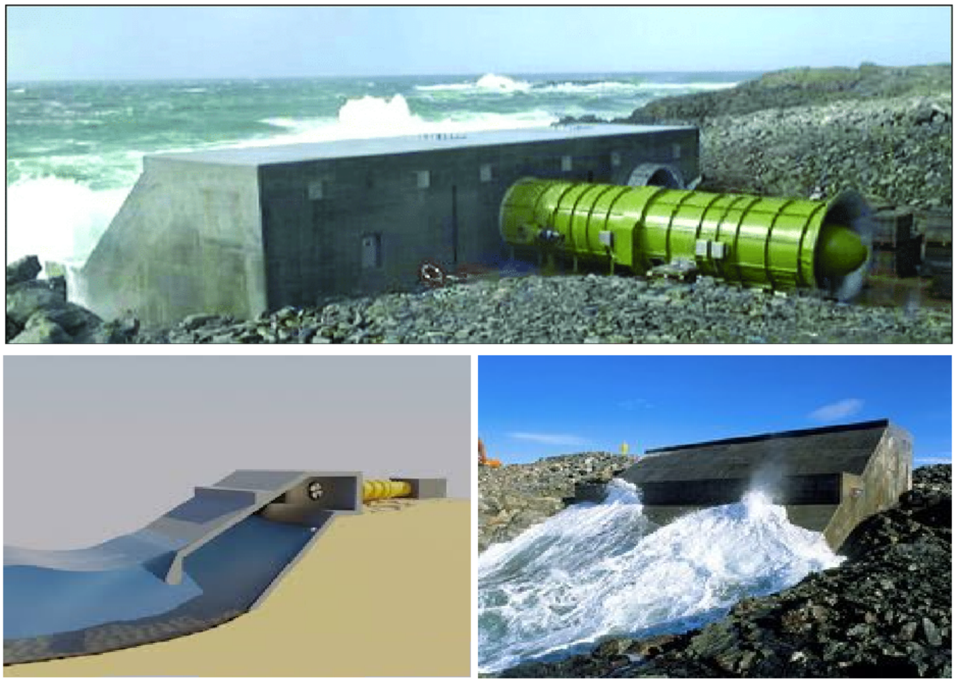

Figure 13. Panoramic view of an oscillating water column wave energy device.

Figure 13 shows the device where the passing of waves raises the water level inside a chamber of a semi-submerged structure, causing the enclosed air to be compressed and flow into the atmosphere, allowing the action of a turbine. Finally, Table 4 indicates the technology data and name of the manufacturer, as well as indicating that the development stage is currently a full-scale prototype connected to the electrical grid, with a technological development level of TRL 8, 500 kW installed capacity, and development and testing in Scotland [33].

3.2.4. Point Absorber Wave Energy Device

A point absorber is a floating structure that absorbs energy from all directions of wave action due to its small size relative to the wavelength. The absorber can be designed to resonate with the natural periods of the waves and maximize the power it can capture. The power take-off system can take many forms, from hydraulic to linear generators. It uses the motion that waves confer on a body, which in turn is transmitted to a system capable of converting this mechanical energy into electrical energy (turbines or electrical converters) [32]. Figure 14 shows some representative images of this device, while Table 5 indicates the main technical specifications.

Table 5. Point absorber specifications—wave energy device.

Parameter	Value	Units
Technology Name	Powerbuoy PB150	-
Supplier Vendor Name	Ocean Power Technologies (Monroe Township, NJ, USA)	-
Development Stage	Full Scale Prototype	-
TRLs	TRL 7	
Device Installed Capacity	150	kW
Country of Origin	Developed in USA and tested in Scotland	-

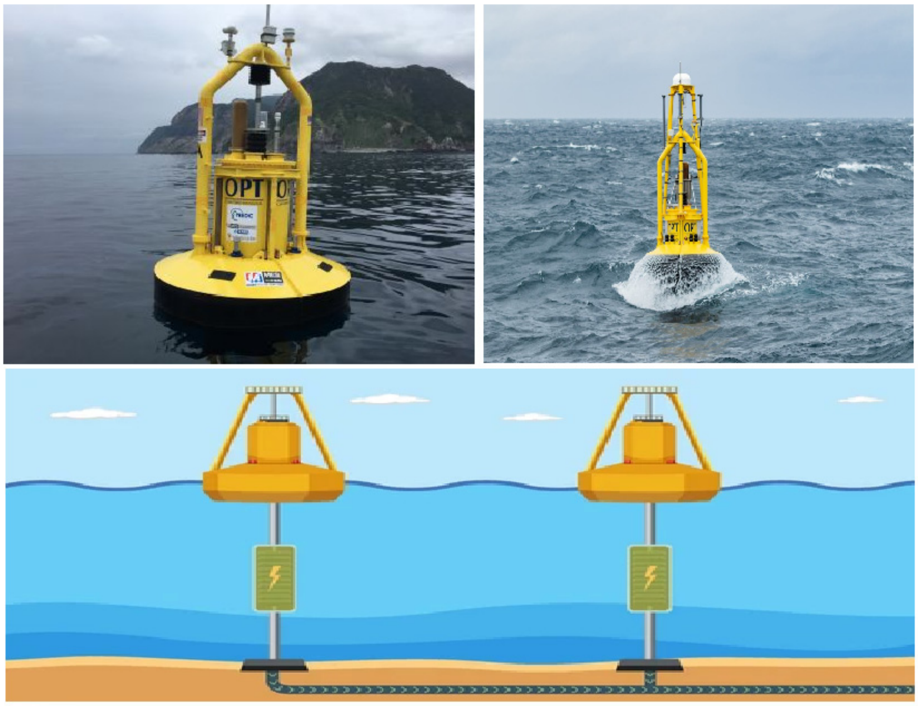

Figure 14. Panoramic view of point absorber wave energy device.

Figure 14 shows the device where the floating or submerged buoy generates energy from the movement of the buoy caused by sea waves in all directions relative to the base connection. Finally, Table 5 indicates the technology data and name of the manufacturer, as well as indicating that the development stage is currently a full-scale prototype, with a technological development level TRL 7, 150 kW installed capacity, and development in the USA with testing in Scotland [33].

3.2.5. Oscillating Wave Surge Converter Wave Energy Device

An oscillating wave converter extracts energy from the wave motion of waves. They are usually seabed-mounted devices located close to the shore. The collector of the device is driven by the wave action of the waves, producing a pendulum-like motion that is then converted into useful energy [32]. Figure 15 shows some representative images of this device, while Table 6 points out the main technical specifications.

Table 6. Oscillating wave surge converter specifications—wave energy device.

Parameter	Value	Units
Technology Name	Oyster 800	-
Supplier Vendor Name	Aquamarine Power (Edinburgh, UK)	-
Development Stage	Full Scale Prototype	-
TRLs	TRL 7	-
Device Installed Capacity	800	kW
Country of Origin	Developed and tested in UK	-

Figure 15 shows the device where the structure uses the wave motion to capture energy with an oscillating arm. Finally, Table 6 indicates the technology data and name of the manufacturer, as well as indicating that the development stage is currently a full-scale prototype, with a technological development level TRL 7, 800 kW installed capacity, and development in conjunction with testing in the UK [33].

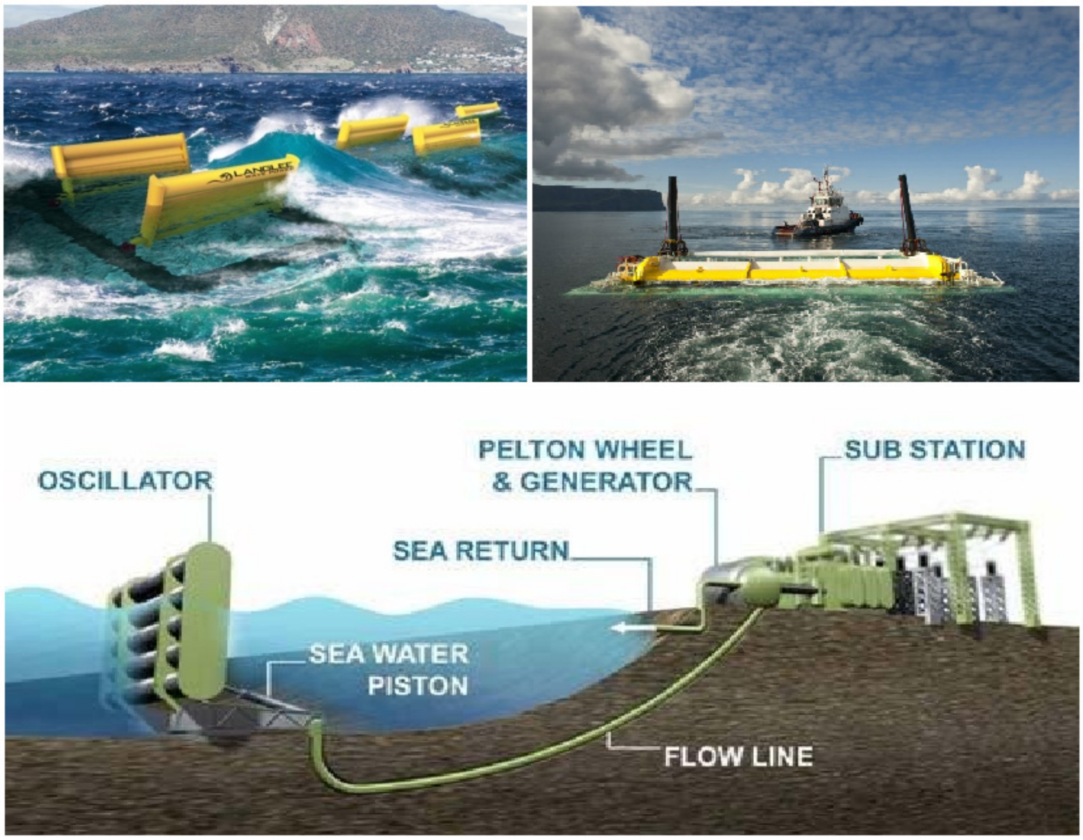

Figure 15. Panoramic view of oscillating wave surge converter wave energy device.

3.2.6. Wave Surge Converter Device—Brazil Case Study

The prototype uses two large floats that take advantage of the incessant movement of sea waves. This development by the Brazilian National Electric Energy Agency (ANEEL) was carried out off the coast of Porto do Pecém, in São Gonçalo do Amarante (Ceará state), and represents an important step towards generating wave energy in South America [37].

Each module is made up of a 10-metre diameter buoy, a 22-metre-long mechanical arm and a pump connected to a closed circuit of fresh water. When seawater through sea waves reaches the modules, the buoys move up and down, also moving the mechanical arm. This activates the hydraulic pump which, through a closed circuit, injects fresh water into a high-pressure system. This releases a jet of fresh water with a pressure equivalent to a 400-metre water column, a number like that of many hydroelectric plants. This causes the turbine to rotate, which activates the electric generator, and thus the system produces electric energy with an installed power of 50 kW [38].

Figure 16 shows some representative images of this device, while Table 7 indicates the main technical specifications.

Figure 16 shows the operation of the device, where an additional advantage of this technology is the possibility of coupling with desalination systems, where reverse osmosis desalination is an effective way to obtain drinking water from the sea. Finally, Table 7 indicates the technology data and the name of the manufacturer, in addition to indicating that the development stage is currently a full-scale prototype, with a technological development level TRL 8, 50 kW of installed capacity, and development in conjunction with testing in Brazil [37].

Figure 16. Panoramic view of wave surge converter device—Brazil case study.

Table 7. Wave surge converter Brazil case study specifications—wave energy device.

Parameter	Value	Units
Technology Name	Wave Surge Converter Brazil Case Study	-
Supplier Vendor Name	Agencia Nacional de Energía Eléctrica (ANEEL) Brasileña and Subsea Technology Laboratory of Coppe (Rio de Janeiro, Brazil)	-
Development Stage	Full Scale Prototype	-
TRLs	TRL 8	
Device Installed Capacity	50	kW
Country of Origin	Developed and tested in Brazil	-

3.2.7. Point Absorber Device—Chile Case Study

On the coast of Las Cruces, San Antonio Bay, in the Valparaíso Region, Chile, the Open Sea Lab project of MERIC—an institution co-founded by Enel Green Power Chile and Naval Energies—installed the first full-scale wave energy converter in the country. This innovative system is capable of converting wave energy into electrical energy, which is stored in a 50 kWh battery system inside the PB3 PowerBuoy, and which feeds the different oceanographic sensors that monitor the marine environment [39].

The buoy of the PB3 PowerBuoy measures 13 m long in total (10 m below the sea surface) and will be anchored, floating at a depth of 35 m. To produce electricity, the buoy takes advantage of the energy generated by the movement of the waves. With these, the float moves up and down the mast. This vertical movement drives a rotating mechanical system, which, in turn, moves an electric generator [39]. Figure 17 shows some representative images of this device, while Table 8 points out the main technical specifications.

Table 8. Point absorber—Chile case study specifications—wave energy device.

Parameter	Value	Units
Technology Name	PowerBuoy PB3	-
Supplier Vendor Name	Ocean Power Technologies (Monroe Township, NJ, USA)	-
Development Stage	Full Scale Prototype	-
TRLs	TRL 7	
Device Installed Capacity	15	kW
Country of Origin	Developed in USA and tested in Chile	-

Figure 17. Panoramic view of point absorber device—Chile case study.

Figure 17 shows the operation of the device, where the energy generated is stored in batteries located inside the buoy itself and is used to maintain the different instruments that depend on it, such as an acoustic profiler of marine currents, which allows measuring the direction of currents, waves, and the energy generated by the waves. It also has a radar that measures currents and waves throughout the San Antonio Bay in the Valparaíso region of Chile. Finally, Table 8 indicates the technology data and name of the manufacturer, in addition to indicating that the development stage is currently a full-scale prototype, with a technological development level TRL 7, 15 kW of installed capacity, and development together with testing in Chile [39].

3.2.8. Point Absorber Water Desalination Device—Peru Case Study

Atmocean, a US-based wave energy developer, launched the second phase of its ocean wave energy demonstration program in Ilo Bay, southern Peru. Atmocean redeployed its wave energy system, which was recovered on 29 July 2015, after having been in sea trials for three weeks. In this second phase of testing, the system was deployed in the ocean for up to six months to confirm performance and durability data. According to Atmocean, the objectives of the second phase were met by mid-summer 2016, allowing commercial operations to begin. Atmocean's demonstration system consists of five pumps and five buoys and represents one third of the complete commercial system. The system can produce both electricity and fresh water from seawater using the desalination process. As previously reported, the system will not produce electricity for the time being and will focus solely on producing fresh water through the desalination process using Atmocean's zero-electricity reverse osmosis system [33]. Figure 18 shows some representative images of this device, while Table 9 outlines the main technical specifications.

Table 9. Point absorber—Peru case study specifications—water desalination device.

Parameter	Value	Units
Technology Name	Power sea water desalination buoy	-
Supplier Vendor Name	Atmocean Technologies (Santa Fe, NM, USA)	-
Development Stage	Full Scale Prototype	-
TRLs	TRL 5	
Device Installed Capacity	5	kW
Country of Origin	Developed in USA and tested in Peru	-

Figure 18. Panoramic view of point absorber water desalination device—Peru case study.

Figure 18 shows the operation of the device, where the Atmocean wave energy system works by capturing the up and down motion of ocean waves to drive a piston in a cylinder that pressurizes seawater. By connecting several seawater pumps as an array, this pressurized seawater can be sent to converters on land.

Finally, Table 9 indicates the technology data and name of the manufacturer, as well as noting that the development stage is currently a full-scale prototype, with a technological development level TRL 5, 5 kW of installed capacity, and development in the USA with testing in Peru [33].

3.3. Types of Tidal Range and Tidal Stream Technological Devices

Analogies with wind energy have made tidal energy a developed technology, ready to become a new renewable source for all purposes

Marine energy from tidal flows, also known as tidal range (tidal barrage) and tidal stream (tidal current), is due to the formation of horizontal water currents that are created because of the vertical variation of the level of water masses linked to the tides [34].

These currents affect areas where the action of the tides acts in opposite ways (high tide on one side, low tide on the other) and the flow changes direction as the level of the tide changes. In this case, the primary energy comes from a horizontal flow of water, like what happens with the use of wind energy [34].

In fact, the machines capable of capturing and using this energy (Tidal Energy Converters) are, for the most part, two- or three-bladed turbines with a horizontal axis, of a size suitable for operating on the seabed [32].

The analogy with wind technology has helped tidal energy to reach an excellent level of technological development. Current systems are much more advanced than wave energy converters, so tidal energy is ready for large-scale expansion [33].

3.3.1. Tidal Barrage System—Tidal Range Energy Device

A tidal barrage is a dam-like structure used to capture the energy of water masses entering and leaving a bay or river due to tidal forces. Instead of holding back water on one side like a conventional dam, a tidal barrage allows water to flow into a bay or river during high tide and releases it during low tide. This is done by measuring tidal flow and controlling gates at key times in the tidal cycle. Turbines are placed on these gates to capture the energy as the water flows in and out [32]. Figure 19 shows some representative images of this device, while Table 10 points out the main technical specifications.

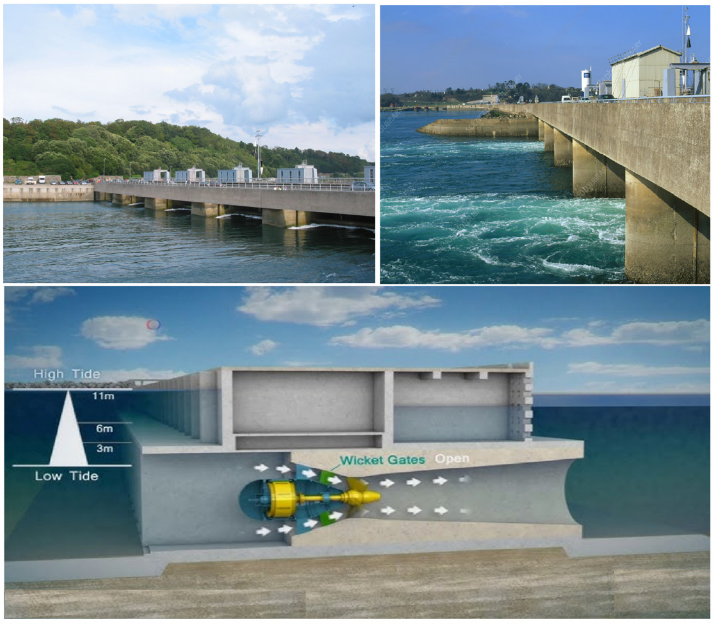

Figure 19. Panoramic view of a tidal barrage system—tidal range energy device.

Table 10. Tidal barrage system specifications—tidal range energy device.

Parameter	Value	Units
Technology Name	Tidal Barrage System	-
Supplier Vendor Name	Emec (Stromness, Orkney, UK)	-
Development Stage	Commercial Scale, grid connected	-
TRLs	TRL 9	
Device Installed Capacity	>1.0	MW
Country of Origin	Developed and tested in Ireland	-

Figure 19 shows the operation of the device, where water entering a closed tidal basin with a high tide level is released into a low tide zone and this generates electricity as this water passes through turbines. Finally, Table 10 indicates the technology data and name of the manufacturer, in addition to indicating that the development stage is currently commercial scale connected to the electrical grid, with a technological development level TRL 9, greater than 1.0 MW of installed capacity, and development together with testing in Ireland [33].

3.3.2. Horizontal Axis Turbine Tidal Stream Energy Device

These devices have two or three blades mounted horizontally to form a rotor; the kinetic motion of the current creates lift on the blades causing the rotor to spin and drive an electric generator [32]. Figure 20 shows some representative images of this device, while Table 11 indicates the main technical specifications.

Table 11. Horizontal axis turbine specifications—tidal stream energy device.

Parameter	Value	Units
Technology Name	SeaGen Turbine	-
Supplier Vendor Name	Marine Current Turbines (Emersons Green, UK)	-
Development Stage	Commercial Scale, grid connected	-
TRLs	TRL 8	
Device Installed Capacity	2.0	MW
Country of Origin	Developed and tested in Ireland	-

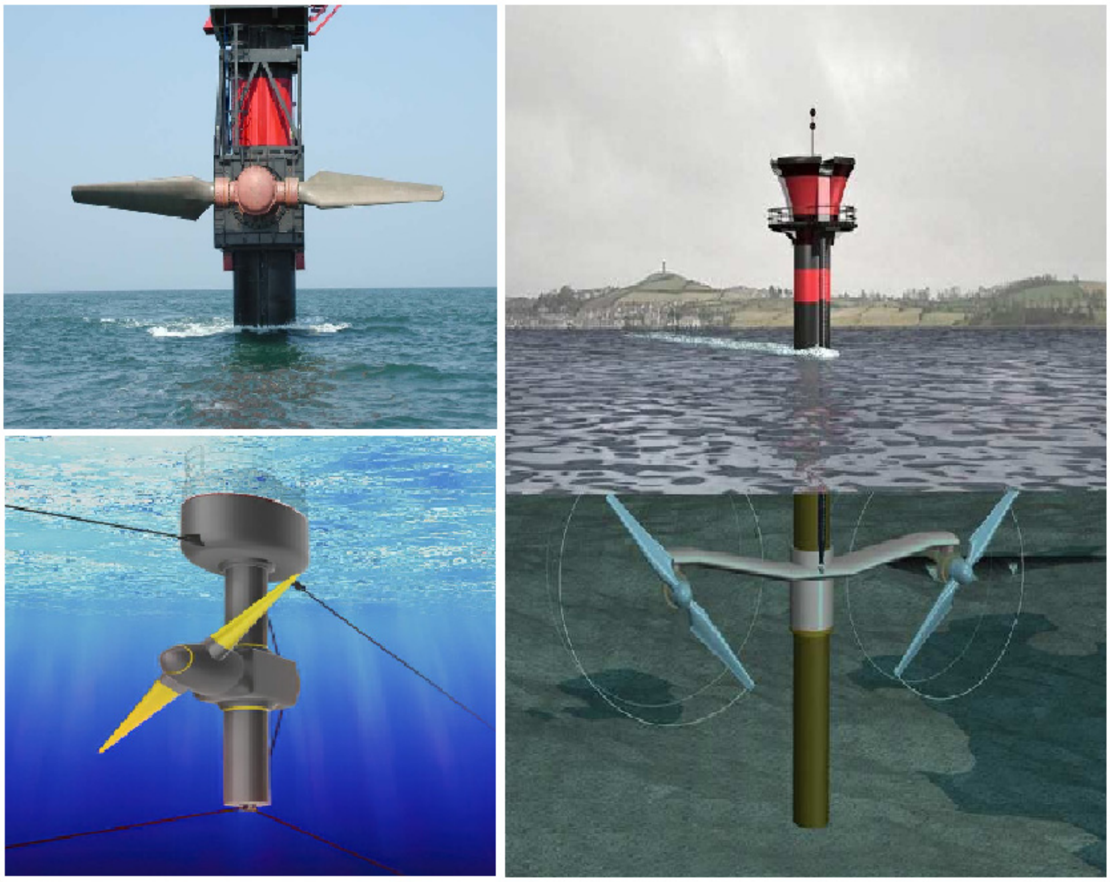

Figure 20. Panoramic view of a horizontal axis turbine tidal stream energy device.

Figure 20 shows the operation of the device, where the flow of the tidal currents passes through the blades that are radially connected to a horizontal shaft, which causes rotation that generates mechanical energy similar to an underwater wind turbine. Finally, Table 11 indicates the technology data and name of the manufacturer, in addition to indicating that the development stage is currently commercial scale connected to the electrical grid, with a technological development level of TRL 8, 2.0 MW of installed capacity, and development and testing in Ireland [33].

3.3.3. Vertical Axis Turbine—Tidal Stream Energy Device

These devices typically have two or three blades mounted along a vertical axis to form a rotor. The kinetic motion of the current creates lift on the blades, causing the rotor to rotate and drive the electric generator [32]. Figure 21 shows some representative images of this device, while Table 12 lists the main technical specifications.

Table 12. Vertical axis turbine specifications—tidal stream energy device.

Parameter	Value	Units
Technology Name	EnCurrent	-
Supplier Vendor Name	New Energy Corporation Inc. (Calgary, AB, Canada)	-
Development Stage	Full Scale Prototype	-
TRLs	TRL 5	
Device Installed Capacity	25	kW
Country of Origin	Developed and tested in Canada	-

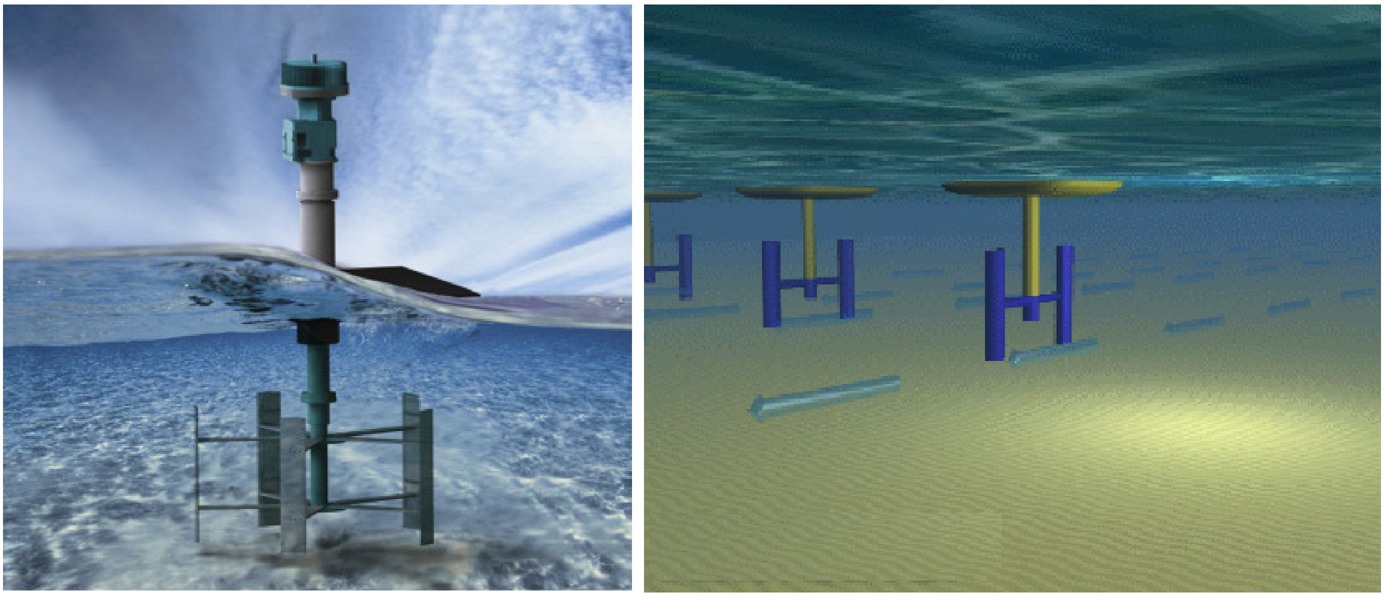

Figure 21. Panoramic view of a vertical axis turbine tidal stream energy device.

Figure 21 shows the operation of the device, where the flow of tidal currents passes through a set of blades parallel to a rotating shaft, generating energy in the direction of the flow. Finally, Table 12 indicates the technology data and name of the manufacturer, as well as indicating that the development stage is currently as a full-scale prototype, with a technological development level TRL 5, 25 kW installed capacity, and development together with testing in Canada [33].

3.3.4. Oscillating Hydrofoil—Tidal Stream Energy Device

This device works like an airplane wing, but in water, which is like a fluid. Control systems modify its angle in relation to the water current, creating lift and drag forces that cause the device to oscillate. The physical motion of this oscillation feeds an energy conversion system [32]. Figure 22 shows some representative images of this device, while Table 13 points out the main technical specifications.

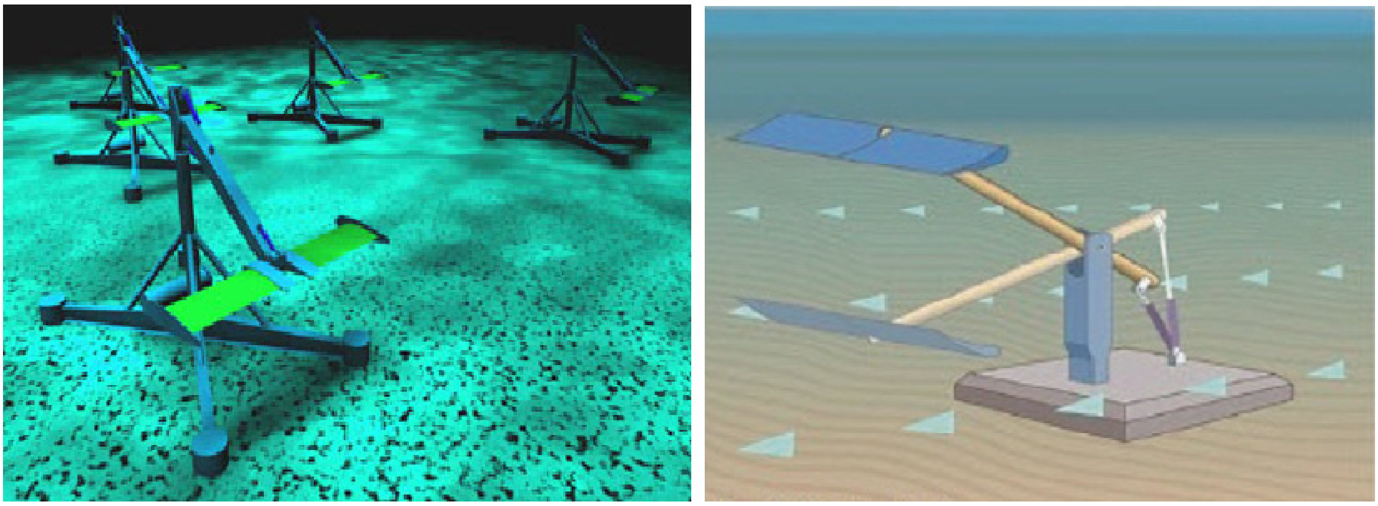

Figure 22. Panoramic view of an oscillating hydrofoil tidal stream energy device.

Table 13. Oscillating hydrofoil specifications—tidal stream energy device.

Parameter	Value	Units
Technology Name	Pulse-Stream 100	-
Supplier Vendor Name	Pulse Tidal (Sheffield, UK)	-
Development Stage	Full Scale Prototype	-
TRLs	TRL 5	
Device Installed Capacity	100	kW
Country of Origin	Developed and tested in UK	-

Figure 22 shows the operation of the device, where the tidal flow lifts an oscillating hydrofoil attached to an arm, which rises and falls, causing a piston to generate energy. Finally, Table 13 indicates the technology data and the name of the manufacturer, as well as indicating that the development stage is currently that of a full-scale prototype, with a technological development level of TRL 5, 100 kW of installed capacity, and development and testing in Canada [33].

4. Socio-Economic and Environmental Impacts of Marine Renewable Energy in Peru

The Peruvian coastline extends over more than 3000 km. As a result, the possibility of finding suitable areas for the implementation of marine energy generation projects is high. However, even though marine energy is a renewable energy source, this does not mean that it does not generate negative impacts on marine ecosystems and coastal human populations. These impacts have the potential to affect the Peruvian population in areas adjacent to areas where marine energy generation projects are implemented. Likewise, there is the potential to harm the environment and ecosystems with undesirable externalities.

4.1. Identification of Potential Socio-Economic Impacts

The implementation of marine energy in Peru has the potential to generate negative impacts in different social spheres. One of the most worrying impacts is the possible impact on fishing activities in areas close to energy generation projects. This is because the marine ecosystem of Peru, which includes the northern segment of the Humboldt system, has no comparison in terms of the tonnage of fishing landings, and in terms of production of fishing biomass [40].

In 2015, the total population of artisanal fishermen on the Peruvian coast was estimated at 67,427 individuals [41]. It was also reported that at the time there were approximately 87 artisanal landing sites. It should be noted that these landing sites are distributed along the entire Peruvian coast and not within a particular area. Consequently, fishing covers may be close to a region with significant offshore renewable resources [40].

The implementation of large marine energy generation infrastructures can also affect the normal functioning of marine ecosystems, thus altering the behavior of marine fauna, as well as the transport of sediments and the routes of migratory fish [42]. This would result in a reduction in catches by artisanal fishermen, thus generating a reduction in economic income for coastal communities and the fishing industry.

On the other hand, marine energy generation projects are developed on the seashore or in areas close to it, which generates a possible reduction in the coastal space available for recreation in the areas of location, and thus, sports and leisure activities such as surfing, diving, and sailing could be affected. Furthermore, in the case of wave energy, ocean wave energy (OWE) capture devices remain completely submerged, partially submerged, or floating [43]. These can cause visual pollution and alteration of the coastal landscape, as well as the underwater landscape.

In addition, in Peru there is a notable tourism industry focused on the beauty of diverse coastal landscapes and experiences of contact with marine life. However, the installation of marine energy generation plants leads to the restriction of access to certain coastal areas. This would potentially affect certain tourist navigation routes. Therefore, the implementation of areas where marine energy is produced leads to the formation of a new cultural landscape and the original facilities are affected [44].

4.2. Identification of Potential Environmental Impacts

The construction of marine energy generation plants will have an impact on the ecological environment of the site, because the presence of any foreign element in the ocean can be dangerous for the environment [43]. The Peruvian Sea is considered the most productive in the world. Therefore, the marine ecosystem located off the coast of central and northern Peru has emerged as the "world champion" producer, by a large margin, of exploitable fish biomass [40]. Likewise, it has great marine biodiversity; around 4500 species have been identified in its waters, including fish (1081 species), mollusks (1128 species), algae (602 species), and crustaceans (518 species) [41].

Therefore, it is important to consider the impacts that could be caused within the Peruvian ocean by installing marine energy production plants. There are various externalities generated from the operation of these marine energy generation plants. These include the alteration of the habitats of benthic organisms, noise pollution, the generation of electromagnetic fields, and the impact of marine animals with rotor blades or other moving parts [42].

In the case of a possible implementation of marine wave energy generation sources, the presence of various devices in the ocean can cause underlying changes in aquatic creatures both below and above the water level [43]. There is also a possibility of affecting mammal species and coastal birds due to the risk of collision with facilities located in and out of the water. The moving rotor blades can cause injuries to fish and/or birds [43].

Regarding acoustic disturbance, it has been observed that noise from tidal turbines can induce behavioral disturbances in marine mammals and, potentially, in fish or benthic invertebrates in the area near the turbine [45]. In addition, aquatic creatures that are highly dependent on acoustics within the marine environment are affected. Without an adequate acoustic atmosphere, detection of prey or predators, orientation, and reproduction are hampered [43].

Furthermore, it is known that noise pollution can have a number of effects on marine mammals, particularly cetaceans, which spend their entire lives underwater and are highly dependent on sound [46]. Depending on the distance between underwater turbines, noise zones can overlap, leading to an increase in cumulative noise levels, and therefore impact [45]. Therefore, sound waves with various frequencies emitted by marine power plants can generate various types of negative interference in the life of these marine mammals.

Furthermore, of all the ways in which noise can affect the lives of marine mammals, "masking" is perhaps the most predominant [47]. In the case of marine energy generation, aquatic turbines and energy-generating devices are the sources of sound interference that cause masking. In this sense, it is important to remember that auditory masking, or masking, occurs when the ability to detect or recognize a sound of interest is degraded by the presence of another sound (the masker) [47]. This phenomenon consequently generates alterations in the interaction of marine fauna such as seals, sea lions, walruses, and orcas, among others, which generates changes in the behavior and socialization processes of these animals, including those related to mating, breeding, social interaction, group cohesion, and feeding [47].

In addition, due to the change in habitat generated by the implementation of aquatic turbines, it is expected that there will be impacts caused by shock, collision, and entanglement in the blades [43]. Small animals such as penguins and seals and fish would also be at risk of impacting or getting caught in such installations. Rotors moving at high speed on a horizontal axis can be dangerous for some fish, marine mammals, and diving birds [43]. Furthermore, the possible reduction in hunting and feeding areas, as well as the effects of altered water movement when generating energy, have the potential to alter the way in which phytoplankton and zooplankton are distributed in the deployment area.

Furthermore, with the implementation of large submerged and floating marine energy generation facilities, there is a risk of changing tidal amplitude, tidal current, water temperature, water flow pattern, and some physical and chemical parameters [44]. The alteration generated in marine currents and flows, for example, would also cause greater food stress in the food chain, and consequently the migration routes of fish, birds, and mammals could be altered. In the case of seals, it has been shown that there is a significant decrease in abundance up to 2 km away from the turbine during periods of operation, suggesting that they may be perceived as aversive by seals [48].

Such modification of the natural flow of water in the coastal strip within the site area has the potential to cause changes in sedimentation patterns, erosion, and characteristics of the coastline, thus generating hydrological and ecological impacts. Since the residence times of the water parcels and the particles carried by passive drift can be especially important for the dynamics of the ecosystem within an upwelling zone [40]. Similarly, in terms of impacts on erosion, sediment deposition and change in water flow; extracting energy from the tidal current will undoubtedly reduce the speed of the current and, in some cases, may alter the direction of the flow. In addition, the reduction in water speed will hinder the deposition of particles, which will affect the benthic zone and modify the water level [43].

4.3. Proposal of Solutions to Mitigate Socio-Economic Impacts

The implementation of marine energy in Peru can cause negative impacts such as those mentioned above. However, these impacts can be gradually mitigated if they are addressed appropriately. Regarding the social component, it is vital to have initiatives and projects that not only offer training and environmental education but also active participation by the actors involved. Likewise, regarding environmental conservation, it is essential to have sustainable solutions that protect the affected ecosystems and allow the integration of renewable energy generation technologies with a lower impact.

Environmental education is one of the most important actions to mitigate the most relevant social impacts. Therefore, it is necessary to have environmental education projects. Informing the population in a clear and transparent way about the positive impacts of the use of marine energy contributes to reducing or avoiding possible rejection by the population. Furthermore, renewable energy sources generate great benefits not only from an environmental point of view but also from a socio-economic point of view. In Peru, the coastal area is not only surrounded by large and widely developed cities; there are also small developing communities. In these places, access to electricity throughout the day is often limited or non-existent. For this reason, a key objective is to increase access to electricity in rural areas, which is crucial for economic development and poverty reduction [49]. A key focus is increasing electricity access, particularly in rural areas, which is crucial for economic development and poverty reduction, and that is why it is necessary to have an informed population that does not only observe the negative externalities.

In addition, it is essential to address the negative social impacts, taking into account community participation. In the case of the impact on artisanal fishermen, for example, it is key to highlight the important role that institutions such as IMARPE would play. Programs such as "Strengthening Artisanal Fishing" not only promote more responsible fishing, but also provide useful scientific information to obtain greater fishing productivity [41]. This would help artisanal fishermen adapt more easily to the new marine conditions generated by the existence of marine energy generation projects.

In addition, training programs should be provided where all the efforts and precautions that would be taken to reduce the negative socio-environmental and economic impacts are made known. With an adequate management and use plan for marine energy generation, a positive economic impact will be produced in Peru. Marine energy can influence the economic system of an entire region, contributing to the sustainable development of the entire economic system and providing clean energy for human development [44].

On the other hand, if there is a sustainable development program in marine energy generation areas and an adequate coastal zoning plan, recreation activities, fishing, the tourist industry, and navigation, among others, will be able to recover from the possible impacts that energy generation in the place could generate. With the existing resources, the improvement of technological efficiency could substantially increase the economic production and environmental conditions of the maritime industry [44]. In addition, with having a good sustainable development program, exclusive zones for both artisanal and industrial fishing will be clearly defined. In this way, the existence of zones exclusively assigned to the production of marine energy can also be guaranteed, thus achieving a relationship of mutual benefit for society in the place.

In tidal power generation projects, for example, the use of barrages as part of the power generation infrastructure is quite common. However, such barrages are located in the littoral zone, which could lead to the isolation of ships and create socio-economic problems. In addition, a case study on the west coast of the UK showed that the area has five estuaries with the potential for tidal barrage power generation. However, the installation of such an infrastructure could increase the tidal amplitude on the east coast of Ireland, resulting in coastal flooding. This, in turn, would again have social and material repercussions, affecting recreation activities in the area and changing the landscape.

4.4. Proposal of Solutions to Mitigate Environmental Impacts

One of the actions to mitigate negative environmental impacts in the implementation of marine energy in Peru is the adequate control of underwater noise levels. Due to the numerous effects that noise pollution can cause, it is important to characterize marine soundscapes in terms of sound pressure levels [50], since this type of pollution would affect a large number of marine species present in the Peruvian sea. The inclusion of acoustic metrics in marine spatial plans will allow us to achieve conservation objectives more quickly than trying to mitigate them after a habitat has been degraded [47]. We encourage spatial planners to work with existing gradients in noise distribution levels and marine mammal distributions.

In turn, it is important to carry out a detailed environmental impact study that takes into account possible geomorphological changes and their impact. In addition, analyses or studies that relate the efficiency of marine energy generation with the level of environmental impact in certain areas would be highly recommended. In this sense, it is vital to better define marine conservation and protection zones. According to the Ministry of the Environment MINAM in Peru, today, 7.48% of the maritime domain is protected through protected natural areas in the marine and marine-coastal sphere. This shows that there is great potential for improvement and growth in terms of marine conservation areas in the country. In addition, continuous monitoring in the areas where projects are located, as well as in their surroundings, will provide the opportunity to evaluate negative externalities over time and consequently allow the generation of solutions that are adapted to said externalities.

Negative externalities resulting from the location of dams or facilities in areas close to coastal edges for the generation of marine energy can affect the activities and behavior of marine mammals, fish, and birds. This is why an appropriate mitigation solution is presented when ship locks and fish passages are added to the dam, since new safe spaces of connection between the sea and the shores are added as part of these projects, thus facilitating entry routes to certain coastal parts. In this way, interference with fish migration and navigation channels is avoided and the development of tidal power projects is allowed in less environmentally sensitive places [51].

5. Discussion: Challenges, Opportunities, and Future Directions for the Insertion of Marine Renewable Energy in Peru

5.1. Challenges

The research gap covered in this review is a comprehensive analysis of marine energy implementation in Peru considering a blue energy concept which was not covered by previous researchers.

Peru, with 3000 km of coastline and a great internationally recognized potential in marine energies, has set its intention to adopt an active role in the development of these technologies in the country. A call for tenders must be made for the implementation of a Research Center of Excellence. In order for this effort to materialize, it is essential to support the implementation of pilot research projects in the country.

The individual efforts of national entrepreneurs and developers must be supported. The mining industry can be a great ally of this type of technology, associated with energy generation, water pumping, and desalination. In addition, it is necessary to develop instruments to support the installation of marine technologies in remote areas where the cost of energy is high. Although the costs are currently high, in several countries (especially in the United Kingdom and Scotland) it has been observed that implementing systems to support the development of these types of technologies results in important positive impacts, both social and economic. These impacts are mainly related to the industry created around marine energy, which involves the creation of jobs and a supply chain of products and services required by the industry.

The challenge of renewable marine energy in Peru involves the development of a marine plan for the use of the sea and the coastal border with a vision for the future. The entire marine environment must be planned and managed considering all the actors, including civil society, military, industry, authorities, and NGOs. This implies defining activity zones such as fishing, tourism, recreation, natural reserves, etc. Such planning and management must be done in latitude/longitude and depth of the seabed.

To achieve this objective, a strategic environmental planning instrument for the use of the sea must be created, and be constantly updated with the advance of time and technologies.

It is also noted that in terms of classification and recognition of energy potential in marine areas within Peru, there is still a wide potential for improvement, since there is very little information available that quantitatively exposes the real energy potential of specific areas within the Peruvian coast for the generation of wave or tidal energy. Such quantified information would, however, be of great interest, since it could concretely demonstrate how feasible the implementation of this type of project is within Peru, and thus it would be possible to obtain the attention of the authorities as well as companies investing in this type of energy generation projects in specific areas. For this reason, it is necessary to strengthen the national regulatory framework in terms of environmental research in order to achieve the effective promotion of the development of technologies and innovations within the marine energy generation sector.

Furthermore, it is known that the implementation of pilot projects for the generation of this type of renewable energy can be extremely expensive. For this reason, it is necessary to propose a strategic collaborative approach to be able to finance part of these pilot projects. This could be achieved, for example, through a financing network based on cooperation with public and private entities, universities, and research centers interested in applied research on marine energy, as well as through the support of external investors within the energy industry who are interested in developing projects of this type in the future on the coasts of Peru.

Finally, the following Table 14 presents a comparative analysis considering wave energy and tidal energy devices presented in this review.

Table 14. Comparative analysis of wave and tidal energy devices.

Characteristics/Devices	Wave Energy Converter	Tidal Energy Converter
Number of Presented Devices	8	4
Maximum Installed Capacity	11.0 MW (overtopping wave energy device (Wave Dragon))	2.0 MW (horizontal axis turbine tidal stream energy device (Sea Gen Turbine))
Technical Advantages	- Structures can be aligned with the direction of waves having the potential to absorb energy coming from different directions - Structures are placed offshore	- Work thanks to the difference of water flows in bays (tidal cycles) - Structures are closer to the coastline making access to them easier
Environmental Advantages	Since offshore, does not directly affect the coastal ecosystems and does not generate changes in the water levels	Since on the coastline, the risk of affecting big mammals and marine live the colliding accidents with these structures is lower
Technical Disadvantages	Because of the emplacement, the operation cost and the maintenance of the systems can be high, reducing the feasibility	For systems such as barrages, the cost of construction is high and it requires a modification of the coastal zone of placement
Environmental Disadvantages	It can lead to problems such as masking, marine live disorientation, and marine live fatalities due to collisions or entanglements	It could change the coastal currents affecting the wildlife on the coast and change patterns of the marine ecosystem behavior

As a conclusion, considering Table 14, wave energy converters and tidal energy converters offer advantages and disadvantages that need to be considered for the coast of Peru. According to the characteristics of the coast of Peru and its wave energy potential, wave energy converters will be more popular in the following years to develop marine energy.

5.2. Opportunities

Peru is to marine energy reserves what Saudi Arabia is to oil reserves on the planet. This forces us to ask ourselves some questions: (i) Is Peru interested in studying and taking advantage of this renewable energy reserve? (ii) If it is going to take advantage of marine energy, will it be a simple user of technology? (iii) Or will it take advantage of this competitive advantage to build a globally deployed technological industry?

The pillars of the development of the marine renewable energy industry in Peru to be considered today for a successful future consider the following opportunities:

- Regulatory framework: Current policies, leases and concessions, planning of marine and hydrological space, and permits and licenses. A consistent and clear regulatory framework facilitates the development of new industries.

- R&D and technology: Research developed and in progress, potential lines of research, market niches, state of the art of national and international technology. Collaboration between the academic world and the private sector makes it possible to identify research needs with greater development potential. Technological development must focus its efforts on current market niches, for example, areas of water scarcity.
- Knowledge transfer: Study centers and collaboration and dissemination networks. International cooperation is key to advancing the marine renewable energy industry.
- Infrastructure and supply chain: Electricity grid, maritime, port, and industrial infrastructure, and supply chain and local skills. Adequate infrastructure has the role of enabling the marine energy industry. Integration between the marine renewable energy industry, the fishing industry, the port industry, the oil and gas industry, the naval tourism industry, the shipbuilding industry, and the offshore wind energy industry, among others.
- Financing: Determining factors in the financial viability of marine and river energy, markets for marine energy, and industry needs and support currently available.

Taking advantage of the potential for generating marine and wave energy will allow for a diversification of the energy matrix in Peru. In this way, the percentage of energy generated from renewable energy sources will be increased and the dependence on the consumption of fossil fuels for energy generation will be reduced. In this way, it will be aligned with the objectives of sustainable development. Likewise, the implementation of wave energy generation projects will contribute to achieving the international goals and commitments assumed by the country in the framework of the fight against climate change and the promotion of a sustainable future. Peru could become a benchmark in the generation of clean energy from marine water resources.

On the other hand, opportunities for development, research, and application of theoretical knowledge would be generated within the technological industry of marine energy generation in the Peruvian territory, thus achieving an increase in the competitiveness and relevance of Peru in this area within South America. In addition to this, with the implementation of pilot projects, feasibility studies can be carried out for the larger-scale development of these technologies within the country, thus increasing the possibility of a transition to a blue economy.

Furthermore, it will be possible to provide better training opportunities to students and professionals specialized in renewable energy generation, hydraulic engineering, and professionals within the field of sustainability and environmental management, thus encouraging research and attracting potential international collaborators who contribute to the development of these technologies, as well as the optimization of the same for their use within the region, while achieving the growth of the scientific community and research in sustainable matters in the area.

5.3. Future Directions

Industry 4.0 technologies are also part of the development of renewable marine energy, where it refers to technologies such as artificial intelligence, the Internet of Things, big data, sensors, cloud computing, and data analytics, but also refers to advanced robotics applications, advanced mathematical modeling, and prediction programs, among others. Some of these applications are advancing and being adopted by different renewable energy plants to improve performance and create an efficient energy management system [52]. In this sense, there are currently projects that investigate how to apply recent technology to evaluate marine energy systems in order to create a sustainable environment [52].

The implementation of Industry 4.0 technologies is present in a large number of industrial activities today. Regarding their uses in marine energy generation, it is observed that these types of technologies are applied in the modelling of the operation of marine energy generation plants. An example of this is an artificial intelligence (AI) model based on data from the La Rance tidal dam, in which the data on the operation of the power plant are used to parameterize the turbine, gate, and basin models [53].

On the other hand, in terms of feasibility analysis of marine energy generation projects, recent research also uses drone-based technology to measure tidal range and sea depth. Furthermore, in the operational stage of such power generation plants, data mining and analysis are also used to predict or forecast tidal energy resources and measure future load demand of the tidal power plant [52].

Furthermore, in the case of artificial intelligence, tidal and wave energy can also benefit from the data-driven conclusions and predictive models of AI [53]. This could contribute to better prediction and reduction of impacts from renewable energy generation from the use of marine energy. In addition, future use of artificial intelligence in marine energy generation may contribute to the development of robotic automation system for tidal power plant maintenance, and a machine learning-based reliability measurement system for tidal power system. In this way, it is possible to develop an artificial intelligence-based control mechanism for tidal power system. The height of the tide and waves is the input parameter for supervised and unsupervised learning of artificial intelligence systems [52].

On the other hand, artificial intelligence can also be used in wave energy generation projects to achieve improvements in energy capture efficiency and cost reduction within the project. In 2021, a dynamic model study was carried out for a wave energy converter. In this study, an algorithm was developed that controlled wave energy in real time through predictive control models and artificial intelligence. This algorithm was able to predict the possible future strength of the waves, and thus generate a dynamic response to these conditions. It was concluded that, thanks to the implementation of real-time control, energy capture efficiency increased by around 30% [54]. In addition to this, the authors concluded that this algorithm also proved to be a robust model for wave conditions, which means that its use can be applied in a wide range of maritime sites [54].

Regarding the role of AI in marine energy, in the case of tidal and ocean power generation, artificial intelligence technology is key to improving the performance of these energy production systems. In tidal power generation projects, for example, difficulties may arise during the operational phase that require accurate analysis, including system maintenance. Tools such as reliability analyses provide information on various parameters that could indirectly and directly affect the system's performance. For cases like this, an improved model worked with artificial intelligence provides a positive contribution. Moreover, this improvement is only possible since artificial intelligence helps to improve predictions and modeling, and creates a relationship between the various parameters involved in marine energy generation.

In another study, through the use of an optimized artificial neural network/artificial intelligence, the aim was to evaluate the wave energy resource available in a Mediterranean energy generation project throughout its useful life. The most suitable locations for the construction of generation projects within the study area were also highlighted. All of this took into account the possible effects of climate change on wave energy generation projects. In this study, it was concluded that the results demonstrated the potential of the artificial neural network model to evaluate the long-term availability of wave energy, significantly reducing the computational cost [55]. Furthermore, it was stated that this technology represents a useful tool to assist engineers, managers, and policy makers in the selection of more promising locations for wave energy facilities, taking into account the effects of climate change [55].

6. Conclusions

Peru has excellent conditions in terms of marine resources to produce wave energy, and the installation of different devices in the coming decades will represent a great advance in issues of sustainability, energy transition, and the fight against climate change. In addition, ocean energy technologies could facilitate the integration of variable renewable energy sources during the day, such as photovoltaic solar energy and wind energy.

Currently, in 2025, most ocean energy technologies have not reached commercialization and are still in the development stages; most technologies are in the prototype phase, with the exception of some that are reaching early commercialization.

Marine energy has the following competitive advantages: (i) It is renewable energy, (ii) available 24/7, 365 days a year; (iii) the energy produced is more stable and more predictable (high capacity factor CF); (iv) there is abundant statistical information; (v) waves contain 1000 times more kinetic energy than wind; (vi) it is an attractive technology to be implemented in isolated places; (vii) energy consumption areas are relatively close to the coastline; (viii) good availability of access roads (current and under construction) in areas with potential; (ix) the existence of adequate bays for maintenance and operation of equipment; (x) growing demand for energy in the country; (xi) need for generation with clean technologies (environment); and (xii) need to diversify the energy matrix.

Although there are uncertainties regarding the cost of producing electricity from marine energy, the potential for cost reduction in the future is high and the socio-economic benefits in the sector that they could create for Peru are significant.

The ongoing energy transition seeks to establish a sustainable and secure global supply for human activities. While most attention has been directed towards continental systems, promising blue economy markets (BEMs), ranging from offshore aquaculture to seawater desalination and green hydrogen production, will require an increased energy supply to meet their projected growth. Whether it is powering sensors or the electricity demand of electric ships, energy needs must be met with sustainable solutions, both from an economic and environmental perspective. To this end, several sources of marine renewable energy (MRE) can provide suitable on-site options, at acceptable costs, while promoting the energy independence of BEMs.

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Abbreviations

TRLs	Technology Readiness Levels (TRLs) is a scale from 1 to 9 where 1–3 represent the research phase, 4–5 represent the development phase, 6 represents the demonstration phase, and 7–9 represent the deployment phase (with 7 representing prototype demonstration and 9 a fully deployed, proven, and operational technology).

R&D	research and development
MRE	marine renewable energy
OTEC	Ocean Thermal Energy in Celsius Degrees
BEM	blue economy market
EMEC	European Marine Energy Center
ESMAP	Energy Sector Management Assistance Program
IRENA	International Renewable Energy Agency
CF	capacity factor
WEC	wave energy converter
EIA	environmental impact assessment
MINAM	Environmental Ministry of Peru
IMARPE	Sea Institute of Peru
RER	renewable energy resources
ENSO	El Niño Southern Oscillation
kW	kilowatts
MW	megawatts
GW	gigawatts
MWh	megawatt-hour
GWh	gigawatt-hour
TWh	terawatt-hour
Ha	hectare
masl	meters above sea level

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