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Review

A Review of Offshore Renewable Energy in South America: Current Status and Future Perspectives

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Abstract: This paper addresses the current status and future research and development perspectives associated with technologies to harness offshore renewable energy, including offshore wind, waves, tides, ocean currents, and thermal and salinity gradient, in South America (SA). It focuses on five countries: Argentina, Brazil, Chile, Colombia and Uruguay. At first, a comprehensive survey presents the number of scientific papers classified based on the resource to show the tendency and importance of such subjects in the academic community. Each country's electricity matrix and grid connection are shown to understand the region's renewable source participation situation. The potential of offshore renewable resources is addressed by considering the published technical papers in scientific journals. The main conflicts and synergies associated with ocean space utilization are presented by considering the exclusive economic zone of each country. The status of the regulatory frameworks to promote and development of offshore renewable energies is presented. Two sections are dedicated to presenting the active, decommissioned and planned projects, research groups and laboratory infrastructures to develop the technologies. The last section discusses the future perspectives on the development of this sector in SA. It is observed that SA, with more than 25,000 km of coastline, has a great potential for offshore renewable energy; however, so far, these resources have not been explored commercially. Larger investment in the sector, establishing an adequate legal framework and deploying full-scale demonstration projects at sea are necessary for the commercialization of such technologies in SA.

Keywords: South America; marine energy; offshore wind; renewable energy

1. Introduction

In ratifying the energy sector's decarbonization strategies and in response to climate change, with the fulfillment of conservation and emission reduction goals, as well as the search for energy development and security within the scope of the Paris Climate Agreement's common goals, renewable energy technologies are regarded as important measures to achieve them, in harmony with economic, social and environmental development. The ocean is the largest ecosystem on our planet, covering approximately 71% of the Earth's surface [1] and has provided civilizations with various existentially important services. To strengthen the international cooperation required for the development of scientific research and innovative technologies that can connect ocean science with societal needs, UNESCO's Intergovernmental Oceanographic Commission (IOC) has declared the period 2021–2030 as the Decade of the Oceans for Sustainable Development, an idea directly linked to the 2030 Agenda [2]. In addition to its critical role in climate regulation and ecosystem services, the ocean is critical to the global economy, with over 90% of trade using sea lanes and providing jobs for millions of people, as well as hosting a growing range of new related economic activities and constant innovations (OECD, 2022) [3]. The use of ocean wealth is in the context of the blue economy and the discussion of sustainability, which includes renewable energy resources, with the ocean representing a massive source of untapped energy. According to the OECD (2016) [4], the blue economy will more than double from USD 1.5 trillion (in 2010), a very conservative global economic value, to more than USD 3 trillion in 2030 and will generate around 40 million jobs in a sustainable scenario (in 2010 there were 31 million).

Offshore renewable energy (ORE) sources can be divided into two categories, as shown in Figure 1. The first one is marine energy which includes the sources originating from seawater and is defined as energy captured by technologies that utilize motion, heat or chemical potential. It includes ocean surface waves, tidal range, currents, thermal and salinity gradients and ocean currents. The second one includes the sources available in the ocean space, such as offshore wind and floating solar.

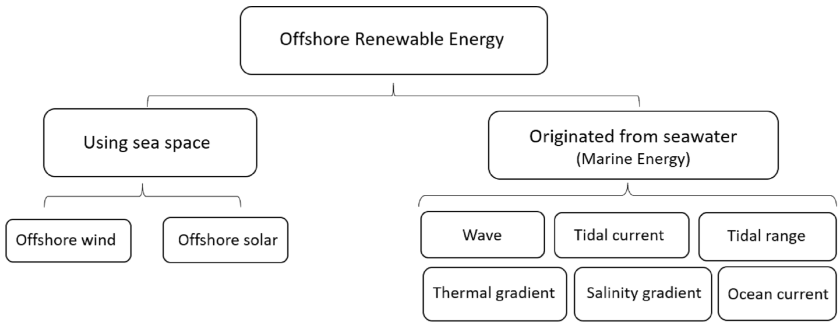

Figure 1. Offshore renewable energy categories.

The air–sea surface interaction induced by wind is the origin of the waves exploited by the ocean wave energy converters (WECs). Wind needs to blow over a sufficiently large area of the sea, called "fetch," with an adequate velocity to form waves. Consequently, the wave size increase and will continue to exist even when the wind stops blowing. The most energetic waves on Earth can be observed between 30º and 60º latitudes generated by extra-tropical storms [5]. The global theoretical wave energy potential is estimated to be about 32,000 TWh/year [6]. The tidal energy derived from the changes in water level results from the filling (flood tide) and emptying (ebb tide) of the coastal areas. It can be harnessed in two ways: tidal range, which is the potential energy resulting from high and low tides, and tidal current, which is the kinetic energy of the horizontal movements of water resulting from the tidal rise and fall. Tides are generated from the gravitational and centrifugal forces of the Earth–Moon–Sun system. The global theoretical potential of tidal energy (tidal range and current) is estimated to be about 500–1000 TWh/year [7]. Ocean currents originate from the latitudinal distributions of winds and thermohaline ocean circulation. The relatively low ocean current velocity and the fact that they often occur in deep waters imply major technical and economic challenges regarding the real application of the devices to extract such energy.

A significant part of the energy from the Sun is stored in the ocean as thermal energy. Consequently, the superficial layers are warmer than those near the ocean floor, mainly composed of water coming from the poles and high latitudes [8]. Accordingly, the existing thermal gradient along the water column in the ocean can be harnessed to produce electricity. The ocean thermal energy conversion (OTEC) has a theoretical net power production of 30 TW (259,200 TWh/year, assuming a constant supply throughout the year). A more realistic and environmentally safer approach suggests a potential up to 7 TW [9]. Deep ocean water (DOW), which has emerged recently, is the cold water (around 5 °C) located far below the ocean's surface. The DOW is an exploitable resource with several applications. For instance, its low temperatures can power a cooling system, such as seawater air conditioning (SWAC) [10]. It can also produce electricity and desalinized water using the temperature gradient with surface water through OTEC (Nihous and Gauthier, 2012 [11]). Arias et al. (2019) [12] applied a methodology to five cities (Bridgetown (Barbados), Montego Bay (Jamaica), Puerto Plata (The Dominican Republic), San Andres (Colombia) and Willemstad (Curacao)) in the Caribbean. They found that the average potential of DOW is about 50 m^3/s per city, enough to supply more than 100% of a city's demand for air conditioning and 60% of its electricity demand (1000 GWh of energy per year in all five cities). Ocean thermal gradient offers a great opportunity mainly for countries near tropical latitudes. The salinity gradient energy (SGE) (also called osmotic energy or blue energy) is available to mix two water bodies with different salt concentrations. This process occurs naturally in river mouths [13] and coastal lagoons [14]. Alvarez-Silva et al. [13] estimate Global SGE's theoretical potential to be around 1.4–2.6 TW ($\sim$15,102 TWh/year), while the global technical potential is around 0.07 TW (625 TWh/year). Significant potential is observed in SA&C, including Orinoco (Venezuela), Parana (Argentina), Magdalena (Colombia), Uruguay (Uruguay-Argentina), Atrato (Colombia), Doce (Brazil) and Bío-Bío (Chile).

In the scenario of expansion and exploration of offshore renewable sources, cost reduction, technological advances and performance improvements have favored the opening for further development of offshore wind energy. Its global growth reached 25 TWh in 2020 [15] and it is expected to grow 15 times over the next 20 years, reaching USD 1 trillion in business investments [16]. Considering wave and tidal resources, the IEA (2018) [17] predicted that installed power capacity will exceed 30 GW by 2040, with 85 TWh produced. Tidal, wave and other offshore energy sources account for approximately 1100 jobs globally [18], with estimates of 20,000 jobs for marine energy technologies by 2035 [19].

Population growth and socioeconomic development are driving South America's increasing demand for electricity. Total electricity consumption in 2019 was 1002.3 TWh [15]. Argentina, Brazil, Colombia and Chile had higher per capita electricity consumption than the rest of the region. As reported by [20] (Figure 2), Venezuela, Chile, Suriname and Argentina have the highest CO2 emissions per capita from fossil fuels and industry. Due to the persistence of economic and demographic growth dynamics that increase the electricity demand, it is critical to ensure the capacity and environmental sustainability of new energy projects, paving the way for energy efficiency and the promotion of renewable technologies. SA has more than 25,000 kilometers of coastline, which provides a wealth of diversity and opportunities for using ORE sources [21]. In addition to grid-connected electricity generation, "energy islands" with a mix of renewable sources can be attractive alternatives for many isolated communities without electricity access along the SA coastline. However, electricity grid topology and eventually required expansion must be considered to insert ORE sources in the electricity matrix of the countries.

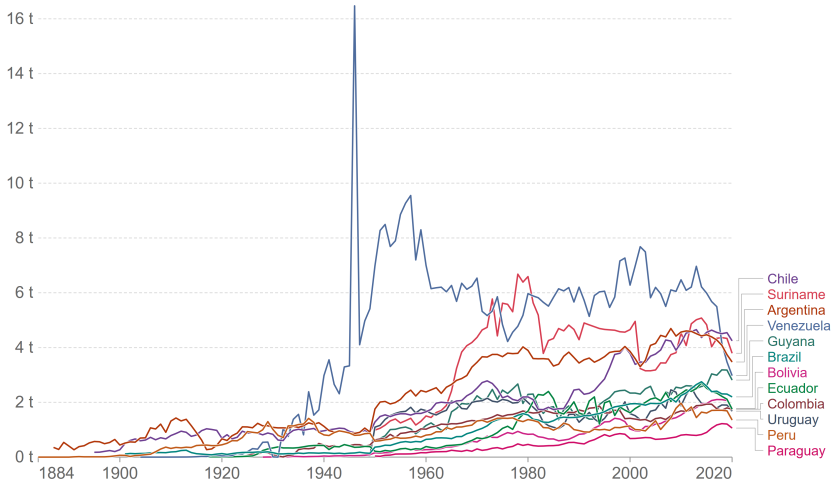

Figure 2. South America's Carbon dioxide (CO_2) emissions from fossil fuels and industry [20].

Considering this potential, this work aims to assess SA's current status and the state of the art regarding resources, technologies, competencies, infrastructures and regulations and point out the gaps and future challenges. The paper focuses on five countries, Argentine, Brazil, Chile, Colombia and Uruguay, and can contribute to the discussion of regional energy integration by providing a comprehensive overview of the current status of ORE in SA. This work is structured in nine (9) sections: A technical work survey showing the scientific publication in this area (Section 2), electricity supply and grid systems (Section 3) and resource potential based on the existing papers and reports (Section 4). Then, the main conflicts and synergies in the use of ocean space (Section 5), regulatory issues regarding the ORE systems' deployment (Section 6) and outstanding projects, including installed prototypes, as well as small-scale models under development (Section 7), are addressed. The main research groups and laboratory infrastructures are identified (Section 8). The last section (Section 9) highlights the major challenges of developing ORE in SA and presents recommendations for the future.

2. Survey of Technical Works and References

Considering the offshore renewable energy resources in the South American context, the meta-analysis research comprises 240 scientific publications between 1972 and 2022. It includes 208 papers from peer-reviewed journals, 28 from conference proceedings, 3 books and 1 book chapter. These works' theme includes current energy (17), ocean thermal gradient (12), salinity gradient (13), tidal energy (39), wave energy (92) and offshore wind (77). Figures 3 and 4 show the works' geographical distribution, revealing the countries' tendencies. Brazil has the largest number of scientific papers (107) with a tendency to offshore wind and wave energy. The principal research areas in Colombia, with 41 technical papers, are related to offshore wind, salinity gradient and wave energy. Chile, Argentina and Uruguay, with 41, 33 and 10, respectively, show a significant tendency to wave energy followed by tidal energy. In Chile, much research is associated with offshore wind energy. Ecuador (1), wave; Guyana (1), wind; Peru (1), wave; and Venezuela (5), tidal, wave and wind are the other South American countries that have worked in this area. The majority of these works are associated with the resource assessment, for instance, [22–25], as well as topics such as techno-economic feasibility [26–28], device performance and application of control systems [29,30], resource variability [31,32], resource complementarity, such as wave energy and ocean current in Brazil as presented in [33]. Additionally, some researches address the environmental and economic impacts of ORE [34,35], investigate the regulatory aspects [36,37] and analyze the environmental licensing [38,39].

2.1. Argentina

In Argentina, most research is related to wave and tidal energy. The Ocean Energy Catalog [40] is the second edition of an inventory on marine energies that compiles studies, initiatives and projects from all over the world. Das Neves Guerreiro and Chandare [41] carried out the first study to assess the wave resource in deep waters along the Argentinian coastline, using reanalysis for 10 years. The project's progress of the first WEC in Argentina, along with the 10 years of research developed by the wave energy team of the National Technological University, Buenos Aires Faculty, can be found in [42]. Regarding the tidal energy, researchers from the Hydraulics Laboratory of the National Water Institute (INA) [43] presented the energy potential of tidal currents in five Patagonian estuaries using numerical modeling where the maximum tidal amplitudes range from 6 m to 13 m.

2.2. Brazil

Most of the scientific publications in Brazil are associated with offshore wind and wave energy resources. In the totality of 107 scientific publications on ORE in Brazil, a total of 46 include offshore wind subjects, including theoretical, technical and economic potential assessment [22,28,44–46], resource complementarity including hydropower, offshore wind and offshore solar [47,48], offshore wind environmental [34] and social [49] impacts and regulatory aspects [36]. Research about wave energy in Brazil started in 2000, focusing mainly on wave resource potential [50,51], wave-to-wire modeling [52], geometry optimization [53] and control systems and strategies [30,54–56], experimental tests including dry tests [57] and reduced scale models in wave tank [58], economic feasibility [27] and environmental aspects [59] of WECs. Some works, including [31,60] and [23], are examples of studies that addressed tidal, ocean current and OTEC, respectively.

Figure 3. South America's technical paper production associated with offshore renewable energies.

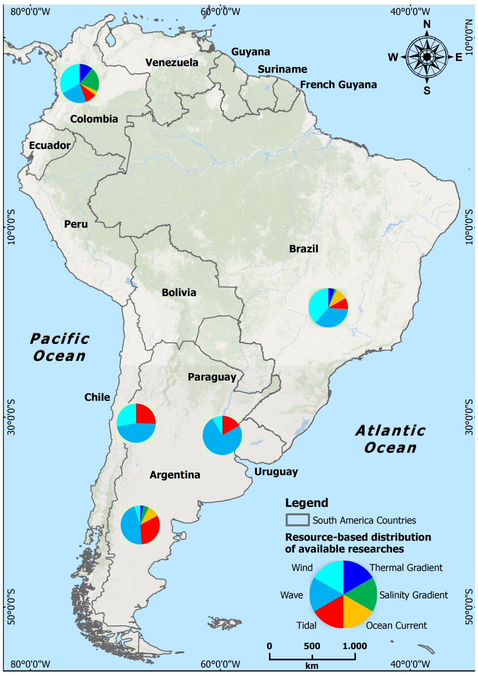

Figure 4. South America's resource-based distribution of available research associated with ORE.

2.3. Chile

Offshore energy research in Chile materialized in 41 scientific papers, started in 2008 with resource potential assessment of wave energy [61] but extended from 2014 to 2017 with the resource assessment of offshore wind [62–65], wave energy [66,67] and tidal [68,69], identifying, for example, places for a potential project for extracting offshore renewable energy. Since 2017, the trends in scientific publications in Chile have led to more applied research, for example, evaluating mathematically the behavior of different devices in the Chilean sea [70–73]. Since the creation of the Marine Energy Research and Innovation Center, MERIC, in 2015, special attention has been paid to the research lines pursued by this center. For instance, biofouling and marine corrosion is a topic that is particularly aggressive on the Chilean coast and requires special treatment to implement ORE devices [74–76]. In recent years, research has mostly focused on improving technologies and novel techniques to make ORE more competitive considering the country's particular characteristics [77–86].

2.4. Colombia

Marine energy research, especially offshore wind, is rapidly growing in Colombia. Over the past 15 years, several scientific documents have been published. Most of them addressed the offshore wind potential at regional [87–89] and national–local scales [24,32,90–94]. Technical aspects of offshore-wind development have been addressed, such as the effect of extreme events [95], opportunities for employing the current shipping building industry [96] and the general feasibility of its implementation in the country [97–99]. Colombia-related researches in wave energy include energy potential assessments [100–103], and technology design [104]. Thermal and salinity gradient assessments include resource quantification and feasibility studies [105–107], identification of technical challenges [108–112], technology design [113], novel applications [12,114] and multidisciplinary studies that would serve as input for roadmaps [115,116]. Furthermore, some research focused on Colombia's marine energy opportunities [115,117,118].

2.5. Uruguay

Located in mid-latitudes with a microtidal coast, wave energy appears to be the most suitable form of marine energy in Uruguay. In this sense, two wave hindcasts were developed [119,120], from which the wave climate was investigated [121] and the wave resource was assessed both isolated [119] and in combination with marine currents [122]. Regarding conversion technologies, prioritizing nearshore devices where electrical energy generation can be onshore, Uruguayan research has focused on a type of WEC known as an Oscillating Wave Surge Converter (OWSC) pumping ocean water onshore using a hydraulic cylinder. Starting from an analytical approach that allowed assessing the technical potential of this device located on the breakwater of the port of La Paloma [123], the research continued with a 1:10 physical model of the OWSC under regular and irregular waves conducted in the large wave flume of the Instituto de Mecánica de los Fluidos e Ingeniería Ambiental (IMFIA), Universidad de la República [123,123]. Numerical studies accompanied the experiment [124] and also an experimental study of the hydraulic cylinder used as power take-off (PTO) [125].

3. Electricity Supply and Grid System

3.1. Argentina

Thermal power plants powered by natural gas (TGC) are Argentina's main electricity generation source. As illustrated in Figure 5, according to the report of the Ministry of Energy, the installed electricity capacity at the end of 2021 reached 42,989 MW, of which 59% corresponds to thermal power plants with fossil fuels, 25% with hydroelectric plants of approximately 50 MW, 4% of nuclear energy and 12% of other renewable energy. According to the Secretary of Energy of Argentina, there are currently 187 renewable energy projects in operation, of which 64% correspond to onshore wind, 20% to solar, 11% to hydroelectric and 5% to biomass. As shown in Figure 6, the Argentina Interconnection System (SADI) is the electrical network of high-voltage lines interconnecting Argentina's regions. The network collects and transports all the electrical energy generated in the country. It has 20,296 km of trunk distribution and 14,197 km of 500 kV lines.

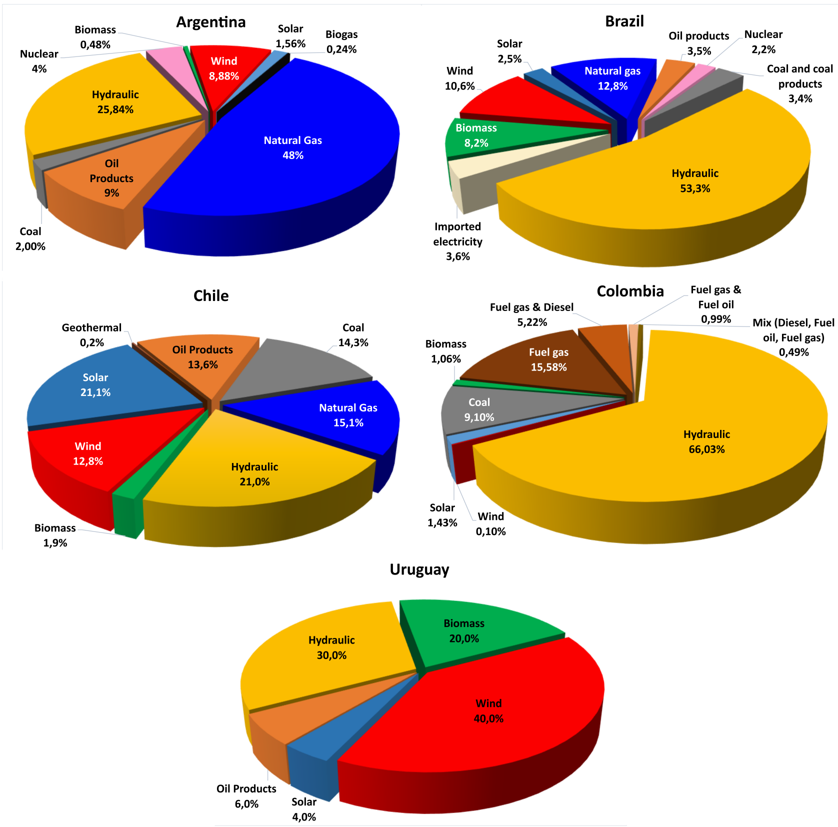

Figure 5. Electricity matrix of the countries.

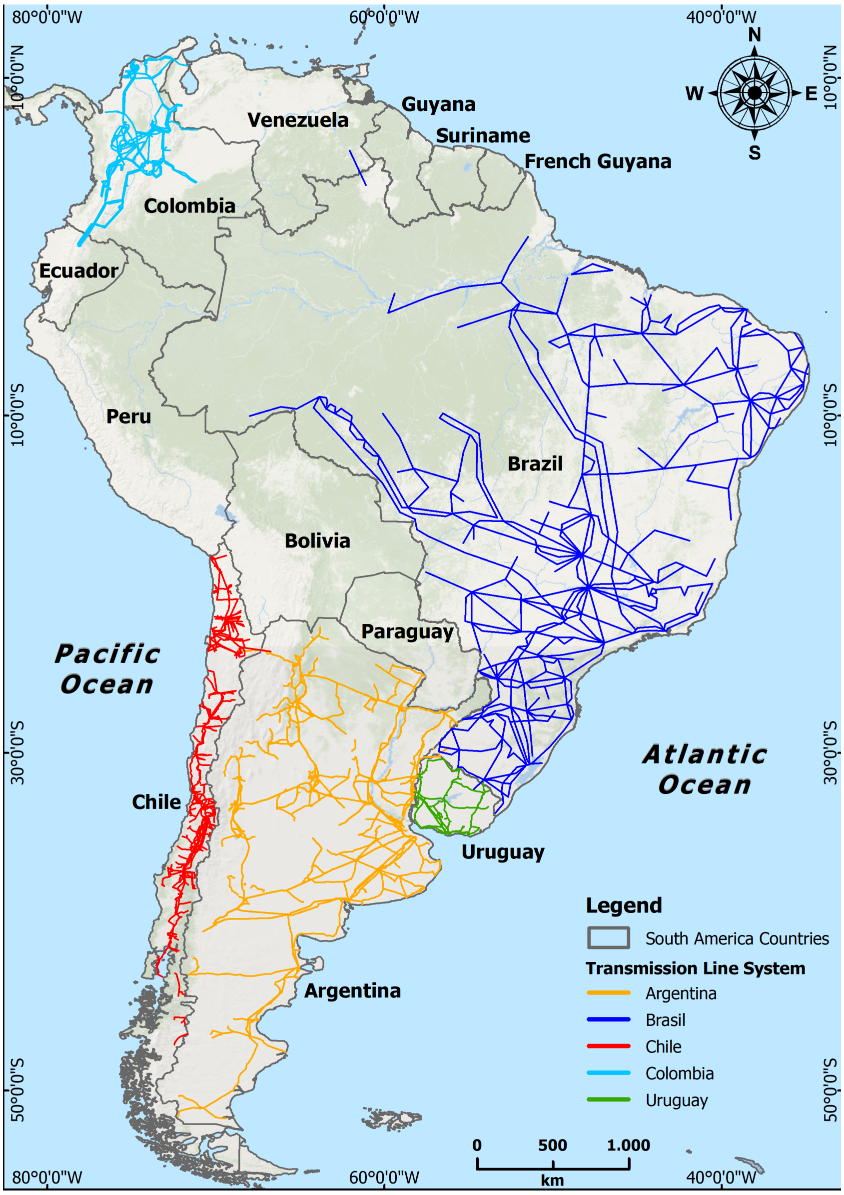

Figure 6. Main electrical grid of Argentine, Brazil, Chile, Colombia and Uruguay.

3.2. Brazil

Brazil, whose electricity generation and final consumption in 2020 were 645.9 TWh and 540.2 TWh, respectively, has a predominantly renewable electricity matrix, as shown in Figure 5, which represents 84.8% of the country's domestic electricity supply. Hydropower is the main source, representing 65.2% of the electricity matrix distributed in 2160 reservoirs. Nonrenewable electricity generation accounted for 15.8% of total national generation in 2020, with a 5.4 TWh decrease in domestic supply, 0.8% lower than 2019 [126]. Onshore wind generation, with 57 TWh (1.9%) and solar generation, with 10.7 TWh (61.5%), advanced and grew significantly [127]. Hydropower has been the predominant source of the Brazilian electric sector for the last 70 years. Nevertheless, the dependency of the electricity matrix on hydropower is a concern, particularly in the context of the seasonal and annual stability of the hydraulic source. Considering growing demand driven by economic growth, population development, environmental issues, energy security and the climate problem, new sources and technologies must be incorporated to avoid vulnerabilities in energy supply, where renewable sources are crucial. The National Interconnected System (NIS), shown in Figure 6, characterizes the integration of the Brazilian Electrical System (BES), which is made up of four subsystems (North, Northeast, South, Southeast/Midwest) that exchange energy across the country. It comprises a complex network of transmission lines (TLs) which was about 145,600 km by 2020, with a projection of reaching 184,054 km in 2025. Additionally, according to the National Electricity System Operator (ONS), the so-called isolated systems power 212 isolated locations in Brazil, whose consumption represents less than 1% of the country's total load. Most of these regions are located in the North of Brazil, including the Roraima state, the only state not connected to the SIN. The ONS is in charge of the NIS's management. The ONS is a body that identifies necessary planning actions, simulations of the NIS's operation and the inclusion of offers and demands to program and control its operation [128]. The existence of electrical grids near the coastline, with a high population concentration, can be observed as an advantage, especially for ORE generation. However, new infrastructures and eventual adaptations of the existing grid would be required in the case of very large offshore renewable plants.

3.3. Chile

As shown in Figure 5, approximately 41% of Chilean electricity originates from fossil fuels. Solar energy with 21.1% follows fossil fuels and hydraulic is next with 20.8 %. Non-conventional renewable energies increased 11.5 GW during the last decade and in 2022, representing 38.1% of the total installed capacity of the Chilean electrical grid [129]. Private sector companies have fully developed the electrical sector, carrying out the generation, transmission and distribution of electrical energy from the generation plants to the final consumers. The state acts as a regulatory, supervisory and subsidiary entity for energy companies. As shown in Figure 6 the Chilean electrical grid comprises three interconnected systems, which connect the power plants and companies responsible for generating, transmitting and distributing electricity. These systems are the SEN (National Electric System), SEA (Aysen Electric System) and SEM (Magallanes Electric System). Throughout Chile, there are isolated locals without access to any electrical grid. To solve this problem, small systems have been subsidized for each community. SEN grids are extended to the coastline, specifically along the northern part of Chile, which facilitates the exploration of offshore renewable energies.

3.4. Colombia

By October of 2022, the electrical system of Colombia had an installed capacity of 18,130 MW [130], whose main contribution (66%) corresponded to hydraulic generation with 11,971 MW, followed by a thermal generation of 5689 MW (31.4%). The cogeneration from biomass of 192.5 MW equaled 1.1%, while the generation from solar (photovoltaic) and wind (onshore)—258.7 MW and 18.4 MW, respectively—accounted for 1.53% of total installed capacity. Most of the power generated is transmitted through the Colombian electrical grid (SIN), which has 28,428 km of transmission lines: 16,474 km of national transmission–STN lines ($\geq$220 kV) and 11,954 km of either regional-STR or local distribution-SDL lines (<220 kV) [130]. As illustrated in Figure 6, the SIN covers around 40% of the country's territory, sufficient to meet the demands of most of the 97% of the population, mainly concentrated in the Andean and central-Caribbean regions [130,131]. Most non-urban coastal areas depend on STR systems, e.g., the north and south Caribbean (La Guajira and Uraba). Furthermore, the Colombian Pacific region only has STR lines to Quibdo, Buenaventura and its surroundings. Its incomplete connection to the SIN infrastructure is due to the vast tropical jungle. In general, non-connected areas fulfill their electrical needs through small systems fed with fuels. As with other energy sources, adopting large-scale offshore and marine energy resources requires an appropriate transmission system [131]. The latter is in line with the SIN's expansion plan, which emphasizes increasing the kilometers of national and regional transmission lines, adding new connection points, renewing technology, facilitating the inclusion of different renewable energy sources and improving other vital aspects [132]. The SIN expansion is expected to cover areas where marine renewable resources in the Caribbean could take place. On the Pacific coast, transmission infrastructure is challenging because the communities are scattered and there are strong environmental restrictions; however, there is a potential for creating microgrid systems to supply local needs.

3.5. Uruguay

Uruguay has an electricity grid of 83,277 km, which allows it to cover 99.8% of households with electricity supply (see Figure 6). The system is composed of two large high-voltage transmission grids. A 1.078 km 500 kV grid links the four hydroelectric dams with the largest demand center, the metropolitan area of Montevideo. On the other hand, 3923 km and 72 stations of 150 kV grid link the remaining generation plants with almost all the provincial capitals and main consumption centers [133]. The state-owned energy company UTE is the main player in the sector. UTE generates and purchases electricity from private producers and is solely responsible for transmission and distribution [133]. Three connections with Argentina and two with Brazil allow Uruguay to exchange electricity with neighboring countries. Uruguay had become a net exporter since 2013 when the transformation of the energy matrix started. In 2019 and 2021, the energy export exceeded 2.800 GWh, which means about 20% of the total generation [133].

4. Offshore Renewable Resource Potential

Figure 7 illustrates the distribution of offshore renewable resources along SA's coastline. This map is created based on each country's available technical papers and reports and does not necessarily show all the possible resources. It reveals the diversity of the resources, especially in northern regions, including the northeast and north of Brazil and Colombia's coastline. This section presents a comprehensive review of the existing literature and international reports that address ORE resources in SA.

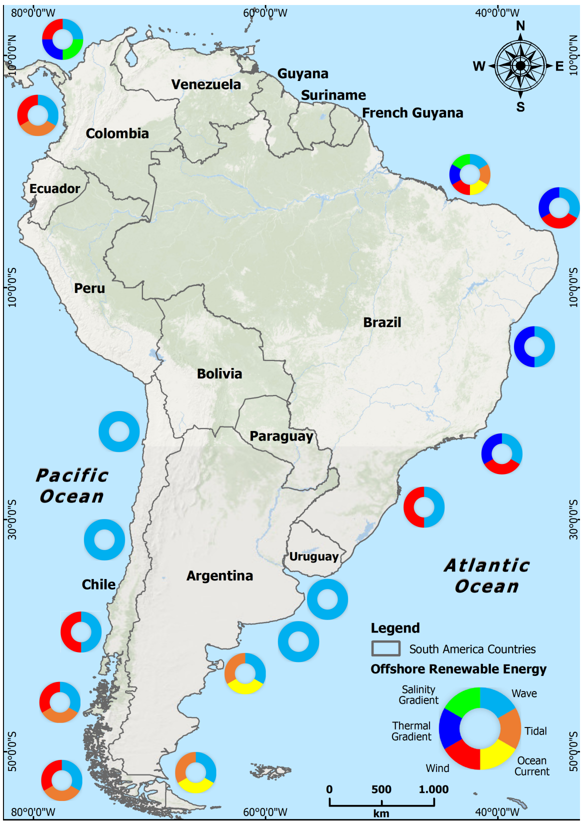

Figure 7. Offshore renewable energy resources along South America's coastline based on the available technical papers and reports.

4.1. Argentina

The Argentinian Sea, with a coastline of about 4725 km, extends from the mouth of the estuary of the Río de la Plata in the north (parallel 35º South) to the island of the States in the south and from the Argentina coastline to the bathymetry of 200 meters including the Malvinas Islands. Waves and tides are two principal energy resources in the ocean studied in Argentina. Wave energy varies from 6 to 60 KW/m along the Argentina coastline. These values are between 30 and 97 kW/m as the water depth increases to 100 meters. The tide amplitude varies between 1 and 2 meters, between ebb and flood tide, in the province of Buenos Aires. The southern region presents higher values of about 15 meters in Rio Gallegos, presenting suitable velocities for tidal current energy harnessing.

4.2. Brazil

Wave, ocean thermal energy, ocean current and offshore wind along the Brazilian coastline are the resources that several works have addressed. According to Shadman et al. [50], using global models of the horizontal resolution of 1/12° (∼9 km), a total wave energy power of approximately 91.8 GW, with an average power of between 7.4 and 21.1 from south to north, was estimated considering a total coastline length of about 7491 km. In practice, only a relatively small portion of this value can be extracted by wave energy devices, which depends on different issues such as technological challenges, environmental issues, the economy, other uses of the ocean space, etc. However, only 20% of this potential is equivalent to approximately 35% of Brazilian electricity demand in 2017 [126]. Considerable ocean current energy can be observed in the north equatorial margin of Brazil with a maximum velocity of 1.52 m/s and power density values greater than 500 W/m^2 [50]. These regions are located between 120 and 300 km from the coast, implying technical and economic challenges for energy harnessing. Shadman et al. [50] observed significant ocean thermal gradient energy, especially along Brazil's north and northeast coastline. They showed that except for the extreme south region below 27° S, the annual average of the thermal difference between depths of 20 m and 100 m is always around or greater than 20°. It was shown that 12 OTEC plants of 10 MW located approximately at a distance between 30 and 200 km from the coast are sufficient to supply 10% of the residential electricity consumption of the northeast of Brazil, which was 27 TWh in 2017 [127]. The results showed that a temperature difference of 20 °C can be reached at depths of up to 500 m, especially in the northeast region. This means less technical complexity, especially regarding structural challenges to bringing cold water. Coastal areas of Maranhão (MA), Pará (PA) and Amapá (AP) are the regions with the highest tidal ranges, up to 13 m, in Brazil. For instance, Neto et al. [60] estimated a tidal energy potential of 22 TWh/year for MA.

The Energy Research Office of Brazil (EPE) estimated [127] a total offshore wind potential of about 1.6 TW within the Brazilian EEZ, with about 700 GW in regions with a water depth of up to 50 m. As reported in the offshore wind roadmap of Brazil [134], significant wind potential can be observed along the Brazilian coastline. It used ERA5 reanalysis with a spatial resolution of 30 km, considering some assumptions, including areas up to 30 km from the coast, average annual wind velocity larger than 7 m/s with height of 100 m and application of 10 MW DTU wind turbine to calculate the energy production and capacity factor. The results reveal three hotspots in the northeast, southeast and south regions, with an average annual wind speed of more than 8 m/s. As shown by [46], the States of Maranhão (MA), Piauí (PI), Ceará (CE) and Rio Grande do Norte (RN) with a wide continental shelf and water depth lower than 50 m are the most interesting regions in the northeast of Brazil for offshore wind farm deployments. In the South region, significant offshore wind resources can be observed along the coastline of the Rio Grande do Sul (RS) and south of Santa Catarina (SC) states, as shown by [22]. The states of Rio de Janeiro (RJ) and Espírito Santo (ES) are two estates with significant potential in the southeast region. However, as shown by [22], an annual average wind speed of about 9 m/s occurs along the southeast coastline in areas with a water depth of between 50 m and 3000 m, where the utilization of fixed-bottom foundations, such as monopile and gravity-based, is not feasible technically and economically. An average capacity factor of 59%, considering the DTU 10-MW wind turbine, can be reached for north, southeast and south regions, while this value is 68% for the northeast region [134]. Note that 86% of the offshore wind resources of the southeast and south regions are located in water depths of more than 50 m [22]. Nascimento et al. [48] addressed the offshore wind and solar complementarity in Brazil. The result showed that the daily complementarity of offshore wind by offshore solar reaches up to 40% along the Brazilian coastline.

4.3. Chile

Garrad Hassan [135] took the first approach to analyze the marine energy resource in Chile. Considering the Chilean coastline of 4200 km, a total wave power of 165 GW was estimated with an average of 39 kW/m. Using spectral wave model WAVEWATCH III, configured with a high-resolution unstructured grid (200–400 m at the coast), Mediavilla and Sepulveda [66] characterized nearshore wave energy resources in central Chile, near the coast of Valparaiso. Accordingly, the south area close to Punta Curaumilla was confirmed as a hotspot for wave energy with the most energetic and frequent sea state characterized by a period T_e of 9–11 s and significant height H_s of 2.4–3.5 m. Additionally, using the SWAN wave model covering the 1989–2013 period, Lucero et al. [67] obtained the wave climate along a segment of the central and central-south coast. They estimate that long-term wave power shows an increase in the median power with increasing latitude, varying between 27 and 38 kW/m in areas close to the coast with a water depth of about 20 m. Regarding seasonal variability, the power variability also increases with latitude increase, with higher events during the winter season. This means that northern latitudes have less energy available but present less variability throughout the year. Significant tidal energy can be found in southern Chile, with Magallanes Strait (Magallanes Region) and Chacao Channel (Los Lagos region) as the sites with the highest power for tidal energy in the country. The power density reaches up to 5 kW/m^2 with a maximum tidal current speed between 4 and 5 m/s. During spring tides, the Chacao Channel and the Desertores Channel can reach a power density of 40 kW/m^2 and 10 kW/m^2 respectively, where a SeaGen S 2MW turbine would have an output of 739 MWh/yr and 348 MWh/yr, respectively [136]. In 2014, Mattar et al. [64] estimated the Chilean offshore wind potential using wind speed information from the "QuikSCAT(V04) wind vectors" (QS) and Reanalysis ERA-interim for the period 1999–2009 and 1979–2012, respectively. They considered three macro zones for the Chilean coastline, including north (A), central (B) and south (C). At 80m, the mean wind velocity increased from north to south, with values of 4.7, 8.1 and 8.9 m/s for the A, B and C zones, respectively. Capacity factor values of about 14.8% (zone A), 35% (zone B) and 34.4% (zone B) were calculated considering the wind turbines with an installed capacity of 3.6, 5 and 8 MW, respectively.

4.4. Colombia

The richness, uniqueness and diversity of energetic maritime resources in the Atlantic and Pacific Basins are a privilege for Colombia. In this sense, the offshore winds and the thermohaline gradients in the Caribbean, the tides in the Pacific and the waves in both basins represent a valuable alternative for electrical supply to either the primary grid, micro-grids (autonomous or grid-connected) or distributed generation to local coastal communities [115]. Colombia's potential for offshore wind energy exceeds the SIN's installed capacity [137]. The north Caribbean has the most abundant resource potential, including Atlántico, Magdalena and La Guajira, where the potential is higher than 1331 W/m^2, reaching a maximum value of about 1700 W/m^2 [90]. OTEC is an interesting alternative in the Caribbean, where sites like Santa Marta, Barranquilla, Arboletes, San Andrés and Providencia have a temperature difference of 20 °C within the first 1000 m depth throughout the year [107]. Specific studies considering the San Andrés and Santa Marta locals estimate the OTEC average technical potentials of 19 MW (varies between 9.5 and 40 MW according to the season) [12] and 10 MW [105], respectively. The ideal temperature difference could be around 750 m water depth in both sites.From a technical perspective, the salinity gradients are Colombia's most abundant marine energy source after the offshore wind and they are available throughout the entire year. Theoretically, around 85% (15.157 MW) of the SIN's current installed capacity could be replaced with the SGE potential of the Magdalena River mouth [106]. A recent study estimated a technical potential of 780 MW [116]. Tides, waves and ocean currents are resources with lower potential in Colombia. However, they are justifiable in terms of supplying electricity for local coastal communities in the Pacific and north Caribbean [115]. The variability in time of those resources could diversify microgrids.

4.5. Uruguay

One part of the Uruguyuan coastline is located in the Río de la Plata Estuary and another in the Atlantic Ocean. Río de la Plata is a large estuary formed by a confluence of the Paraná and Uruguay rivers, with annual average discharges of approximately 16,000 m^3/s and 6000 m^3/s, respectively. The water depth of the estuary varies between 5 and 20 m. Among the offshore renewable resources, wave energy is the most promising [119]. Alonso et al. [119] estimated a wave energy potential of 30 kW/m at the continental shelf break at a distance of about 200 km from the coast. It decreases to 20 kW/m for a distance of 70 km. They estimated the wave power was 10 kW/m near the Atlantic coast on the 20 m isobath. While, in the outer Río de la Plata, due to its shallow water, swells are dissipated by bottom friction and the wave energy resource declines from 7 kW/m to 1 kW/m and even to lower values moving to the intermediate and inner zone of the estuary. Two attributes deserve to be highlighted to complement the Uruguayan wave energy resource overview. One is the little variability of the omnidirectional wave power on a seasonal scale. The swells that come from the east, as they are related to the South Atlantic High, are more energetic and are more frequent in warm seasons, compensating for the opposite behavior of the swells that come from the south, which are related to South Atlantic storms and therefore more frequent and energetic in cold seasons [121]. The other attribute regards relatively extreme events, which result in lower costs associated with the survivability of WECs. As presented in [120], the mean ocean current velocities along the Uruguayan coastline do not exceed 0.4 m/s. The tidal range and the thermal gradient are dismissed because the area is micro-tidal and non-tropical, respectively. Regarding the salinity gradient, two regions where fresh water meets salt water, including the coastal lagoons on the Atlantic coast and the Río de la Plata salinity front, are discarded because of environmental issues. Finally, there is still no specific assessment of offshore wind power since efforts have focused on land-based wind energy [138].

5. Ocean Space Utilization: Main Conflicts/Synergies

This section addresses the socio-economic issues related to the implementation of offshore renewable energies in the countries of analysis. Environmental issues are the most important but also impact the communities surrounding the areas and the coexistence and synergies with other industrial and economic activities.

5.1. Argentina

The most important restrictions are the several environmentally protected areas, some of them having high tidal potential. For instance, the Valdés Peninsula, a place visited by whales, seals, penguins and marine elephants for breeding, was declared a Protected Natural Area in 1983 by Provincial Law 4722 and in 1999 it was declared a World Heritage Site by UNESCO. Conflicts may also occur with commercial activities, such as fishing and navigation, as well as recreational activities, such as boating and surfing.

5.2. Brazil

With approximately 8.698 km from north (4°30′) to south (33°44′) between the intertropical and subtropical zones and 3.5 million km2 (200 nautical miles (370.4 km)) of the marine zone that integrates the EEZ [139], the Brazilian coast stands out for its diversity of environments, activities and existing conflicts. Biological resources, environmentally protected areas, oil and gas activities, shipping lanes, fishing and other activities in the sea can restrict the usable areas for harnessing ORE. For instance, according to the database of the Ministry of the Environment [139] of Brazil, considerable areas in the northeast offshore wind hotspots, with water depths up to 50 m along the coastline of the RN, PI and CE states are classified as of extremely high importance in terms of biological resources. The same scenario for the southeast offshore wind hotspots. This implies possible challenges regarding the environmental impacts of employing bottom-mounted foundations such as monopile and gravity-based [34]. The other conflict areas are the conservation units, including integral protection units (IPUs) and sustainable use units (SUUs). IPUs aim to protect nature, allowing only the indirect use of natural resources, excluding the consumption, collection or damage to these resources. SUUs make nature conservation compatible with the sustainable use of natural resources.

Brazil's offshore oil and gas sector includes exploration and production activities using platforms, wells and pipelines with refineries onshore. The total oil and natural gas production in Brazil [140] was about 47% of the internal energy supply of Brazil in 2018 [139,141]. Offshore production represents 96.9% and 80.8% of the total value of oil and natural gas, respectively. The Campos and Santos basins on the southeast coast (Rio de Janeiro and São Paulo states) located along the offshore wind southeast hotspot are the most productive sedimentary basins with the highest offshore oil and gas potential in Brazil, taking into account the recently discovered pre-salt layer. Additionally, intensive oil and gas activities can be observed in the northeast offshore wind hotspot along the coastline of RN state within water depths up to 50 m. The existence of oil and gas activities in high offshore wind potential might lead to ocean space utilization conflicts in the case of large-scale offshore wind farms. On the other hand, different possibilities of synergy, such as the reuse of the deactivated oil and gas platform avoiding its decommissioning [142–144] or decarbonization by feeding the oil and gas activities by offshore wind power, especially for mature fields [140]. Additionally, the presence of anthropic activities associated with the the oil and gas industry, environmental data and licensing processes can be made use of to develop offshore wind projects in such areas.

5.3. Chile

In Chile, most of the indigenous communities live along the coastline. Consequently, their fishing coves may be close to a region with significant offshore renewable resources. In this case, significant efforts are required to consider these users of the sea as a part of the social acceptance plan. Aquaculture activities are one of the most important potential conflicts, especially among locals close to the southern regions, as Chile is one of the main world salmon producers. On the other hand, it can be considered an interesting synergy to power these activities by ORE devices. Marine traffic and navy practice can be considered another potential conflict since Chile has several important ports along the coast with several islands that need to be supplied. Other restrictions include marine protected areas, including RAMSAR sites (wetlands of international importance) [145], marine mammal migratory routes and the areas with management plans, for instance, for shellfish collectors or tourism. These spaces can be seen in an online map facilitated by the National Fishing Subsecretary (Subpesca) [146]. An important feature of Chile is the frequent occurrence of earthquakes and tsunamis, such as the most recent one, which struck the northern region of Chile of Arica and Iquique in April 2014. Depending on the slope of the nearshore seabed, at a depth slightly larger than 30 m and at a larger distance from the shore of 1/7 the wavelength of the tsunami, offshore devices would not be significantly affected by a tsunami. However, nearshore device effects are being studied [147]. All construction projects in Chile must be adequately designed to withstand these events.

5.4. Colombia

Maritime spatial planning is an issue on which the country has made slow progress. Colombia lacks guidelines and public policy concerning oceanic surface, floor and water column. However, this decade, key national policies have commended institutions for harnessing bio-oceanic resources (CONPES 3990) and energy transition (CONPES 4075). Accordingly, current efforts could favor adopting marine energy and offshore wind, which already has a roadmap [131]. Some space utilization constraints may arise for further marine projects. Over 13% of Colombia's maritime space is declared a protected area, distributed on the Pacific and Caribbean basins (coastal and insular), including the reserve of the biosphere Seaflower [148,149]. A recent national policy aims to reach 30% of protected maritime space (CONPES 4050). Concerning the exploitation of offshore hydrocarbon, the National Hydrocarbon Agency (ANH) reports one active exploitation on La Guajira and over fifteen areas assigned for exploration in the Caribbean. The Pacific Basin lacks exploration or exploitation of hydrocarbons [150]. Additionally, predominant artisanal fishing in the Pacific [151], industrial fishing in the Caribbean and the ports and shipping lines in both basins also represent potential conflicts of interest for maritime space. The Colombian Ocean Commission and the ministerial portfolios must provide guidelines to settle these further discrepancies and promote synergies in ocean space utilization.

5.5. Uruguay

According to the marine spatial planning study presented in [152,153], activities in Uruguayan territorial waters can be classified into two groups. Accordingly, some activities involve permanent infrastructure, such as cables, outfalls, etc., and activities that do not involve permanent infrastructure and are associated with different users, such as marine traffic, fishing and aquaculture, tourism, oil and gas exploration and others. According to this study, the most high-demand uses include fishing, with an area of 121,000 km^2, hydrocarbon exploration, 62,500 km^2, and navigation in the navigation corridors, with an area of 3600 km^2. According to FREPLATA [154], numerous riverine, coastal and maritime species undergo their life cycles in Uruguayan territorial waters and several migratory species use these waters. Many of them are internationally recognized as being of high conservation value, e.g., whales, turtles, albatrosses, etc. In particular, the study identifies Priority Water Areas based on three ecological criteria, including species richness, species of particular interest and population and ecosystem processes. Along the Uruguayan coast, large high-priority water areas may cause possible conflicts with the activities associated with offshore renewable harnessing.

6. Regulatory Aspects

Table 1 shows the specific regulatory framework developed for ORE harnessing. Although each country has general regulatory frameworks associated with maritime activities and environmental and concession issues, only Brazil has established a regulatory framework dedicated to offshore renewable resources. Details of the regulatory frameworks of each country are discussed below.

6.1. Argentina

The most relevant law is Law 27191, which refers to the "National promotion scheme for the use of renewable energy sources for the production of electricity. Objectives. Scope of application. Enforcement authorities. Policies. Investment scheme. Beneficiaries. Benefits. Sanctions Renewable Energy Trust Fund". Regulatory Decree 531/2016 refers to the national promotion scheme for using renewable energy sources to produce electricity.

Table 1. ORE's specific regulatory frameworks and possible conflicts/synergies in SA.

Country	Possible Conflicts/Synergies in Hotspot Areas	Regulatory Framework	Auction Bids
Argentina	Environmental protected areas, commercial activities (navigation, fishing) and recreational activities (boating, surfing)	Not yet	Not yet
Brazil	High importance biological area, O & G activities	IBAMA Reference Term (Environmental licensing), Decreto N° 10.946, de 25 de Janeiro de 2022 (Concession authorization)	Being planned
Chile	Fishing coves, indigenous communities, environmentally protected areas, marine mammals routes, aquaculture, marine traffic/island and remotes areas	Not yet	Not yet
Colombia	Protected areas, biosphere reserves, oil and gas concessions, artisanal fishing areas and shipping routes	Not yet	Not yet
Uruguay	Fishing, hydrocarbon exploration, shipping line and high importance biological areas	Not yet	Not yet

6.2. Brazil

Wind power development in Brazil can be considered a reference for a combined energy and industry policy. The former refers to the Incentives Program for Alternative Energy Sources (Proinfa) and the latter is associated with the established rules for financing through the National Bank for Economic and Social Development (BNDES). Electric Energy Trading Chamber (CCEE) is responsible for conducting the energy auctions through the National Agency of Electrical Energy (ANEEL) that manages the entire process, while the Eletrobras execute the power purchase agreements (PPAs). In Brazil, offshore oil and gas and onshore wind concession and permitting process are based on the tender regime. The regulatory agency offers specific sites where the energy can be extracted. However, an open-door regime, in which the investor can apply for a certain region that the regulatory agency does not offer, is an alternative that can be used in Brazil. The first phase of offshore wind development includes area concession and environmental license. In Brazil, ANEEL is the regulatory agency responsible for the concession process and the Brazilian Institute of Environment and Natural Renewable Resources (IBAMA) is responsible for environmental licenses. Brazil employs a three-phase system including preliminary, installation and operation for environmental licensing, as described in Decree No. 99,274/1990, with issuing of different licenses for each phase. CCEE and EPE are the principal governmental institutions and agencies in this phase. Of course, the National Congress has a fundamental role in establishing the necessary laws to support this process. Offshore wind roadmaps of the EPE [134], environmental Term of Reference of IBAMA [155], a bill, which is under analysis in the Brazilian Congress, to regulate the authorization of using ocean space for renewable energy harnessing [156] and a presidential decree (Decreto Nº 10.946, de 25 de Janeiro de 2022) that regulates the cession of use of ocean space and natural resources in ocean, under the domain of the Federal Government, for the generation of electric energy are four important things that have occurred since 2020.

6.3. Chile

All the uses of the maritime space will be managed by different port captaincies and the maritime space cannot be used before obtaining the maritime concession, which is the permit for the use of this space and has to be requested through the Sub-Secretary of Army Forces [157]. In 2014, Marine Energy Research and Innovation Centre (MERIC) published a practical guideline to environmental regulations applicable in Chile [157]. It develops the general and particular aspects of the maintenance and commissioning of projects. It considers water, soil, air, noise, flora and fauna, cultural heritage and waste. Additionally, environmental licenses and specific environmental requirements are discussed. An important part of the regulation is the environmental impact assessment system, which allows the authority to determine before executing a project whether it complies with current environmental legislation and addresses potential significant environmental impacts. This tool, mandatory for some investment projects, is a voluntary process for others, considerably favoring interaction with the environment.

The environmental regulations and requirements in force in Chile are a key element in assessing the feasibility of developing marine energy projects in Chile. The regulation of the Environmental Impact Assessment System (SEIA), Supreme Decret (D.S) 40/2013, in article 3 about "Types of projects or activities", does not include typology for marine energy projects. Regarding social impacts, there is a compulsory measure called Social License, a signed document with the local communities involved with the project that must agree to it before it can go forward. Even if the service has environmentally approved the project, the project would not be able to carry on without this Social License. On the other hand, due to the "169 International Agreement" from International Labour Organization (ILO) [158] to which Chile is a signatory, there is a compulsory scheme for integrating the indigenous community into the development of a project that is affecting or being developed on indigenous territory. This is one of the requirements for environmental impact study and maritime concession.

6.4. Colombia

Law 1715/2014 provides the main legal framework for adopting renewable energies. The law notes exemptions for VAT and income taxes and accelerated depreciation discussed elsewhere [159]. It also ordered the creation of the FENOGE, a dedicated fund for renewable initiatives. Moreover, Colombia has a carbon tax [160] of 5 USD/tonCO_2. Non-conventional renewable energy sources (NCRESs) have played a principal role since the promulgation of Law 1715/2014. Although Law 2099/2021 introduced some modifications to Law 1715/2014, marine energy still occupies a demoted spot in the energy transition policy. After a failed auction in February 2019 [161], Colombia held its first successful auction for renewable energy in October 2019 through a mechanism that involved sellers and buyers [162]. The result was 12,050 MWh/day allocation from onshore solar and wind projects [163]. Similarly, the third (and latest) auction assigned 4596 MWh/day for onshore solar projects [164]. These precedents aimed to have more than 2500 MW of NCRES installed capacity with a long-term fixed price by 2023. To regulate onshore wind, the National Agency of Environmental Licenses (ANLA) published RES 1312/2016, which is the precedent of NCRES environmental regulation for the upcoming offshore wind adoption. Likewise, other laws apply to future marine and offshore wind energy projects. Law 10/1078 and Decree 1436/1984 define Colombian marine space, managed by the Maritime General Direction (DIMAR) [165]. Accordingly, the DIMAR issued the Colombian Maritime Regulation (REMAC), recently modified by the RES 794/2020 and RES 240/2021, to dictate guidelines and limitations for the concession of NCRES projects in the ocean space [131]. The Colombian offshore wind roadmap was released in 2022 [131] and addresses resource assessment, transmission infrastructure, environmental and social considerations, supply chain, ports and others. As part of the strategy, the government published RES 40284, which defines the guidelines for further auctions of offshore wind projects in the Caribbean. According to the resolution, the bidders will compete for a temporal occupation permit for up to 8 years for feasibility assessments that can be upgraded to a wind-farm construction and operation license for up 30 years with an optional 15 years extension. The maximum area assigned per project will be 270 km^2.

6.5. Uruguay

The Uruguayan Energy and Water Service Regulatory Unit (URSEA) is the state institution that regulates, supervises and advises on electricity generation, transmission and distribution. Law No. 16.832 permits electricity generation by any public or private entity;

however, it establishes that UTE, a state entity, manages transmission and distribution. Currently, there is no specific regulation regarding ocean renewable energies. Meanwhile, the regulatory framework is covered by more general regulations on using marine areas, environmental protection and renewable energy promotion. Law No. 17.033 delimits the Uruguayan marine area and regulates its use respecting the Treaty of the Río de la Plata and its corresponding Maritime Boundary. Regarding environmental protection, the Environmental Protection Law (No. 17283) and the Environmental Impact Assessment Law (No. 16466) are worth noting. The latter requires prior completion of an environmental impact study for power generation projects of more than 10 MW, including projects in the coastal area. To develop the renewable energy sector, there is a set of decrees of the Law for the Promotion and Protection of Investments (No. 16.906), which have been successfully implemented for onshore wind and solar. It is worth highlighting that Decree 354 of 2009, which grants specific tax incentives, explicitly includes wave energy resources.

7. Industrial and Academic Projects

7.1. Argentina

Currently, there is no marine energy device operating in the Argentinian Sea. However, there are three projects under development. The wave energy project of the Buenos Aires Faculty of the National Technological University [42] started in 2009. The WEC is a point absorber consisting of a floating buoy coupled with a direct mechanical-drive PTO by a rigid arm. The wave-induced movement of the buoy, upward and downward, is transformed into a rotational movement adequate for driving an electrical generator. Depending on the dimensions of the WEC, the installed capacity may vary between 30 and 100 kW per buoy. Pelissero et al. [42] tested a 1:10 scale prototype of the device in the wave channel of the National Water Institute, subjected to different regular waves. The next phase under development is the construction of a full-scale prototype and its installation on a breakwater located on the Buenos Aires coast.

The study of marine energy resources in southern Patagonia (EREMPA Project) started in 2013. It is carried out by Y-TEC (YPF Tecnología) and the Santa Cruz Faculty of National Technological University. The project aims to study the tidal energy potential of the southern coastline of the Province of Santa Cruz using in situ measurements and the construction of prototypes of small power plants to take advantage of these energy sources and collect information about their technical performance. The project of the National University of Southern Patagonia [166] aims at estimating the wave and current resources of Caleta Paula in the province of Santa Cruz. The project also focuses on constructing test facilities, including hydrodynamic channels and developing converters' scaled models for wave and current energy. The current energy channel has a circulation pump with a variable fluid velocity of up to 4 m/s. The wave channel has a water churning system to produce regular waves of varying amplitude and period. The scaled-model devices are a submerged turbine for current and a floating tilting electro-mechanical tube with permanent Ne-Fe-Bo magnets and induction solenoids as a wave energy converter.

7.2. Brazil

Brazil is responsible for installing the first full-scale prototype of a wave energy converter in Latin America. As shown in Figure 8, this is a single device of 100 kW installed capacity that was installed in 2011 in Pecém port of the Ceará state located in the northeast of Brazil. The device was decommissioned after about 12 months of operation due to the port extension project. The COPPE hyperbaric Wave Converter comprises a floating body connected to the pumping modules, a hydrodynamic accumulator, a hyperbaric chamber and a generating unit. The motion of the floating body in the vertical direction (heave) due to the wave–body interactions drives the pump actuator, displacing the water inside the closed circuit to a hydro-pneumatic accumulator. The accumulator is connected to a pressurized hyperbaric chamber. Then, the pressurized water drives a hydraulic turbine coupled to an electrical generator. More details about the device performance and control system can be found in [55,167,168]. The second project is a nearshore wave energy converter designed to be installed in the relatively shallow water of 25–30 m off the Rio de Janeiro coast. The technology is at the research and development stage, TRL 4, and is undergoing medium-scale laboratory tests. The system is a point absorber WEC type with a capacity of 50 kW that consists of an oscillating buoy, a bottom-mounted support structure and a direct mechanical-drive PTO system. More details about the system can be found in [30,53,54].

Figure 8. Projects, universities and research centers that work on offshore renewable energy in South America.

Another project is a new model of a tidal power plant proposed by Neto et al. [60] for the Bacanga Estuary located in São Luis, the estate of Maranhão. The tidal plant has an annual energy production of about 14 GWh/yr, considering a reservoir water limit of +2.5 m and a Kaplan turbine with double regulation provided by Andritz Hydro [169]. The project is in the incipient stage of research and development. More details about the Bacanga Estuary and tidal power plants can be found in [170,171]. There is no installed wind turbine along the Brazilian coastline. However, as revealed by the IBAMA [172], as of September 2022, 66 projects have already initiated the environmental licensing process with a total installed capacity of approximately 170 GW, which is 93% of the total installed capacity of the Brazilian grid [173]. Recently, some initiatives [174,175] have focused on producing renewable hydrogen using hybrid renewable sources, including offshore wind. These projects are in the initial development phase with a signed memorandum of understanding.

7.3. Chile

Since 2012, at least 10 different projects associated with marine energy have been developed either as prototypes installed at sea or scaled models tested in laboratories. The prototype was created in 2012; an oscillating wave surge converter for nearshore applications named Wilefko with a theoretical installed capacity of 61.5 kW from six paddles at full scale. Nevertheless, only a prototype device was built at a small scale and its working principle was tested at sea without further development. Afterward, many other concepts were developed and tested. Some have innovative working principles and patented technologies, such as GUH and Etymol. In 2019, the point absorber wave energy converter named WaraQocha was designed by Universidad Católica del Norte and installed in Antofagasta, producing a 3 kW average during that year. It is currently under improvement [176]. In 2022, Universidad del Bío-Bío has planned to start the construction of a nearshore point absorber WEC, named Lafkenewen, a project financed by the local government of Bío-Bío region, with expected installation by 2024. In 2021, Chile finalized the Open Sea Lab (OSL) for marine energy systems, designed to be a catalyst to accelerate the development and commercialization of such system validation of studies performed within the MERIC research program. In such a lab, during the same year, the research center MERIC installed the PB3 Power Buoy device, a point absorber WEC with a 3 m buoy as its main component, to investigate the device's performance in relevant environmental conditions at sea.

7.4. Colombia

The Colombian academic sector has conducted several projects in recent years, primarily aiming to identify potential sites, environmental constraints and policy effectiveness; nonetheless, recent and ongoing projects aim to develop local technology and tests in natural conditions. The Universidad del Norte and Universidad Nacional de Colombia are currently working to install the first pilot unit of salinity gradient energy in the country at the Magdalena River mouth. This project aims to deploy a system of 150 W of installed capacity by 2023 to devise technical and environmental challenges for harnessing SGE at a large scale. The technology chosen for this purpose is reverse electrodialysis. The Universidad de Antioquia also carried out some studies of SGE potential at the Atrato river mouth. The Universidad Nacional de Colombia and Universidad Jorge Tadeo Lozano have identified potential sites for OTEC; however, the country lacks technology studies. Additionally, the Universidad Militar de Nueva Granada, Universidad del Norte and Universidad de la Costa have developed a series of projects based on offshore technology and mariculture, reaching the milestone of SRL 3 and TRL 3, with plans to reach level [177]. The Universidad del Norte is also designing a device to harness wave energy on La Guajira, with laboratory and on-site tests planned for 2023 and 2024. On the other hand, the Universidad Cooperativa de Colombia has worked towards aquatic energy; for instance, its project SWEET focused on floating solar PV.

7.5. Uruguay

Research and development activities associated with ORE are incipient in Uruguay. Only three projects were carried out with the support of the National Agency for Innovation and Research through its Energy Sector Fund, that is, URU-WAVE I (2010–2012), URU-WAVE II (2014–2016) [178] and "Viability of hydrokinetic generation in Uruguay from the tides" (2014–2016). There is no installed technology in a relevant operational environment.

8. Research Groups and Experimental Infrastructure

Figure 8 shows the universities, research groups and institutions that work in the ORE field. It also illustrates the testing facilities, including the open sea Lab in Chile, LabOceano in Brazil and a wave channel in Argentine. As discussed in the previous section, two WEC prototypes installed in Brazil and Chile are the only full-scale systems deployed in a relevant operational environment.

8.1. Argentina

The Buenos Aires Faculty of the National Technological University (UTN-FRBA) has patented a wave energy converter that was tested, on a 1:10 scale, in the wave channel of the National Water Institute. The Argentina National Water Institute (INA) studies hydraulic problems associated with rivers, dams and coasts through theoretical and experimental analyses. It has a hydraulic laboratory with a wave channel 30 m long and 60 cm wide that can generate waves up to 10 cm high and periods of up to 1 s. The Argentina Institute of Oceanography (IADO) has developed and built coastal environmental monitoring stations (EMAC) and oceanographic buoys. They have an instrumentation development Laboratory that develops most of the mechanical components of the buoys and sensors. There are more than 30 operational EMACs, in lakes, rivers, estuaries and open seas. Other support resources include two boats (14 m and 7 m in length), aerial and aquatic drones, a tide gauge station, current acoustic meters ADCP, ADP and ADV, CTD/OBS and multiparametric probes. The Faculty of Engineering of the University of Buenos Aires (FIUBA) has a wave channel with a length of 72 m that allows testing of the shape of a boat, for instance, about 5 m long, prototypes and their respective propulsion systems. This channel is equipped with updated high-precision instruments, allowing tests for the local industry and other countries to develop.

8.2. Brazil

Different Brazilian universities such as the Federal University of Rio de Janeiro, the Federal University of Maranhão (UFMA), Federal University of Itajubá (UNIFEI), Federal University of Rio Grande do Norte, Federal University of Santa Catarina (UFSC), the Federal University of Pará (UFPA), Federal University of Rio Grande and University of São Paulo (USP) have worked on ocean renewable energies through master and doctoral theses and publishing scientific papers, as well as testing scaled models and even full-scale prototypes at open sea (see Section 7). Nevertheless, to our knowledge, Grupo de Energias Renováveis no Oceano (GERO) and Instituto Nacional de Energias Oceânicas e Fluviais (INEOF) are the two formal research groups working actively in this area. GERO [179] is a research group of the Ocean Engineering Program of the Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE) of the Federal University of Rio de Janeiro (UFRJ). It was formed in 2001, focusing on developing research and innovation in ocean renewable energy areas, especially wave, current and offshore wind energy. Two wave energy converters, which are mentioned in Section 7, are GERO's outstanding projects. CFD application on large-scale offshore wind turbines, design and control of WECs and ORE assessments are some research areas pursued by the GERO team.

The Ocean Engineering Program of the COPPE/UFRJ has two laboratories for experimental tests of marine floating and fixed structures. The laboratory of wave and current (LOC) is equipped with a channel for wave and current simulations of 1.4 m width and 0.6 m height and is suitable for small and ultra-small models. The ocean technology laboratory (LabOceano) is a wave basin located in the technology park of the UFRJ with a tank 30 m wide and 40 m long, reaching a depth of up to 25 m capable of generating wave, current and wind. Several experimental tests associated with WEC projects were carried out in LabOceano [167]. Additionally, USP has a wave tank with dimensions of 14 m $\times$ 14 m and 4 m depth with an active wave generation and absorption system. The UNIFEI fan laboratory has a high-pressure axial fan, where the characteristic curves of hydrokinetic and wind turbines are raised. The UNIFEI fan laboratory has a high-pressure axial fan that enables studies on the characteristics of the hydrokinetic and wind turbines. The equipment has a 1.130 m diameter pipe 9 m long, a 2.40 m flux rectifier and a 1 m diameter injector nozzle. The A 12.5 hp motor with a rated speed of 1160 rpm and flow rate of 14 m^3/s generates the flow. The Instituto Nacional de Ciência e Tecnologia em Energias Oceânicas e Fluviais (INEOF), coordinated and headquartered at the Federal University of Maranhão [180], is a network project with the participation of UFMA, UFRJ, UFSC, UFPA and UNIFEI for research, development and innovation in ocean energies with co-financing from FAPEMA, CNPq and CAPES, and has worked since 2017.

The Instituto Nacional de Pesquisas Oceânicas (INPO) was recently established to manage scientific and technological research areas with a focus on the ocean. It will put together the efforts of the universities and research centers to reach strategic results to subsidize public policies for the ocean. ORE is among the institute's strategic areas to be developed in cooperation with established research groups and companies working in related areas. It notes that Brazil has extensive experience in oil and gas exploration and extraction, especially in deep and ultra-deep waters. It implies the existence of adequate infrastructure and laboratories, specialized human resources and experts that can contribute to Brazil's offshore renewable sector's development.

8.3. Chile

Research related to ocean renewable energy is an important area of study for many universities, such as Universidad de Concepción (UdeC), Universidad Técnica Federico Santa María (UTFSM), Universidad Católica de la Santísima Concepción (UCSC), Universidad Austral (UACH), Universidad de Valparaiso (UV), Pontificia Universidad Católica (PUC), Universidad del Bío-Bío (UBB), Universidad de Aysen (UA) and Universidad Católica del Norte (UCN). Some universities, such as UdeC and UV, have focused on resource assessment. In contrast, others, including UACH, UTFSM and UBB, have studied, among other topics, mathematical and numerical models of marine energy converters. There are at least 12 wave channels in Chile, where the largest one, 45 m in length and 2 m in depth and capable of generating irregular waves, is placed in the UACH. The UCSC has a research center focused on researching coastal territorial management, integrating marine energy, aquaculture and other actors in the coastal area. UA has focused on offshore wind energy. Regarding the research centers, the Marine Energy Research and Innovation Center (MERIC) [181] is an active institute working in the field of marine renewable energies. MERIC was established in 2015 and its goal is to be a multidisciplinary platform able to articulate scientific efforts across Chile to give innovative solutions to develop marine energies in Chile. Among others, one of the most important achievements of this center was the inauguration of the Open Sea Lab (OSL) for marine energy systems and the installation of the first full-scale wave energy converter in 2021.

8.4. Colombia

The knowledge and research capabilities in offshore wind and marine energy in the country are mainly concentrated in universities such as Universidad Nacional de Colombia (primarily at Medellín Campus), Universidad del Norte, Universidad Cooperativa de Colombia, Universidad de Militar de Nueva Granada, Universidad de la Costa, Universidad del Valle, Universidad de Antioquia and Universidad Jorge Tadeo Lozano. The Colombian-German center CEMARIN and DIMAR centers have also experienced this. In addition to the typical oceanographic sensors in some universities and the DIMAR, the Universidad Nacional de Colombia (specifically the Facultad de Minas) has a wave flume and an electrochemistry laboratory adapted to test salinity gradient energy technology (Salinity Gradient Energy) at Medellín Campus.

8.5. Uruguay

Currently, marine energy research in Uruguay is centralized in the Fluid Mechanics and Environmental Engineering Institute (IMFIA) of the Universidad de la República. IMFIA has researchers with vast experience in met-ocean data analysis, hydrodynamic modeling at different scales, wave modeling, field data collection, CFD and physical modeling. IMFIA has a large wave flume 60 m long (wave direction), 1.5 m wide and 1.8 m deep, equipped with a piston-type wavemaker. This wavemaker is controlled by AwaSys 6 [182], which can generate regular and irregular waves with active wave absorption of reflected waves. It is suitable for experimental tests for small-scale WEC models. Additionally, the flume is equipped with a controlled carriage that reaches velocities of up to 3.4 m/s, offering the possibility of testing hydrokinetic turbines.

9. Future Perspectives

9.1. Argentina

Creating research centers for marine energy and specialized laboratories to support the research activities and testing the scaled models of the devices is necessary to develop this area. These initiatives would attract private investment, both national and international. The main challenge for Argentina is to achieve 20% renewable generation by 2025 and offshore renewable resources can play an important role in achieving this goal.

9.2. Brazil

In 2020, 83.3% of the Brazilian electricity matrix originated from renewable sources. However, that value reduced to 78.1% in 2021 because of a reduction in hydropower generation due to a drought event. This reveals the dependence of the Brazilian electricity matrix on hydropower, with a participation of about 60%. Considering fossil fuels' high cost and emissions, diversifying the electrical matrix profile by inserting renewable energy sources becomes urgent. Onshore wind and solar, with 10.6% and 2.5%, respectively, experienced significant growth over the past decade. However, studies [22,50] indicate a significant amount of ORE sources along the Brazilian coastline. Regulatory aspects regarding the ocean space concession and offshore wind auction still need to be established. However, only the first pipeline of offshore wind projects that initiated the environmental licensing process presents an installed capacity about 9 times larger than the Brazilian Hydropower plant Itaipu, which is the second-largest in the world. Additionally, offshore wind and wave energy resources in the regions with intense offshore oil and gas activities create opportunities for synergy for the decarbonization of the petroleum industry.

Hydrogen production from offshore wind and solar is another important subject pursued by some of Brazil's large-scale initiatives. The extensive experience of Brazil in the deep and ultra-deepwater oil and gas industry could contribute to the development of the offshore renewable sector through a technology transfer process. Creating open sea laboratories for testing large-scale prototypes in a relevant environment is necessary for commercializing marine energy technologies in Brazil. The new national institute, INPO, has a special interest in supporting the efforts to obtain data on renewable resources in the exclusive economic zone of the Brazilian ocean and to develop and test devices for electricity generation and desalination. Applications for the decarbonization of oil and gas production infrastructure and hydrogen production from offshore renewables are also of interest for restraining the effects of climate change.

9.3. Chile

Currently, no commercial project is associated with offshore wind and marine energy in Chile. However, CORFO, a public agency for the Production and Development of the economy in Chile and ANID, the National Agency for Science, Technology and Research, provide several mechanisms for funding opportunities that could be focused on technology demonstration of wave and tidal energy devices. Today, grid-connected marine renewable energy in Chile is not competitive compared to gas and carbon power plants, hydropower and the renewables established in the country as solar and wind, which are the principal sources of electricity. Nevertheless, remote areas and islands with high energy costs can be an interesting opportunity for marine energy sources. These areas are not connected to the central electrical network and comprise about 20% of the Chilean territory (CNE, 2022). Additionally, the R&D center MERIC, financed mainly by the government, was created to promote marine energy in Chile, providing the Open Sea Lab as the first site in Chile where a wave energy converter platform was installed to understand the behavior of the machine and the ecosystem around it. Thus MERIC plays a key role in coordinating the different stakeholders, preparing the necessary R&D, and focusing the efforts for the correct implementation of these types of initiatives, thus diminishing the gaps in the areas of law, permits, environment, supply chain and technology that exists in the country. In the long term, carbon neutrality goals and the insertion of renewable hydrogen are expected to boost the use of alternative energy sources, including marine energy. More research and efforts may be necessary to address the insertion of marine energy as integration in remote communities and hydrogen projects.

9.4. Colombia

Colombia has a significant potential to harness ocean energy (offshore and marine); however, the environmental and maritime space use regulations still need to be revised to promote large-scale project investments. Thus far, public funds finance most basic science research, whose outcomes mainly serve academic purposes. The offshore wind roadmap will likely facilitate the deployment of such technology in the mid-term, depending on the upcoming temporal occupation permit auctions described in RES 40284. In the meantime, the government should broaden the scope of the regulations and prioritize marine sources, which would develop an industry around ocean energy. In this regard, all areas (academic, business, government and communities) must join efforts to strengthen and build local capacities, not only in technology development but also in integrated environmental monitoring strategies, submarine cabling deployment, maritime construction and many other aspects adapted to the local conditions. Critical assessments of Colombian social, ethnic and economic conditions and environmental baseline definition are also necessary for success in these projects. The available potential in the country encourages diving into the long-term, investing in developing local capacities and strengthening inter-institutional and inter-sectoral cooperation.

Ocean energy can play a critical role in the sustainable development of coastal communities by complementing local energy grids and providing, besides electricity, services such as water (from seawater desalination) and transportation by either generating electricity or producing hydrogen.

9.5. Uruguay

Uruguay's vigorous renewable energy sector has positioned the country as a green energy world leader. Because of the available space for more wind and solar farms on land and probably due to the lack of maritime vocation in the country, the sector has not considered the sea an environment where it can expand. However, the recent interest in green hydrogen caused the sector to look to the sea for the first time, opening a window of opportunity for marine energies. The country's small scale, and lack of critical mass, make international scientific collaboration a necessity to develop this new opportunity.

10. Conclusions

This paper addresses the ORE's current status and future perspectives in SA. Wave energy and offshore wind are the resources with the highest number of published papers. Brazil has the largest number of scientific publications in this area, followed by Chile, Colombia, Argentina and Uruguay. Most of these papers address the resource potential showing the diversity of offshore renewable resources available along SA's coastline. Significant wave energy is available along almost the whole of SA's coastline. Considerable offshore wind potential is observed along the Brazilian, Colombian and Southern Chilean coastline. The region with the most diversified resource type is observed along the north of Brazil, where offshore wind, wave, tidal, ocean currents and thermal gradients are available. Brazil and Uruguay have the most renewable electricity matrix, followed by Colombia, Chile and Argentina. Regarding the regulatory aspects, Brazil has the most advanced status, having established the environmental licensing process, a law for the concession of the sea space to the project owners and discussing the first offshore wind auction bid in 2023. Besides the fishing activities and shipping lines, the possible conflicts common in coastal countries, indigenous communities in Chile and intense offshore oil and gas activities are the most important activities that can be considered as opportunities for synergies.

High important biological areas and marine environmentally protected areas are identified along the coastline of the studied countries. There are no commercial projects in SA; however, there are several ongoing projects in different technological phases. Brazil and Chile are the countries that have already installed a full-scale WEC prototype. A salinity gradient project has been planned to be installed in Colombia. A promising perspective of offshore wind in Brazil can be observed considering 66 projects, totaling approximately 170 GW of installed capacity, that have already initiated the environmental licensing process. The UFRJ's wave basin, Laboceano, in Brazil, Chile's Open Sea Lab, the electrochemistry laboratory of the Universidad Nacional de Colombia and wave channels of the INA and IMFIA in Argentina and Uruguay, respectively, are examples of laboratory infrastructure that can contribute to the development of the offshore renewable system. This comprehensive survey of the existing resource potential, competencies and research infrastructures in Argentine, Brazil, Chile, Colombia and Uruguay reveals the important role that SA can assume in the global energy transition scenario.

Significant offshore renewable potential along the coastline with considerable population concentrations can be considered an advantage for the countries' energy supply. Public policies to incentivize the offshore renewable sector, adequate regulatory framework, investment in research and development, creation of specialized technological centers, and full-scale prototype deployments are necessary to commercialize offshore renewable systems in SA. Exchanging ideas and experiences of the SA countries through establishing an integrated governmental program could accelerate the technological advances in this sector.

The electricity demand is expected to grow in the next years in South America, and the increase in electric energy generation needs to be planned according to this expectation. The more diverse and flexible the future energy matrix, the more efficient the use of sources and capabilities required to fulfill the energy demand will be. Renewable energy sources will be critical in this variation of the energy scenarios in South American countries. In particular, offshore renewables are important since the largest population core is on the coast. However, the different geographical, political, socioeconomic and technical conditions of the countries involved will lead to adapting different policies and actions by the different agents involved. Some factors have been identified as conditionings to evaluate the possibilities of success in the future: political support, the implementation of new experimental infrastructures, access to data related to energy resources, electric grid and industrial capabilities, innovation capability, etc.

Once all these factors are identified and evaluated numerically under certain indicators, some recommendations must be provided to the agents in charge of implementing energy policies. It is intended to include these considerations in the different roadmaps related to the future energy scenarios of the countries. The final objective is to take advantage of the global conditions not only of each country but the possibilities of connection and collaboration of the surrounding countries in terms of resources, grid stability and industrial capability.

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Abbreviations

The following abbreviations are used in this manuscript:

ANEEL	National Agency of Electrical Energy
ANH	National Hydrocarbon Agency
ANLA	National Agency of Environmental Licenses
AP	Amapá
BES	Brazilian Electrical System
BNDES	National Bank for Economic and Social Development
CE	Ceará
COPPE	Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering
D.S	State-owned energy company UTE Supreme Decret
DIMAR	Maritime General Direction
DOW	Deep OceanWater
EMAC	Coastal environmental monitoring stations
ES	Espírito Santo
ES	Renewable Energy Systems
FIUBA	Faculty of Engineering of the University of Buenos Aires
GERO	Grupo de Energia Renovável no Oceano
GHG	United Nations Climate Change
IADO	Argentina Institute of Oceanography
IBAMA	Natural Renewable Resources
ILO	International Labour Organization
IMFIA	Fluid Mechanics and Environmental Engineering Institute
IMFIA	Instituto de Mecánica de los Fluidos e Ingeniería Ambiental
INA	Argentina NationalWater Institute
INA	NationalWater Institute
INEOF	Instituto Nacional de Energias Oceânicas e Fluviais
IPUs	Integral protection units
LabOceano	Ocean technology laboratory
MA	Maranhão
MERIC	Marine Energy Research and Innovation Center
NCRES	Nonconventional renewable energy sources
NIS	National Interconnected System
ONS	National Electricity System Operator
OSL	Open Sea Lab
OTEC	Ocean thermal energy conversion
OWSC	OscillatingWave Surge Converter
PA	Pará
PI	Piauí
PPA	Power purchase agreements
PTO	Power take-off
REMAC	Colombian Maritime Regulation
RJ	Rio de Janeiro
RN	Rio Grande do Norte
RS	Rio Grande do Sul
SA	South America
SAC	South America and the Caribbean
SADI	Argentina Interconnection System
SC	Santa Catarina
SEA	Aysen Electric System
SEIA	Environmental Impact Assessment System
SEM	Magallanes Electric System

SEN	National Electric System
SGE	Salinity gradient energy
SIN	Colombian electrical grid
SUU	Sustainable use units
SWAC	Seawater air conditioning
TGC	Thermal power plants powered by natural gas
TLs	Transmission lines
UACH	Universidad Austral
UBB	Universidad del Bío-Bío
UCN	Universidad Católica del Norte
UCSC	Universidad Católica de la Santísima Concepción
UdeC	Universidad de Concepción
UFMA	Federal University of Maranhão
UFPA	Federal University of Pará
UFSC	Federal University of Santa Catarina
UNIFEI	Federal University of Itajubá
URSEA	Uruguayan Energy andWater Service Regulatory Unit
USP	University of São Paulo
UTE	Administración Nacional de Usinas y Trasmisiones Eléctricas del Estado
UTFSM	Universidad Técnica federico Santa María
UTNFRBA	National Technological University
UV	Universidad deValparaiso
WEC	Wave energy converters

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