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Review

Renewable Energy from Wind Farm Power Plants in Peru: Recent Advances, Challenges, and Future Perspectives

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Abstract: Peru is one of the most diverse countries in the world, and its climatic characteristics, biodiversity, cultural heritage, and location on the planet give it a vast potential for wind energy, both on its coast and within the 200 miles which comprise the Peruvian coastline on the Pacific Ocean. Likewise, the northern and central areas of the country represent the regions with the greatest potential for wind energy use. In this context, wind energy is a viable alternative to mitigate the effects of climate change in local territories and, thus, meet the Sustainable Development Goals (SDGs) outlined in the 2030 United Nations (UN) Agenda. This article presents the potential for generating wind-type electrical energy both on-shore with 20.5 GW and off-shore with 347 GW. In addition, the main advantages, benefits, and restrictions in the implementation of this type of energy plants in Peru are presented, considering the following: (i) the mitigation of climate change considering the insertion of renewable energies in the energy matrix; (ii) the potential of the available wind resource; (iii) the characterization of seven existing wind power plants, considering a total installed capacity of 668 MW; and (iv) the implementation of future wind power plants considering a portfolio of 31 projects for 7429 MW of total installed capacity projected. Finally, recent advances, challenges linked to territorial implementation, and future perspectives in developing the renewable energy sector from wind resources to address climate change are discussed.

Keywords: renewable energy; wind energy; on-shore; off-shore; wind farm; sustainability

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1. Introduction

1.1. Contribution of Peru for the Mitigation of Climate Change

The effects of climate change not only pose a serious threat to humanity but also to the environment [1,2]. The replacement of fossil fuels with the use of renewable energies, of which wind is one of the key technologies, is recognized by several governments as a fundamental axis for the reduction in greenhouse gases (GHG) [3–6]. This phenomenon is caused by gases, such as carbon dioxide (CO_2), that are emitted into the atmosphere through fossil fuels and are the main causes of global warming, which is considered the most serious problem facing humanity [7,8]. Likewise, other energy sources such as solar, hydroelectric, geothermal, tidal, and biomass systems help mitigate the effects of global warming [9–11].

Over the past ten years, global wind energy capacity has grown at an average cumulative rate of more than 30% [4,12], according to the Global Wind Energy Council (GWEC) [13]. If the growth path of the world's installed wind capacity is maintained, by 2050 nearly a third of the world's electricity demand could be generated from this source. Today, the wind energy industry is the fastest-growing infrastructure with the best prospects in the world [14]. Its generation costs have fallen dramatically over the last 15 years, approaching those of conventional energy sources [15].

Promoting sustainable development with low greenhouse gas (GHG) emissions has become fundamental for governmental planning and policy making worldwide ever since 193 countries and the European Union ratified the Paris Agreement in 2016 [16]. This agreement aimed to combat climate change, keep the average global temperature below 2.0 °C concerning the pre-industrial levels, and continue trying to keep the temperature below 1.5 °C. Peru was the first Hispanic country to ratify the Paris Agreement by Supreme Decree No. 058-2016-RE on the 22 of July 2016 [17].

The Paris Agreement states that all parties must make and communicate ambitious efforts related to their nationally determined contributions (NDCs), which constitute the global response to climate change [18]. According to the latest National greenhouse gas (GHG) Inventory of Peru, in 2019, the country's net GHG emissions were 210.4 Mt of carbon dioxide equivalent (CO_2eq), of which 30% corresponded to electricity production. Currently, the Peruvian State aims to keep its GHG emissions in the year 2030 below 179 Mt CO_2eq (equivalent to a 40% reduction in the projected emissions for 2030) [17].

Since 2014, wind power projects have produced 11,640 GWh of clean energy in the Peruvian electricity market, mitigating 4.62 Mt of CO_2eq. Figure 1 shows the annual electricity production and the corresponding CO_2eq mitigation from 2014 to 2022.

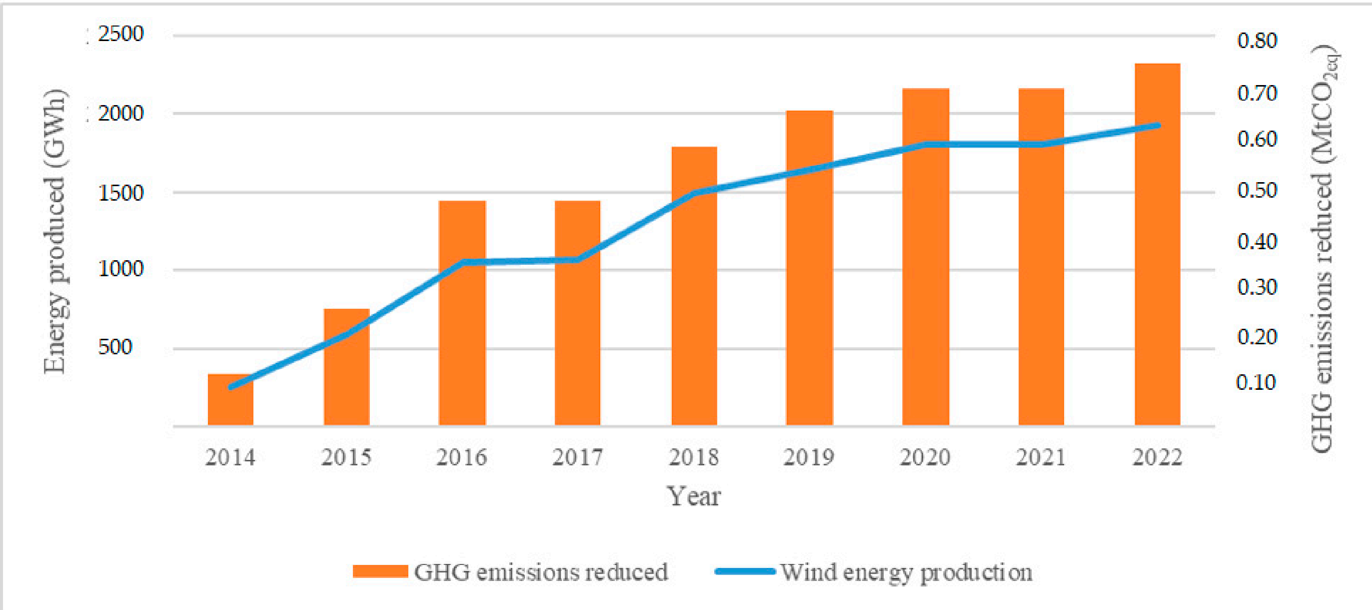

Figure 1. Energy produced and GHG emissions reduction from wind power plants in Peru [19].

The ambition scenario of the NDCs of Peru, analyzed in the framework of the Final Report of the Multisectoral Working Group for the implementation of the NDCs 2018 [17], estimated the GHG reduction potential of a "combination of renewable energies" mitigation measure, considering a penetration of 6.8% of renewable sources in the electrical matrix. However, the ambition of the electricity sector has been expressed under the objective of increasing by at least up to 15% the participation of renewable energy in the total national energy generation [20]. This means an increase in the value approved in the tentative programming, from 3.79 Mt CO_2eq to 7.00 Mt CO_2eq in the year 2030 approximately [17].

The Peruvian government is working on increasing the country's current mitigation, such as through the "combination of renewable energies", identifying new mitigation actions which allow the government to achieve its climate commitment in 2030 [17]. This task requires identifying opportunities for greater effectiveness and impact in reducing GHG emissions and ensuring the broad participation of public and private actors in closing the gap.

1.2. Description of Energy Matrix of Peru and Implementation of Renewable Energies

Peru had a total installed capacity of 13,419.8 MW up until December 2022 [19]. In 2022, the maximum annual demand was 7467.5 MW, representing 55.6% of the system's installed capacity [19]. This means that, currently, there is a surplus of installed capacity in the energy sector, which can be explained by the delay in critical infrastructure and mining projects, which are supposed to be the primary energy consumers [21].

In terms of energy, in 2022, the total annual energy production reached 56,084.20 GWh, of which 50.8% came from hydropower plants, 43.0% from natural gas thermal power plants, 3.4% from wind power plants, 1.5% from solar power plants, 0.6% from biomass power plants, 0.5% from Diesel2/Residual500/Residual 6 thermal power plants, and 0.2% from coal thermal power plants [19] (see Figure 2). This distribution does not consider the wind farm project "Punta Lomitas" production, which began its commercial operation in July 2023. It is the biggest wind farm in Peru, with an installed capacity of 260 MW, but it will have an additional future expansion of 36.4 MW [19].

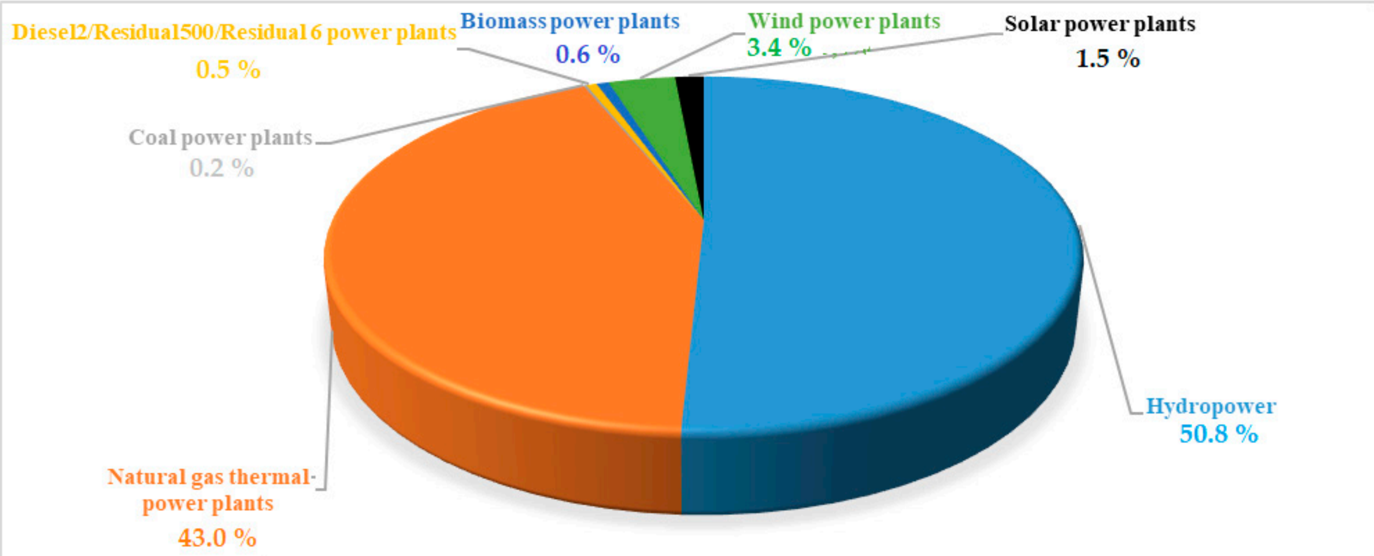

Figure 2. 2022 annual energy production in Peru considering distribution by the type of power plants [19].

There is an efficient generation offer of 819 MW until 2025 in the National Interconnected Electricity System (SEIN), comprised of a portfolio of projects with high execution certainties. Given the probable lack of efficient generation in the SEIN from 2026 and considering a projected increase in the average demand by 2030 of 1600 MW, efficient energy generation will be required, which should ideally come from renewable sources [19].

According to the latest Wind Atlas of Peru of 2016 [22], Peru has a total on-shore wind potential of 28,395 MW, of which 20,493 MW can be used (20.5 GW), excluding archaeological zones, national parks, natural reserves, historical zones, protected areas, recreational areas, etc. However, until now, there has only been a total installed capacity of 668 MW from wind power plants [19].

Up until February 2016, there were only four auctions for renewable energy resources (RER) generation, assigning contracts to solar, wind, biomass, and small hydroelectric power plants (less than 20 MW). In the four auctions, 64 RER projects were awarded, for a total installed capacity of 1274 MW [22]. Seven of those projects were wind farms, accounting for 392.47 MW of the installed capacity. The average levelized cost of electricity for the awarded wind power projects started at 80.4 USD/MWh in the 1st auction and decreased to 69 USD/MWh in the 2nd auction and 37.7 USD/MWh in the 3rd auction [22].

According to the information published by the Economic Operation Committee of the National Interconnected Electricity System (COES—SEIN), the production of electrical energy of the SEIN in 2012 was 37,617.6 GWh, while, in 2022, it was 56,084.2 GWh, corresponding to an increase of 49.1% compared to 2012 [19]. This trend has continued in recent years as a reflection of the increase in electricity demand in Peru due to strong economic, technological, and population growth in the country [23,24].

To respond to this increase in energy demand, the supply of electricity generation that the country requires must be met in the short term. In this sense, and given the international pressure towards a sustainable energy matrix, energy generation must tend towards being clean [25,26]. Thus, considering the renewable energy potential which Peru has, a viable option is to increase the energy supply through electrical generation that uses non-conventional renewable energy resources such as solar, wind, tidal, and geothermal energy [27–29]. It is in this context that wind energy is taking an important role in Peru's energy matrix, being one of the most attractive non-conventional renewable energy alternatives for investors [18,24,30].

1.3. Aim of the Article

Wind energy is a viable alternative to mitigate the effects of climate change in local territories in Peru and, thus, meet the Sustainable Development Goals (SDGs) in the 2030 United Nations (UN) Agenda. This article presents the potential for generating wind-type electrical energy both on-shore and off-shore in Peru. Also, the future of the generation of electrical energy from wind sources is presented, considering that the portfolio of investment projects in Peru is promising, where an on-shore installed capacity of more than 7429 MW has been projected, to be implemented in the next decades and, thus, meet the committed carbon neutrality goals by 2050. In addition, the main advantages, benefits, and restrictions in the implementation of this type of energy plants in Peru are presented, according to the following: (i) the mitigation of climate change considering the insertion of renewable energies in the energy matrix; (ii) the potential of the available wind resource; (iii) the characterization of existing wind farm power plants; and (iv) implementation projections of future wind farm power plants. Additionally, recent advances, challenges linked to territorial implementation, and future perspectives in the development of the renewable energy sector from wind resources to address climate change are discussed.

2. Potential of Wind Energy Resources in Peru

2.1. On-Shore Wind Energy

According to the map of wind speed at a 100 m height generated by the Global Wind Atlas (GWA), Peru has a considerable and underutilized wind potential [31]. These conditions are mainly concentrated along almost the entire Peruvian coast and, in some areas, in the interior of the northern Peruvian Andes. While, in the Amazon, the potential is minimal and of little consideration (Figure 3). Regarding this wind resource information, this comes from the analysis of wind speed with the Weibull probabilistic distribution, taking into account the wind conditions at different heights and validating seasonal behaviors. The Weibull probabilistic distribution is considered by using data from the Global Wind Atlas platform [31] and its processing in the WAsP software [32], in addition to considering the roughness length of the environment. Likewise, currently, the country has seven wind farms in operation (information last reviewed in August 2023). These are active and fully operational. All these on-shore wind power plants are connected to the National Interconnected Electricity System (SEIN).

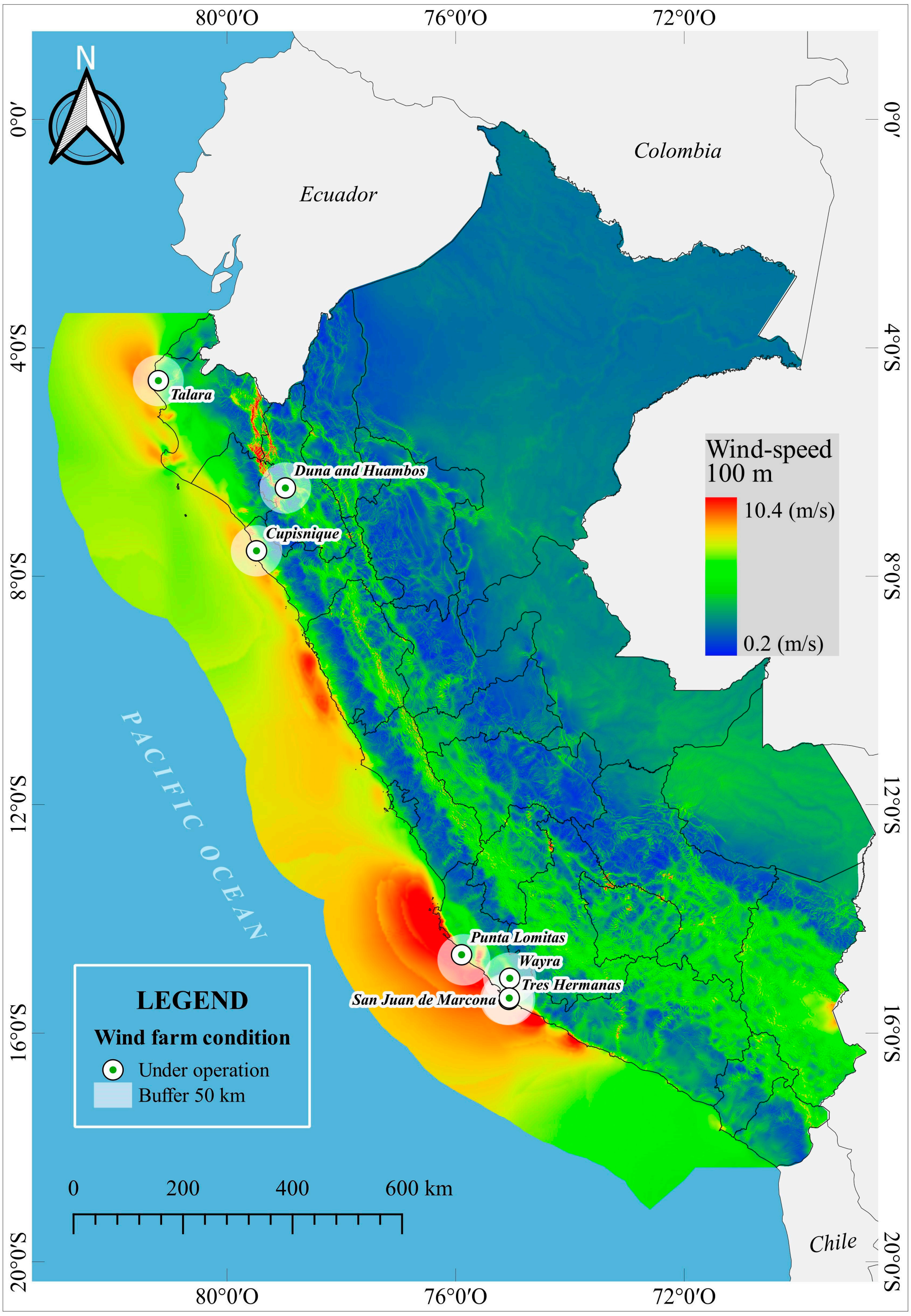

Figure 3. Map of the wind potential at an average wind turbine height of 100 m and the location of the wind farms under operation in Peru.

The distribution of the wind farms is quite localized. On the Peruvian coast, there are several wind farms, which are located no more than 500 masl. The largest number are found in the coastal regions of Ica (Tres Hermanas, San Juan de Marcona, Wayra and Punta Lomitas), La Libertad (Cupisnique), and Piura (Talara). Also, there is one wind power plant in the northern part of the Andes in the country, specifically in the Cajamarca region (Duna and Huambos). This last region, along with the Andean part of the Piura region, has great wind potential in a large part of the Andes mountain range (Figure 4).

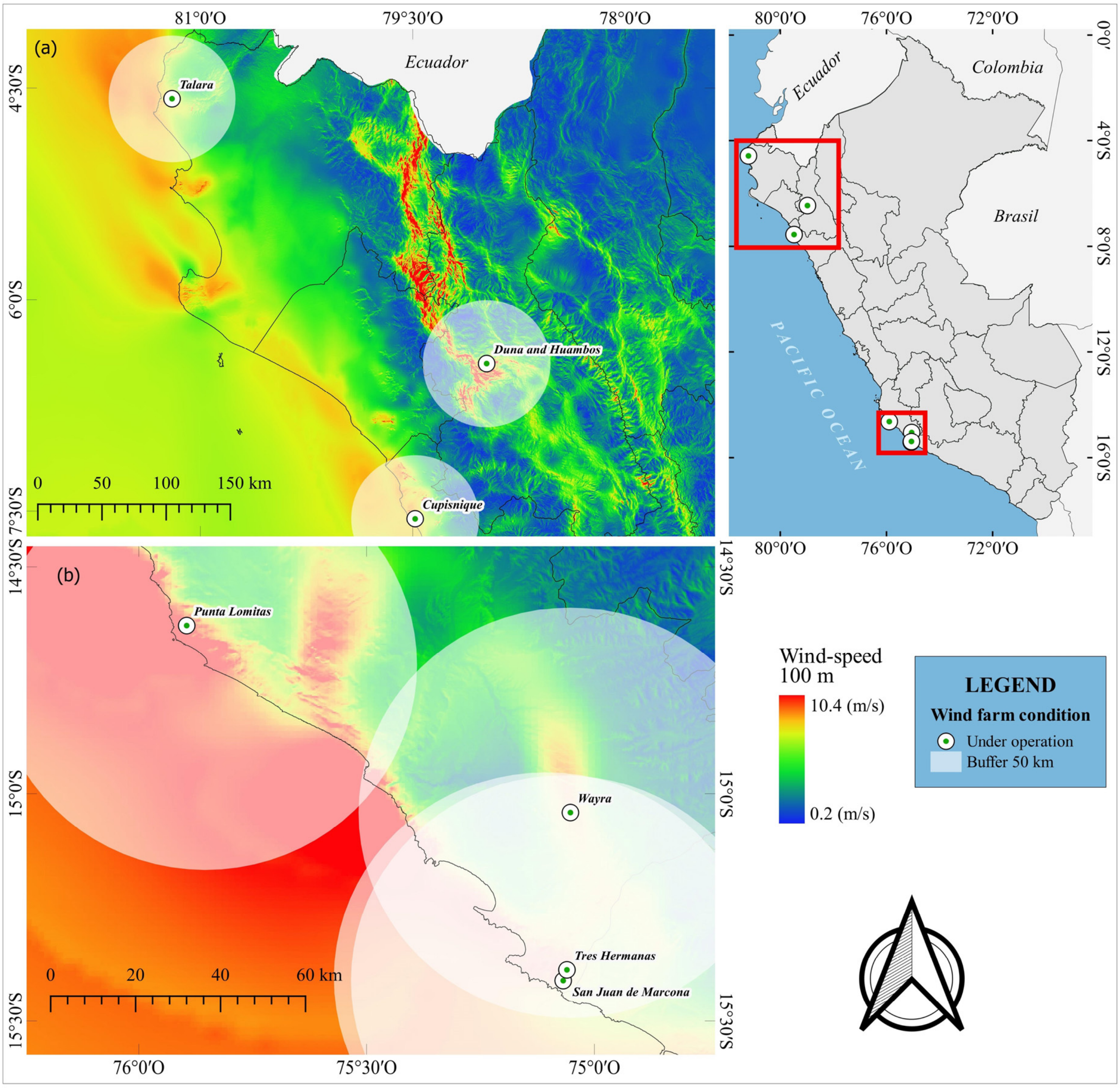

Figure 4. Occupation of wind farms in the north and south of Peru and a reference area of influence of 50 km radius.

These regions are characterized by presenting wind speeds of classes I and II (standard called IEC 61400-1 Wind Turbine Generator Systems) [33], at 80 and 100 m of height (height of the hub) [31], in addition to presenting high-capacity factors, between 43 and 55% [34]. This condition allows for adequate energy transformation that is also intensified during peak hours, which, in economic terms, gives better commercial conditions for the SEIN [19].

The production of wind energy depends on the wind conditions, which increase or decrease depending on the seasonal period of the year; however, wind power plants present a very similar hourly behavior, so that production increases accordingly. Figure 5 shows the average hourly wind energy production profile registered in Peru considering the seasonal period of the year and the seven wind farms under operation.

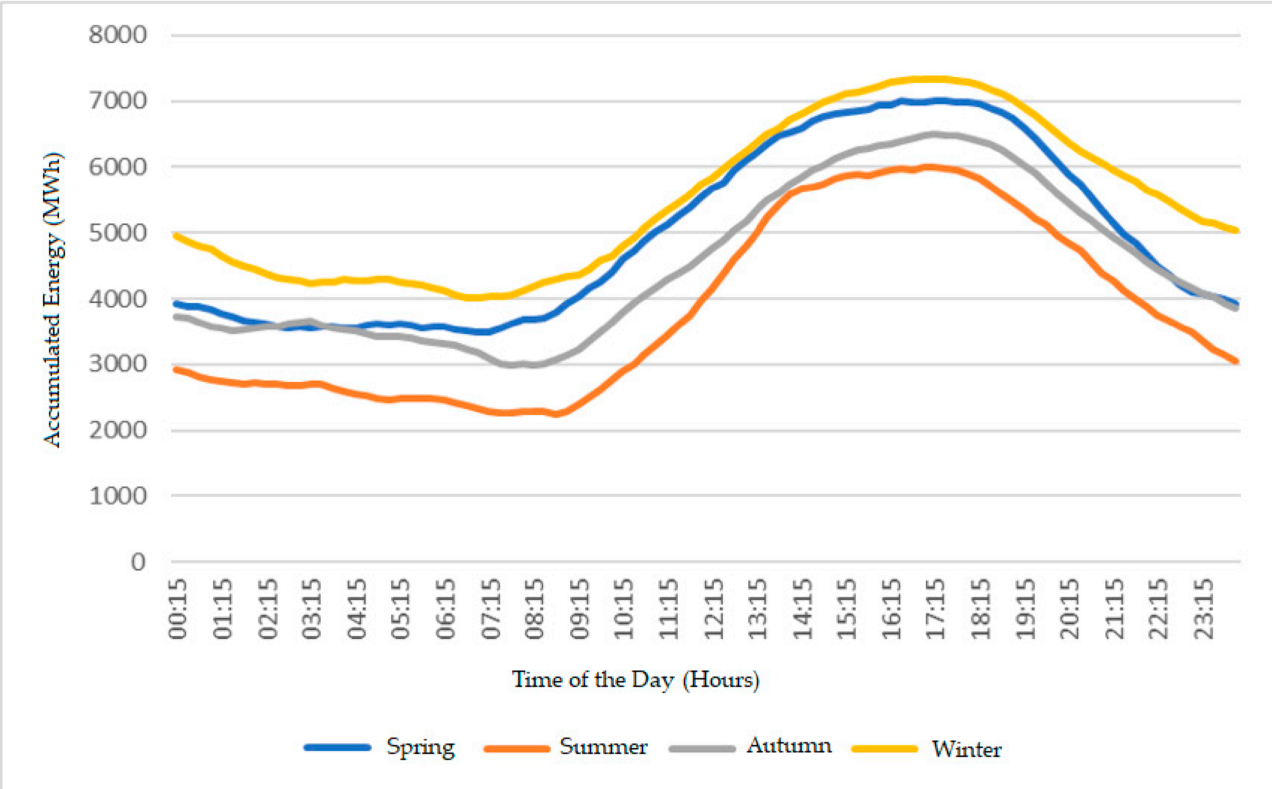

Figure 5. Average hourly wind energy production profile registered in Peru.

Figure 5 shows that the hours of the day during which the least amount of electrical energy is generated in on-shore wind farms corresponds to the period between 01:00 a.m. and 08:00 a.m. On the contrary, the hours of the day during which the greatest amount of electrical energy is generated in on-shore wind farms corresponds to the period between 1:00 p.m. and 7:00 p.m. Furthermore, it is possible to appreciate the seasonal variations according to the time of the year, according to which the least amount of energy is generated in the summer season, and, on the contrary, the greatest amount of energy is generated in the winter season, and, finally, both in the autumn and in the spring, an intermediate amount of energy is generated compared to the extreme cases of the time of the year mentioned above. This complements the availability of water resources for the generation of energy from hydroelectric sources, which is higher in the summer and lower in the winter.

More than 80% of the on-shore wind farms that are currently in operation in Peru are located on the coastal edge, in areas with a desert landscape. In these areas, significant amounts of wind are generated during the majority of the day (Figure 6). Overall, Peru's on-shore wind resource has been estimated to result in a potential of 20.5 GW [22], while, by 2023, only 3% of the aforementioned potential has been used.

To estimate the total wind potential, preferential areas have been identified for the future construction of wind farms or wind turbines. The criteria include: (i) power density from moderate to excellent (P > 300 W/m^2) at 100 m height; (ii) frequency distribution of the favorable wind; (iii) slope of the land less than or equal to 20%; (iv) proximity to passable access roads; (v) proximity to populated centers, to existing medium and high voltage lines and substations; (vi) existing wind farms; and (vii) altitude of the site less than 3500 masl. The total wind potential results from the sum of the usable wind potential plus the excluded one. The difference between these two concepts is that the first includes areas suitable for the construction of wind turbines and wind farms and the second is the potential that cannot be used due to legal provisions (archaeological zones, national parks, nature reserves, historical zones, among others). The usable on-shore wind potential is

20,493 MW and the excluded wind potential is 7,902 MW. Table 1 shows the details of the regions of Peru with the greatest wind energy potential.

Figure 6. An example of a wind farm power plant that is located in a desert landscape in Peru.

Table 1. Regions of Peru with the greatest on-shore wind energy total potential and usable potential [22].

Region	Total Potential (MW)	Usable Potential (MW)
Piura	8601	7098
Lambayeque	9114	7017
Ica	5295	2280
Arequipa	1176	1020
La Libertad	1185	921
Cajamarca	1173	891
Ancash	816	708
Lima	618	429
Amazonas	417	129
	28,395	**20,493**

Table 1 shows that the regions of Peru with the greatest potential for wind energy are Piura, Lambayeque and Ica. They highlight the outstanding potential of Piura and Lambayeque, but it is striking that by 2023 there is only one wind farm in operation in these regions, while the region that has the largest number of wind farms in operation currently is Ica with four. Finally, the other regions that currently have one wind farm in operation each are La Libertad and Cajamarca.

2.2. *Off-Shore Wind Energy*

The Peruvian coast presents conditions for the use of wind resources; this has a greater impact on the coast of the Ica, Arequipa, Ancash, and Piura regions. However, unlike in the land area, no meteorological stations are placed on buoys that allow the resource to be evaluated with greater precision. The information available comes from some ships that make measurements, but there are no historical data. On the contrary, the information comes from platforms such as the Global Wind Atlas (GWA) [31]. In this sense, the annual variability concerning the average annual speed is lower, close to 13%, which gives greater stability.

Although the off-shore wind resource is attractive, its use presents engineering challenges related to foundations, platforms, and anchors, due to the high depths near the Peruvian coast.

The depth of the seabed is currently being evaluated to determine the platforms that provide stability to the off-shore wind turbines in marine environments, considering waves, tides, and even the risk of tsunamis. Due to this, bathymetry studies are essential for assigning areas where fixed- or floating-base installations are recommended. Areas with depths < 50 m are recommended for off-shore fixed-base installations, such as the monopile, tri-pod, or jacket, while, for depths > 50 m and up to 200 m, floating installations such as spar-buoys, tension-leg platforms, semi-submersibles, or hybrids of these concepts are recommended (Figure 7) [35].

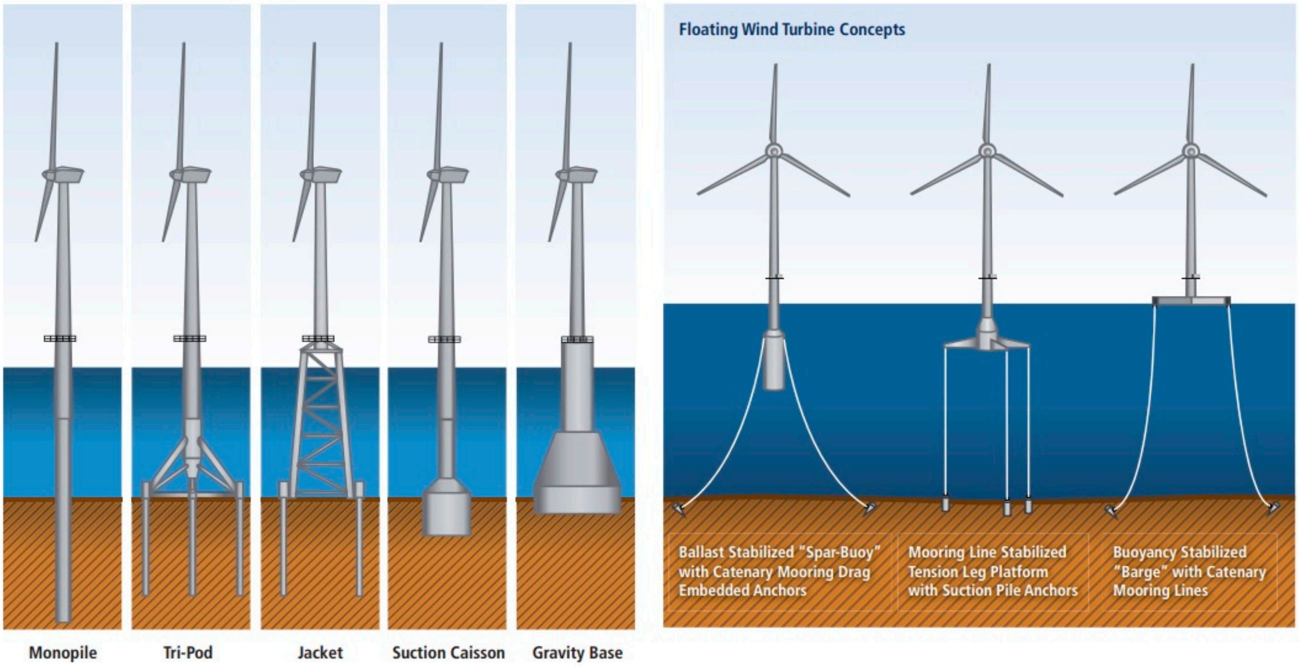

Figure 7. Off-shore wind turbines for depths < 50 m consider fixed-base installations (**left**), while for depths > 50 m floating installations are preferred (**right**).

One of the most interesting aspects of this technology is the decrease in the price of energy generation over time, where it is observed that, in the last 10 years, it has decreased from 100–200 USD/MWh to values of 50–100 USD/MWh. The current record is 50 USD/MWh for an off-shore installation in the United Kingdom, registered in September 2019 [36]. This naturally makes off-shore wind technology a viable economic option in countries whose energy costs are high such as, for example, those countries with a high dependence on fossil fuels.

Figure 8 shows a map of the off-shore wind resource potential in Peru, indicating the wind speeds in off-shore areas in northern, central, and southern Peru [36].

Figure 8 shows that the areas where fixed-base off-shore wind farms could be installed are located in the north of the country, from Tumbes to Chimbote, approximately, while the areas for floating off-shore installations go from Tumbes in the north to Arequipa in the south.

It should be noted that, within the 200 miles of the Peruvian coastline, it is advisable to install off-shore systems in the first 8.6 miles of distance due to the visual impact and the ratio of voltage drops due to underwater wiring. However, it is necessary to have a study related to the marine fauna routes to identify the areas with the greatest potential and least environmental impact more accurately.

Overall, Peru's off-shore wind potential has been estimated to result in a potential 32 GW for fixed-base off-shore installations and 315 GW for floating off-shore installations, resulting in a total of 347 GW [36].

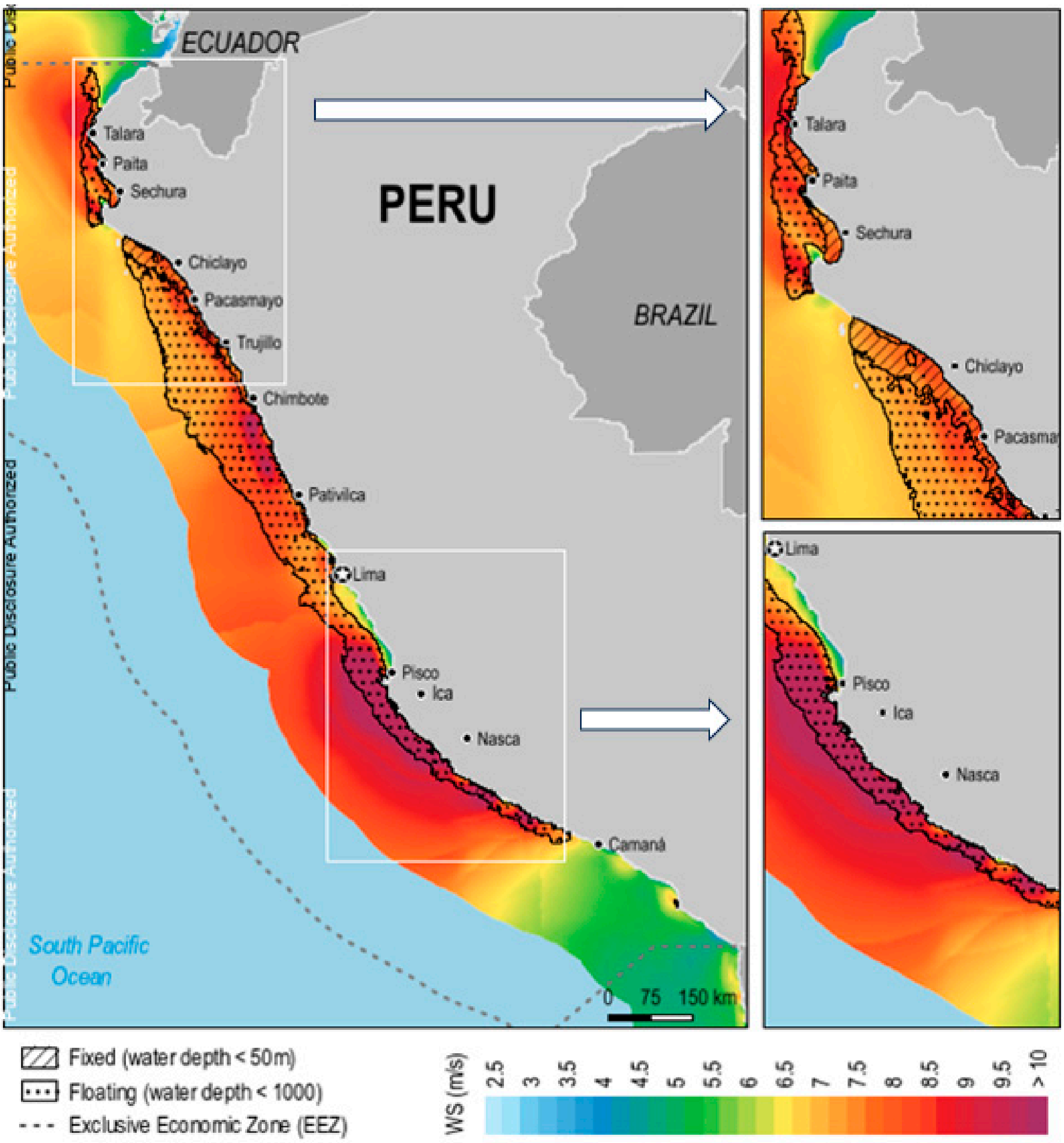

Figure 8. Off-shore wind technical energy potential in Peru [36].

3. Wind Farm Power Plants Experiences in Peru—State of Practice

Below, the information and practical experience of the implementation of wind farms in Peru is presented in detail, considering the following: (i) projects in the operation stage, (ii) projects in the construction stage, and (iii) future projects currently in progress (stage of technical studies and/or environmental impact assessment (EIA) studies).

3.1. Projects in Operation

Below are the wind energy investment projects currently in operation in the Peruvian territory.

3.1.1. Cupisnique Wind Farm Power Plant—La Libertad Region

The Cupisnique Wind Farm is a facility located in the district of Cupisnique, province of Pacasmayo, Department of La Libertad, 675 km from the city of Lima, at an elevation of 20 masl. It has a capacity of 81 MW from 45 wind turbines, belonging to the Peruvian subsidiary Energía Eólica S.A. from the American company Contour Global. This wind farm began its construction phase in 2012 and came into operation in 2014. Figure 9 shows panoramic images of the wind farm, and Table 2 provides some key technical data on this energy generation facility.

Figure 9. Panoramic view of wind turbines in the Cupisnique wind farm power plant.

Table 2. Cupisnique wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	La Libertad Region	-
Concession Owner	Contour Global Perú S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	45	-
Turbines Manufacturer/Model	Vestas 100/1800	-
Diameter of Turbines	100	m
Hub Height	70–90	m
Installed Capacity per Turbine	1.8	MW
Total Installed Capacity	81	MW
Capacity Factor	0.42	-

Considering Figure 9, it is possible to see that the Cupisnique wind farm is located in an area close to the coastal zone, in a desert landscape in which no contiguous human settlements are located.

According to Table 2, this wind farm has a total of 45 wind turbines from the manufacturer Vestas, with a sweep diameter of the blades equivalent to 100 m. Furthermore, the height of the towers from the ground level to the hub is between 70 and 90 m. Each wind turbine has an installed capacity of 1.8 MW, so, considering all the wind turbines, the wind farm has a total installed capacity equivalent to 81 MW, with an estimated capacity factor of 0.42.

3.1.2. Talara Wind Farm Power Plant—Piura Region

The Talara wind farm is located in the department of Piura, province of Talara, in the district of Pariñas, 1000 km from the city of Lima, at 11 masl. It has an installed capacity of 31 MW made up of 17 wind turbines with an individual capacity equivalent to 1.80 MW. This wind farm began its construction phase in 2012 and came into operation in 2014. Figure 10 shows panoramic images of the wind farm, and Table 3 provides some key technical data on this energy generation facility.

From Figure 10, it is possible to see that the Talara wind farm is in a desert area where there are no adjacent human settlements.

According to Table 3, this wind farm has a total of 17 wind turbines from the manufacturer Vestas, with a sweep diameter of the blades equivalent to 100 m. Furthermore, the height of the towers from the ground level to the hub is between 70 and 90 m. Each wind turbine has an installed capacity of 1.8 MW, resulting in a total installed capacity of 31 MW, with an estimated capacity factor of 0.55.

Figure 10. Panoramic view of wind turbines in the Talara wind farm power plant.

Table 3. Talara wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Piura Region	-
Concession Owner	Contour Global Perú S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	17	-
Turbines Manufacturer/Model	Vestas 100/1800	-
Diameter of Turbines	100	m
Hub Height	70–90	m
Installed Capacity per Turbine	1.8	MW
Total Installed Capacity	31	MW
Capacity Factor	0.55	-

3.1.3. Duna and Huambos Wind Farm Power Plants—Cajamarca Region

This wind farm is located in the district of Huambos, province of Chota, in the department of Cajamarca, more than 2276 masl. It was the first to be installed and operated in the Andes mountain range of Peru, a geographically strategic place due to its exceptional meteorological conditions for the generation of this type of energy, with around 5000 net hours of wind per year.

With an installed power of 36 MW, this wind farm will contribute to the National Interconnected Electrical System (SEIN) for a period of 20 years. Grenergy is a Spanish company in charge of the operation of the wind farm and the execution of the concession. This wind farm began its construction phase in 2019 and came into operation in 2020. Figure 11 shows panoramic images of the wind farm, and Table 4 provides some key technical data on this energy generation facility.

From Figure 11, it is possible to see that the Duna and Huambos wind farm is in an Andean area where agricultural properties, livestock sectors, and adjacent human settlements are located.

According to Table 4, this wind farm has 14 wind turbines from the manufacturer Siemens-Gamesa, with a sweep diameter of the blades equivalent to 114 m. Furthermore, the height of the towers from the ground level to the hub is between 70 and 90 m. Each wind turbine has an installed capacity of 2.6 MW, so, considering all the wind turbines, the wind farm has a total installed capacity equivalent to 36 MW, with an estimated capacity factor of 0.55.

Figure 11. Panoramic view of wind turbines in the Duna and Huambos wind farm power plant.

Table 4. Duna and Huambos wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Cajamarca Region	-
Concession Owner	Grenergy/CJR Renewables	-
Type of Wind Farm	On-Shore	-
Number of Turbines	14	-
Turbines Manufacturer/Model	Siemens-Gamesa SG 2.6-114	-
Diameter of Turbines	114	m
Hub Height	70–90	m
Installed Capacity per Turbine	2.6	MW
Total Installed Capacity	36	MW
Capacity Factor	0.55	-

3.1.4. San Juan de Marcona Wind Farm Power Plant—Ica Region

This wind farm is located in the district of Marcona, province of Nazca, department of Ica, approximately 7 km away from the southern Pan-American highway and 10 km away from the city of San Juan de Marcona, at 200 masl. The construction phase of this plant began in 2011, and it came into operation in 2012. Figure 12 shows panoramic images of the wind farm, and Table 5 provides some key technical data on this energy generation facility.

Figure 12. Panoramic view of wind turbines in the San Juan de Marcona wind farm power plant.

Table 5. San Juan de Marcona wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Ica Region	-
Concession Owner	Cobra Peru S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	12	-
Turbines Manufacturer/Model	Siemens SWT-2.5-108	-
Diameter of Turbines	108	m
Hub Height	70–90	m
Installed Capacity per Turbine	2.5	MW
Total Installed Capacity	32	MW
Capacity Factor	0.60	-

From Figure 12, we can see that the San Juan de Marcona wind farm is located in a desert area where there are no adjacent human settlements.

According to Table 5, this wind farm has a total of 12 wind turbines from the manufacturer Siemens, with a sweep diameter of the blades equivalent to 108 m. Furthermore, the height of the towers from the ground level to the hub is between 70 and 90 m. Each wind turbine has an installed capacity of 2.5 MW, resulting in a total installed capacity equivalent to 32 MW, with an estimated capacity factor of 0.60.

3.1.5. Tres Hermanas Wind Farm Power Plant—Ica Region

The Tres Hermanas Wind Farm is located in the district of Marcona, province of Nazca, department of Ica, very close to the coast and to the border with the department of Arequipa, at 496 masl. It has a capacity of 96 MW and has 33 wind turbines. It began its operations in 2012 and was built by the Parque Eólico Tres Hermanas S.A.C consortium. The company is a subsidiary of the Spanish Grupo Cobra. This wind farm began its construction phase in 2011 and came into operation in 2012. Figure 13 shows panoramic images of the wind farm, and Table 6 provides some key technical data on this energy generation facility.

Figure 13. Panoramic view of wind turbines in the Tres Hermanas wind farm power plant.

From Figure 13, we can see that the Tres Hermanas wind farm is located in a desert area with no human settlements around.

According to Table 6, this wind farm has a total of 33 wind turbines from the manufacturer Siemens, with a sweep diameter of the blades equivalent to 108 m. Furthermore, the height of the towers from the ground level to the hub is between 70 and 90 m. Each wind turbine has an installed capacity of 2.9 MW, resulting in a total installed capacity of 96 MW, with an estimated capacity factor of 0.60.

Table 6. Tres Hermanas wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Ica Region	-
Concession Owner	Cobra Peru S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	33	-
Turbines Manufacturer/Model	Siemens SWT-2.9-108	-
Diameter of Turbines	108	m
Hub Height	70–90	m
Installed Capacity per Turbine	2.9	MW
Total Installed Capacity	96	MW
Capacity Factor	0.60	-

3.1.6. Wayra I Wind Farm Power Plant—Ica Region

The Wayra wind complex is located in the district of Marcona, province of Nazca, department of Ica, approximately 480 km from the city of Lima, near the Panamericana Sur highway, at 27 masl.

The Wayra complex is made up of two projects: Wayra I, which came into operation in 2018, after 14 months of construction works, and Wayra II (extension). This wind farm began its construction phase in 2017 and came into operation in 2018. Figure 14 shows panoramic images of the wind farm, and Table 7 provides some key technical data on this energy generation facility.

Figure 14. Panoramic view of wind turbines in the Wayra I wind farm power plant.

Table 7. Wayra I wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Ica Region	-
Concession Owner	Enel Green Power Perú S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	42	-
Turbines Manufacturer/Model	Acciona AW-3150/125	-
Diameter of Turbines	125	m
Hub Height	125	m
Installed Capacity per Turbine	3.1	MW
Total Installed Capacity	132	MW
Capacity Factor	0.57	-

From Figure 14, we can see that the Wayra I wind farm is located in a desert area where there are no adjacent human settlements.

According to Table 7, this wind farm has a total of 42 wind turbines from the manufacturer Acciona, with a blade sweep diameter equivalent to 125 m. Furthermore, the height of the towers from the ground level to the hub is between 70 and 90 m. Each wind turbine has an installed capacity of 3.1 MW, resulting in a total installed capacity of 132 MW, with an estimated capacity factor of 0.57. The new wind power plant, Wayra II, will be made up of 30 wind turbines of 5.9 MW each and will occupy an area of approximately 2443 Ha.

3.1.7. Punta Lomitas Wind Farm Power Plant—Ica Region

The Punta Lomitas Wind Power Plant is located in the district of Ocucaje, province of Ica, department of Ica, at 50 masl. This wind farm began its construction phase in 2022 and came into operation in July 2023. Figure 15 shows panoramic images of the wind farm, and Table 8 provides some key technical data on this energy generation facility.

Figure 15. Panoramic view of wind turbines in the Punta Lomitas wind farm power plant.

Table 8. Punta Lomitas wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Ica Region	-
Concession Owner	Engie Perú S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	50	-
Turbines Manufacturer/Model	Siemens-Gamesa SG 5.0-145	-
Diameter of Turbines	145	m
Hub Height	70–90	m
Installed Capacity per Turbine	5.0	MW
Total Installed Capacity	260	MW
Capacity Factor	0.60	-

From Figure 15, we can see that the Punta Lomitas wind farm is located in a desert area where there are no contiguous human settlements.

According to Table 8, this wind farm has a total of 50 wind turbines from the manufacturer Siemens-Gamesa, with a sweep diameter of the blades equivalent to 145 m. Furthermore, the height of the towers from the ground level to the hub is between 70 and 90 m. Each wind turbine has an installed capacity of 5.0 MW, resulting in a total installed capacity of 260 MW, with an estimated capacity factor of 0.60.

3.1.8. Summary of the Total Installed Capacity of Wind Energy in the Year 2023

Table 9 summarizes the main characteristics of the wind farms in operation in Peru, indicating their installed capacity and the total installed capacity for wind energy in Peru.

Table 9. Wind farm power plant projects in operation in Peru by November 2023.

Number	Wind Farm Power Plant Name	Region	Concession Owner	Installed Capacity (MW)
1	Parque Eólico Cupisnique	La Libertad	Contour Global Perú S.A.	81
2	Parque Eólico Talara	Piura	Contour Global Perú S.A.	31
3	Parque Eólico Duna and Huambos	Cajamarca	Grenergy / CJR Renewables.	36
4	Parque Eólico San Juan de Marcona	Ica	Cobra Perú S.A.	32
5	Parque Eólico Tres Hermanas	Ica	Cobra Perú S.A.	96
6	Parque Eólico Wayra I	Ica	Enel Green Power Perú S.A.	132
7	Parque Eólico Punta Lomitas	Ica	Engie Energía Perú S.A.	260
			Total Installed Capacity	668

Considering Table 9, it is possible to see that, by 2023, there were a total of seven wind farms in operation in Peru, all of the on-shore type. In addition, it is possible to see that three wind farms are located in the northern part of the country in the La Libertad, Piura, and Cajamarca regions, while another four wind farms are located in the southern part of the country, in the Ica region. It is observed that the wind farm with the lowest energy generation capacity is the Duna and Huambos wind farm, with 36 MW, while the Punta Lomitas wind farm is the facility with the highest energy generation capacity, with 260 MW. Finally, considering the seven wind farms in operation, there is a total installed capacity equivalent to 668 MW. This installed capacity for the year 2023 is equivalent to 3% of the usable on-shore wind energy potential of 20.5 GW.

In Figure 16, it is possible to see a summary indicating the amount of annual energy generated in GWh and the capacity factor of each wind farm that is in operation in Peru.

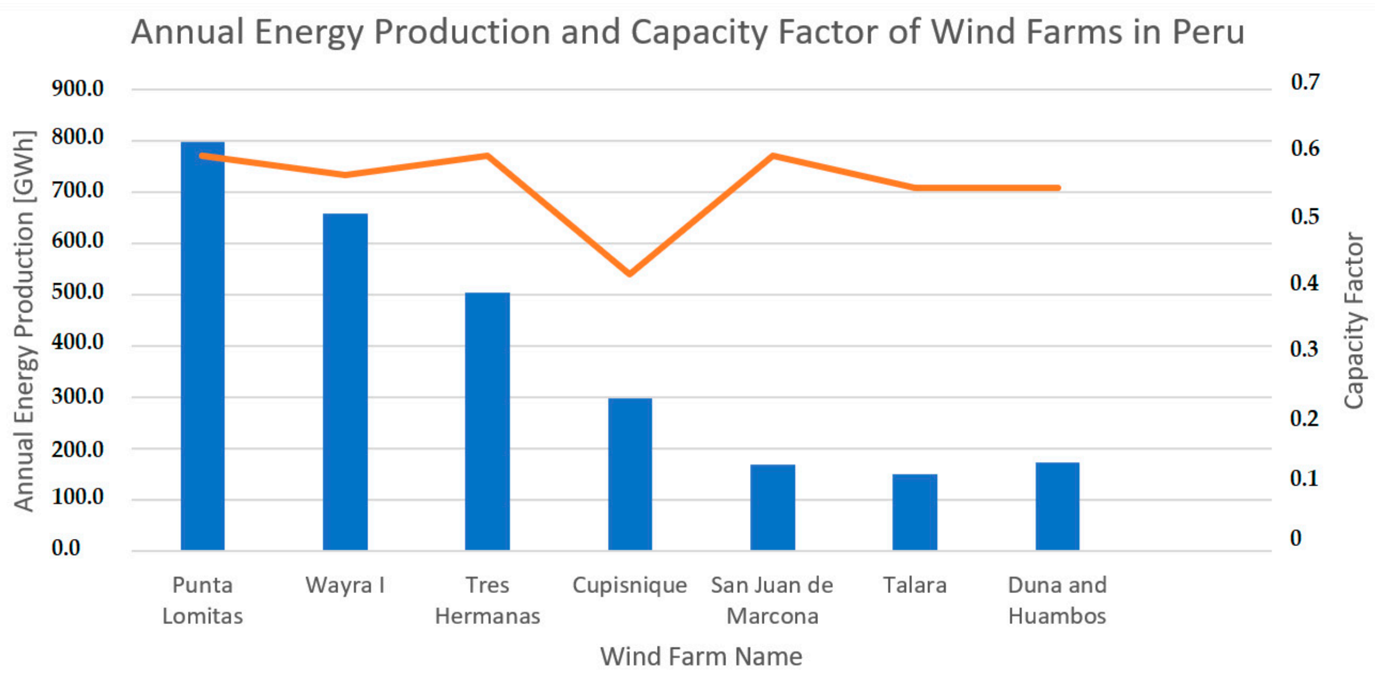

Figure 16. Comparative graph for annual energy production and capacity factor for the wind farm power plants in Peru.

According to Figure 16, the wind farm that generates the greatest amount of annual energy production is Punta Lomitas, with approximately 797 GWh, while the Talara wind farm generates the least annual energy production, with 149 GWh. The Punta Lomitas wind farm generates only 797 GWh of annual energy production because it started its operations in July 2023, but, probably, in 2024, under a complete year of annual operations, it will generate 1367 GWh. On the other hand, the capacity factors oscillate in a range between 0.42 for the Cupisnique wind farm and 0.60 for the Punta Lomitas, Tres Hermanas, and San Juan de Marcona wind farms.

Finally, below, it is possible to see, in Figure 17, the evolution over time of the installed capacity in MW of the on-shore wind energy in Peru.

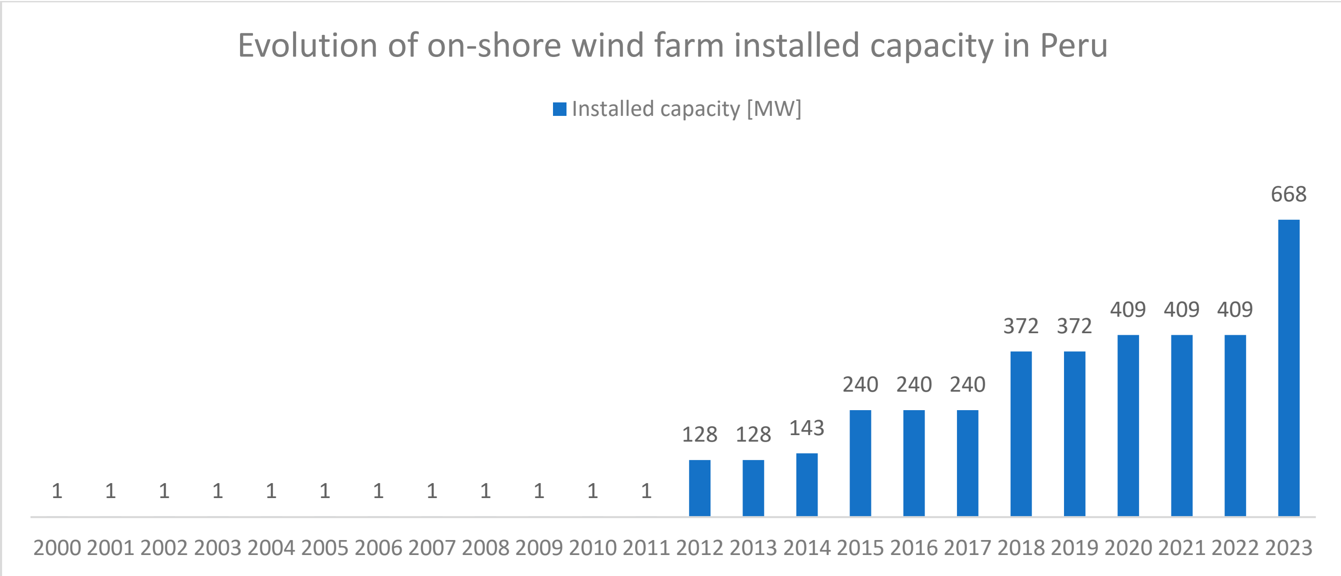

Figure 17. Evolution over the time (years) of on-shore wind farm installed capacity in Peru.

Concerning Figure 17, we can mention that the introduction of wind energy in Peru began strongly in 2012, having sustained growth year after year, from 2012 to 2023.

3.2. Projects Approved under Construction in the Year 2023

In the following paragraphs there are detailed the wind farm projects with environmental impact assessment (EIA) approval that are under construction in 2023.

3.2.1. Wayra II Wind Farm Power Plant—Ica Region

The Wayra II wind farm will have 30 wind turbines, each one with an installed power of 5.9 MW, and, together, they will achieve a power of 177 MW. The Wayra extension, added to Wayra I, will form the largest wind project in Peru, with an installed power of almost 310 MW. The characteristics of each wind turbine to be installed in the Wayra extension are the following: power per wind turbine: 5.9 MW; height: 180 m; and blade length: 76 m. These are all shown in Table 10.

Table 10. Wayra II wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Ica Region	-
Concession Owner	Enel Green Power Perú S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	30	-
Turbines Manufacturer/Model	Acciona AW-3250/180	-
Diameter of Turbines	125	m
Hub Height	180	m
Installed Capacity per Turbine	5.9	MW
Total Projected Capacity	177	MW
Capacity Factor	0.60	-

3.2.2. Caraveli Wind Farm Power Plants—Arequipa Region

Grupo Ibereólica Renovables will promote its first wind farm project in the Lomas district located at 320 masl, in the Caravelí province, Arequipa region, Peru, with a capacity of 220 MW. The project includes the installation of 36 wind turbines, each one with an installed power of 6.1 MW, in an area of approximately 2800 hectares. The wind turbines to be installed will be state-of-the-art turbines, positioned according and suitable to the existing wind regime in the area, incorporating technological elements for reactive power regulation and tension control. Table 11 shows the main characteristics of the Caraveli wind farm.

Table 11. Caraveli wind farm power plant main specifications [37].

Parameter	Value	Units
Location	Arequipa Region	-
Concession Owner	Iberolica Caraveli Perú S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	36	-
Turbines Manufacturer/Model	Siemens-Gamesa SG 6.0-170	-
Diameter of Turbines	100	m
Hub Height	170	m
Installed Capacity per Turbine	6.1	MW
Total Projected Capacity	220	MW
Capacity Factor	0.55	-

3.2.3. San Juan de Marcona Part IV Wind Farm Power Plants—Ica Region

Ten years after the first wind farm built in San Juan de Marcona, which was the first wind energy project in the country, investors are once again returning to the city of Marcona to build a new wind farm. This wind farm will consist of 23 Nordex-model N163-5.9 turbines, each one with an installed power of 5.9 MW and with a 148 m high steel tower. Located in the municipality of Marcona, in the province of Nazca (Ica Region), the San Juan de Marcona wind farm has CJR Renewables for the execution of its EPC (engineering, procurement, and construction), where CJR Renewables is in charge of the engineering, civil works (with 22 km of access and 23 platforms and foundations), and electrical works for the plant (93 km of medium-voltage networks (33 kV) and 14 km of trenches).

The project schedule will end in 2023, with the San Juan de Marcona wind farm operating in parallel with the Wayra II wind farm. Table 12 shows the main characteristics of the new San Juan de Marcona wind farm.

Table 12. San Juan de Marcona part IV wind farm power plant's main specifications [37].

Parameter	Value	Units
Location	Ica Region	-
Concession Owner	Energía Renovable del Sur S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	23	-
Turbines Manufacturer/Model	Nordex N163-5.9	-
Diameter of Turbines	95	m
Hub Height	148	m
Installed Capacity per Turbine	5.9	MW
Total Projected Capacity	136	MW
Capacity Factor	0.55	-

3.2.4. Summary of the Total Installed Capacity of Wind Energy under Construction in the Year 2023

Table 13 summarizes the main characteristics of the wind farms under construction in Peru in 2023, which indicates the installed capacity of each wind farm and the total installed capacity for wind energy in Peru.

Table 13. Wind farm power plant projects under construction in Peru by November 2023 [19].

Number	Wind Farm Power Plant Name	Region	Concession Owner	Installed Capacity (MW)
1	Parque Eólico Wayra II	Ica	Enel Green Power Perú S.A.	177
2	Parque Eólico Caraveli	Arequipa	Iberolica Caraveli Perú S.A.	220
3	Parque Eólico San Juan de Marcona IV	Ica	Energía Renovable del Sur S.A.	136
			Total Projected Capacity	533

Considering Table 13, it is possible to see that, by 2023, there were be a total of three wind farms under construction in Peru, all of the on-shore type. Furthermore, it is possible to see that the three wind farms are located in the southern part of the country, in the regions of Ica and Arequipa. It is observed that the wind farms are large, considering the existing wind farms currently in operation, with an installed capacity of over 100 MW. Finally, considering the three wind farms in their construction stage by November 2023, there is a total projected installed capacity equivalent to 533 MW.

3.3. Projects for the Future—Under Technical Study and Environmental Impact Assessment Processing

The conditions of the wind resource in Peru are adequate for the development of this type of plants; however, the development of financing mechanisms is still required to promote their development significantly. The COES has projected an incoming total energy of 7429 MW from wind power plants by 2028, with the northern zone accounting for 59% of said production, the central zones 37%, and the southern zone 4% [19].

Table 14 summarizes the main characteristics of the wind farm projects planned in Peru for the period 2023–2028, currently under the development of technical studies and the processing of environmental impact assessment (EIA) studies.

Table 14. Wind farm power plant projects in Peru expected for the period 2023–2028 [19].

Number	Wind Farm Power Plant Name	Region	Concession Owner	Installed Capacity (MW)
1	Parque Eólico Pacifico	Arequipa	Ibereolica Pacifico S.A.	215
2	Parque Eólico José Quiñonez	Lambayeque	Invenergy Peru Wind S.R.L.	136
3	Parque Eólico La Espinoza	Piura	Sechin Empresa de Generación Electrica S.A.	475
4	Parque Eólico Cerro Chocán	Piura	Norwind S.A.C.	422
5	Parque Eólico Huascar	Piura	Zeus Energía S.A.C.	300
6	Parque Eólico Gurango	Ica	SL Energy S.A.C.	300
7	Parque Eólico Samaca	Ica	Empresa de Generación Electrica Las Salinas S.A.	168
8	Parque Eólico Colorado	Ancash	Grenery Perú S.A.C.	180
9	Parque Eólico Ciclón	Lambayeque	IGNIS Partners S.L.	402
10	Parque Eólico Naira I	Cajamarca	Gr Huambos S.A.C.	20
11	Parque Eólico Vientos Negritos	Piura	Lader Energy Chile SPA	150
12	Parque Eólico Rosa	Lambayeque	IGNIS Partners S.L.	400
13	Parque Eólico Quercus	Lambayeque	IGNIS Partners S.L.	452
14	Parque Eólico Vientos de Mochica	Lambayeque	Blaud Energy S.A.C.	220
15	Parque Eólico Muyu	Arequipa	Enel Green Power Perú S.A.	217
16	Parque Eólico Expansión Punta Lomitas	Ica	Engie Energía Perú S.A.	36
17	Parque Eólico Torocco	Ica	Bow Power Perú S.R.L.	112
18	Parque Eólico Vientos de Sechura	Piura	Lader Energy Chile SPA	202
19	Parque Eólico Cefiro	Ica	Cefiro Energía S.A.C.	366
20	Parque Eólico Windica	Ica	Fener Perú S.A.	150
21	Parque Eólico Emma	Piura	GR Bayovar S.A.C.	72
22	Parque Eólico Piletas	Ica	Fenix Power Perú S.A.	250
23	Parque Eólico Violeta Eólica	Piura	IGNIS Partners S.L.	452
24	Parque Eólico Zapote	Lambayeque	IGNIS Partners S.L.	164
25	Parque Eólico Norteño	Lambayeque	Kallpa Generación S.A.	131
26	Parque Eólico Cherrepe	Lambayeque	Kallpa Generación S.A.	143
27	Parque Eólico Morrope	Lambayeque	Enel Green Power Perú S.A.	224

Table 14. *Cont.*

Number	Wind Farm Power Plant Name	Region	Concession Owner	Installed Capacity (MW)
28	Parque Eólico Los Vientos	Ica	Kallpa Generación S.A.	365
29	Parque Eólico Shougang	Ica	Shougang Generación Electrica S.A.A.	302
30	Parque Eólico Vientos de Medianía	Lambayeque	Blaud Energía Peru S.A.C.	223
31	Parque Eólico Huarmey	Ancash	Energía Renovable del Centro S.A.	180
			Total Projected Capacity	7429

Considering Table 14, it is possible to see that, by 2023, there were a total of 31 wind farm projects planned for the future in Peru, all of the on-shore type. Furthermore, it is possible to see that the projects are located in the northern zone (Piura, Lambayeque, and Cajamarca), central zone (Ancash), and southern zone (Ica, and Arequipa) of Peru. It is observed that the wind farm project with the lowest expected energy generation capacity is the Punta Lomitas expansion, with 36 MW, while the La Espinoza wind farm project is the wind farm with the highest expected energy generation capacity, with 475 MW. Finally, considering the 31 wind farm projects, there is a total projected installed capacity equivalent to 7429 MW.

4. Discussion

4.1. Recent Advances

Wind energy technology on an industrial scale has already been successfully implemented in Peru, being increasingly popular and a feasible alternative to apply in different places in the territory with wind resource potential. Considering the experience of on-shore wind farms in Peru since 2012, the main advantages and disadvantages are presented in Table 15.

Table 15. Advantages and disadvantages of wind farms considering practical experiences in Peru.

Advantages	Disadvantages
• It is a clean, renewable, and abundant source of energy.	• It is a discontinuous energy source; its intensity and direction change suddenly.
• It does not require fuel for its operation.	• It depends on traditional sources for its operation.
• It is easy to operate and maintain.	• Fluctuation in wind intensity can cause power outages and damage.
• Generates employment opportunities mainly during the construction stage.	• It is not a storable energy source.
• Takes advantage of arid areas or areas that cannot be cultivated due to their topography on land and marine areas that cannot be used in the sea.	• It presents serious technical drawbacks in its production.
• Its environmental impact is low.	• It is not compatible with being implemented in territories of protected natural areas and/or archaeological/cultural heritage.

The main advantages highlighted in Table 15 are that the environmental impacts in the territory with this renewable energy technology are low, and it is also highlighted that its operation and maintenance are easy to execute, while it also generates important employment opportunities mainly during its construction stage [38,39]. On the other hand, some of the disadvantages observed are as follows: it is a discontinuous energy source; it is conditioned to the intensity and direction of winds which can change suddenly; and it is not compatible with being implemented in territories of protected natural areas and/or archaeological/cultural heritage [40,41].

The implementation of the current seven wind farms has served as a precedent and constitutes the basis of the portfolio of future wind farm projects to be built in the north, center, and south of Peru. The experience acquired to date has allowed contractor companies to learn for the construction and assembly of wind farms. In addition, the training of specialized personnel in the operation of wind farms has been carried out, as well as experience has been acquired in the processes of processing environmental licenses for operating such plants and building trust relations with neighboring communities [42].

The insertion of wind energy is contributing to the diversification of Peru's energy matrix, allowing the use of a renewable source; however, its participation is still in its initial stage, despite the vast potential available.

The success stories of the projects in operation have allowed communities to be educated, making known a viable and feasible alternative which can coexist in a territory with the livelihoods of its inhabitants.

For this reason, studies are becoming increasingly necessary to locate wind farm infrastructure where the compromise between the use of wind potential and the minimization of the impacts on the environment is maximized, resulting in the better operation and sustainability of this renewable and alternative energy source [43,44].

Finally, it is important to highlight the contribution of wind energy to other industries, especially the mining sector. For example, the production of electrical energy from the Punta Lomitas wind power plant will allow for the electrical demand of the Quellaveco mine, a world-class copper mining project, to be supported with renewable energy sources, making it the first major mining site in Peru to use 100% green energy for its mine operations.

4.2. Challenges for the Implementation in the Territory

The wind resource of Peru presents characteristics of stability, both in its speed and predominant direction. This is due to the trade winds that come from the south and that, when they impact the terrestrial area, promote constant local winds, such as the Paracas and the Ica. However, despite this, Peru presents climatic phenomena known as El Niño and La Niña (ENSO), which modify the average wind speed in the years during which they occur. [26]. Determining its seasonality is extremely important for wind analysis studies influencing energy production [45].

The standard called IEC 61400-1 Wind Turbine Generator Systems [33] identifies four classes of turbines for different wind conditions: Class I, whose average annual speeds are 10 m/s; Class II, with speeds of 8.5 m/s; Class III, with speeds of 7.5 m/s; and Class IV, with 6 m/s. In this sense, the best wind conditions are for Class I and Class II, as long as the probability of this kind of wind occurring is above 2000 hour per year.

According to the measurements of the SENAMHI meteorological stations distributed in the Peruvian territory, an interesting potential has been estimated in different points of the Peruvian coast and mountain range [45] where the wind resource, measured at a height of 10 m, registers values for Class I and Class II, particularly in the areas of Ica, Piura, Lambayeque, La Libertad, Cajamarca, and Ancash. Table 16 shows some points in these areas with great potential.

Table 16. Wind potential of wind speed V (m/s) and power P (W/m^2) at different heights of wind turbines H (m) recognized in different places in Peru.

Region	Altitude masl	Roughness	Wind Direction	H = 10 m		H = 50 m		H = 100 m		Annual Variability
				V (m/s)	P (W/m^2)	V (m/s)	P (W/m^2)	V (m/s)	P (W/m^2)	
Ica	550	0.005	SE	14.02	2147	15.38	2693	15.87	2836	23%
Ica	411	0.005	S	7.72	446	9.71	766	11.23	1082	19%
Piura	130	0.005	SSE	7.51	362	8.83	530	9.86	687	13%
Piura	2867	0.100	E, ES	15.31	3493	15.95	3526	16.09	3467	15%
Lambayeque	7	0.005	S	5.46	137	7.10	284	7.94	380	16%
Lambayeque	402	0.050	S	7.80	405	9.05	565	9.96	703	14%
La Libertad	301	0.005	SSE	8.49	544	9.57	690	10.51	843	19%
La Libertad	3822	0.100	E	6.81	595	8.40	918	8.70	882	13%
Cajamarca	2187	0.200	NE	11.86	2030	13.10	2450	13.43	2410	9%
Cajamarca	2586	0.050	NNE	9.19	896	10.34	1162	10.92	1261	23%
Ancash	367	0.005	SSE	9.87	896	10.40	919	11.16	1054	29%
Ancash	5127	0.003	NE	11.37	1597	10.38	986	10.40	830	10%

As can be seen in Table 16, coastal areas, at low altitudes, present adequate conditions for using the wind resource. Taking as reference the 3 MW Enercon E-82 E3 wind turbine and considering a hub height of 100 m, the capacity factors that would be obtained in these locations are significant, which are indicated in Table 17.

Table 17. Capacity factors for an E-82 E3 3 MW turbine.

Region	Altitude (masl)	CF (%)
Ica	550	89%
Ica	411	32%
Piura	130	29%
Piura	2867	10%
Lambayeque	7	12%
Lambayeque	402	42%
La Libertad	301	41%
La Libertad	3822	40%
Cajamarca	2187	95%
Cajamarca	2586	61%
Ancash	367	57%
Ancash	5127	74%

According Table 17 in the regions of Ica and Cajamarca, extraordinary capacity factors are obtained. In the case of the Ica region, the main wind energy projects take place in this area. In the case of the Cajamarca region, where the capacity factor is 95%, infrastructure conditions do not allow for the installation of any equipment located at more than 5000 masl.

Concerning technological development, the Peruvian industry is adapting to the needs of the energy sector, which is why the training of human talent who can meet the challenges implicated in energy diversification.

The leap that has been made in using instruments for measurement, collection, and simulation is a task that energy-generating companies and research centers are carrying out; this sum of efforts with the government will allow the creation of digital tools for the quantification and characterization of wind resources.

The implementation of 5 MW wind turbines represents an important milestone for Peruvian engineering that guarantees the stability of the wind farm infrastructure in the country and reduces the risk of failure.

4.3. Futures Perspectives

Although an important and promising industrial development in renewable energy has been achieved in Peru through the on-shore wind farms in operation, the development and promotion of the implementation of renewable wind energy on a smaller scale still needs to be implemented, especially in rural areas, where it could generating energy supply for remote communities. This would benefit many communities that still do not have electricity, promoting rural electrification and access to energy by all citizens in a renewable, equitable, and non-polluting manner [25,26,28].

The link between mining companies and energy companies that generate electricity from renewable energy sources will be a trend in the future, in which the search to achieve low-carbon economies will encourage these alliances. This also improves the reputation of mining activities, which translates into concrete actions of socio-environmental responsibility and giving back to the planet with cleaner and more sustainable extractive activities.

There are high expectations that the government of Peru will promote public policies that seek the implementation of wind farms in different places in the territory, which will allow the generation of renewable energy and provide access to clean energy to more inhabitants and productive activities. This can also be aligned to policies for the implementation of green hydrogen in the country.

It is necessary for Peru to consider as a reference the successful models of wind energy development implemented in neighboring Latin American countries, with the cases of Mexico, Brazil, Uruguay, Argentina, and Chile being references in this matter, countries in which there are an important number of wind farms in operation [46–50].

In Peru, there is an interesting off-shore wind potential that has not yet been exploited. Although the off-shore potential is promising, there are some barriers, such as the bathymetric characteristics of the seabed off the coast of Peru and the associated costs [51]. With respect to the conditions of the seabed, the complexity and depth of the Chile–Peru sea trench make the foundations of wind turbines at sea a challenge for engineering, testing the designs and construction processes for their implementation. Furthermore, tsunami events that occur every 100 years are a threat to off-shore wind farm facilities, where structural measures must be implemented to increase the resilience of these renewable energy systems. In general terms, it is possible to mention that off-shore wind technology is going from being a luxury version of renewable energies to a profitable and attractive option in some countries where the energy prices have not managed to decrease even due to the use of traditional renewable energy (wind, solar, hydraulic, geothermal, biomass, tidal, etc.) [52]. In particular, for Peru, the prices of off-shore wind energy shown are above the current energy costs, so, surely, its appearance in these latitudes of the southern hemisphere will have to wait some more time.

The wind power plants in Peru corresponding to on-shore wind turbines are in sites that, until now, have presented adequate wind potential; however, given the complex site-specific conditions of Peru, considering the diverse characteristics of the topography, geography, and climate in the Andes region, the construction of these power plants demands high capital costs for developing electrical transmission networks and access to roads and bridges. For these reasons, the wind farm power plants currently in use are located mainly along the coast, where the Duna and Huambos wind farm is located at the highest altitude, with 2276 masl, but its annual energy production (per capita) does not exceed that of the wind farms found along the coast. Considering these issues, both the central zone and the northern zone of Peru are those that represent the greatest potential for a wind energy boom; hence, the growth scenarios in the coming years will be concentrated in these regions.

The current development of wind energy in Peru is in its initial stage. The analysis of the wind farms that are currently in operation has been presented in this article: their improvement has been the increase in the power of the wind turbines utilized, since it has gone from 2 MW 3 MW and 5 MW installed capacity.

Finally, it is possible to mention that the future of the generation of electrical energy from wind sources, considering the portfolio of investment projects in Peru, is promising, where an on-shore installed capacity of more than 7429 MW has been projected to be implemented in the next decades and, thus, meet the committed carbon neutrality goals by 2050.

5. Conclusions

Although greenhouse gas (GHG) emissions due to energy generation are not high in Peru, wind energy is presented as one of the alternatives with the greatest projection for decarbonization. Its technological maturity and the reduction in CAPEX and OPEX position it as the most attractive. Likewise, the hourly variability of wind resources means that production is mostly more noticeable during peak hours, which, in economic terms, allows for the recognition of firm power, making this type of project achieve a profitability in the order of 7%. The availability of resources on the Peruvian coast and mountain range is highly adequate; however, the restrictions on the accessibility to mountainous areas force the development of this technology to be on-shore, linked to coastal areas, which is why six of the seven wind power plants currently in operation are located in these types of areas. A different case occurs with the Duna and Huambos power plant of 36 MW, a wind farm plant located in the Andes, whose per capita production does not reach values similar to the rest of the wind farm plants.

In the Peruvian case, the greatest potential for wind energy according to the information from the 2016 Wind Atlas of Peru is in the coastal area, especially in the regions of Piura, Lambayeque, La Libertad, Ancash, Cajamarca, Ica, and Arequipa, with average wind speeds of 6 and 12 m/s (at an average wind turbine height of 100 m) for the development of both terrestrial and marine wind energy. In the Andes mountain range area, the wind speed is between 6 and 9 m/s, with Cajamarca being the most notable wind power region because it has a similar potential to the coastal regions. The Amazon area has less potential compared to the two regions mentioned above. Considering the wind farms currently in operation in Peru, there is a total installed capacity of 668 MW, which is equivalent to 3% of the usable on-shore wind energy potential of 20.5 GW.

The development of digital tools such as the implementation of artificial intelligence (AI) and the implementation of georeferenced systems is a need that must be addressed in the short term: the platforms available for accessing information are not unified, and the existing ones require a greater computing capacity and constant updates. Free-access climate data lack robustness and historical records, so the purchase of bankable data must be considered for pre-feasibility projects to reduce design uncertainties due to the lack of historical records of meteorological information.

In the case of Peru, the effects on the wind considering the El Niño and La Niña climatic phenomena (ENSO) and the effects of global climate change must be studied in more detail. Indeed, the periodicity of these plays a fundamental role in the design and sizing of wind power plants since the generation of electrical energy is seriously affected by them, which implies, at the national level, an increase in the marginal costs of generating electrical energy.

Therefore, the incorporation of wind power plants into the National Interconnected Electricity System (SEIN) has allowed a slow but sustained technological development, which has motivated the training of human talent, the generation of jobs, and the arrival of private investment.

On-shore wind energy will continue to grow gradually, mainly in the north and center of the country, which is why it is estimated that 7.4 GW of installed capacity will be incorporated in the coming years. Off-shore wind energy will require more in-depth studies to guarantee its implementation on the Peruvian coast, which has a complex bathymetry.

At the environmental level, environmental impact assessment (EIA) studies guarantee the installation of wind farm power plants in sites that meet the appropriate conditions, but it is essential to have information and protocols that guarantee the permanent protection of environmentally protected areas, the right to use soil, and care in the face of social conflicts.

With respect to economic terms, the government of Peru should avoid subsidizing on-shore wind energy, since it has demonstrated improvements in its efficiency and a reduction in its costs, in such a way as to allow for the realization of a route for off-shore wind energy that will require the creation of financing mechanisms.

Finally, Peru is a country in the process of growth and development, which will translate in the coming decades into the modernization of its electricity generation matrix with a solid base of renewable energy sources, with wind energy being a fundamental pillar in delivering their contribution to the mitigation of global climate change.

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Abbreviations

SDGs	Sustainable Development Goals
UN	United Nations
GWEC	Global Wind Energy Council
GHG	Greenhouse Gas
CO_2eq	Carbon Dioxide equivalent
NDCs	Nationally Determined Contributions
SEIN	National Interconnected Electricity System of Peru
GWA	Global Wind Atlas
CF	Capacity Factor
EIA	Environmental Impact Assessment
MINAM	Environmental Ministry of Peru
SENAMHI	Meteorological and Hydrological National Service of Peru
COES	Economic Operation Committee of the National Interconnected System of Peru
OSINERGMIN	Energy Investment Supervisory Agency of Peru
CAPEX	Capital Costs
OPEX	Operational Costs
EPC	Engineering, Procurement, and Construction
RER	Renewable Energy Resources
AI	Artificial Intelligence
ENSO	El Niño Southern Oscillation
MW	Megawatts
GW	Gigawatts
MWh	Megawatts-Hour
GWh	Gigawatts-Hour
Mt	Millions of tons
masl	Meters above sea level

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