

Renewable Wind Energy Implementation in South America: A Comprehensive Review and Sustainable Prospects

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Abstract: South America is a region that stands out worldwide for its biodiversity of ecosystems, cultural heritage, and potential considering natural resources linked to renewable energies. In the global crisis due to climate change, South American countries have implemented actions to carry out a progressive energy transition from fossil energies to renewable energies and contribute to the planet's sustainability. In this context, South American countries are implementing green strategies and investment projects linked to wind farms to move towards achieving the sustainable development goals for the year 2030 of the UN agenda and achieving low-carbon economies for the year 2050. This article studies the advances in wind energy implementation in South America, highlighting progress and experiences in these issues through a review of the scientific literature considering the year 2023. The methodology applied in this article was carried out through the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and the generation of scientific maps. As a result, this article presents the main developments, lessons learned/gaps, and future sustainable prospects on the road to 2050. According to the results, renewable wind energy infrastructure was applied in South America during the global climate change crisis era. Different levels of development in on-shore wind farms have been reached in each country. Also, a promising future exists for off-shore wind energy considering the highest potential. Finally, this article concludes that implementing emerging technologies like the production of green hydrogen and synthetic e-fuels looks like a synergetic clean energy solution combined with wind energy, which may transform the region into a world-class sustainable territory.

Keywords: renewable energy; wind energy; wind farm; on-shore; off-shore; South America; green hydrogen; synthetic e-fuels; carbon neutrality; sustainability



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1. Introduction

1.1. Negative Effects of Climate Change in the Generation of Electricity Considering the Use of Conventional Renewable Energies in South America

The global warming that the planet is experiencing, caused by the excessive accumulation of greenhouse gasses in the atmosphere, such as, for example, CO, CO₂, NO, NO₂, CH₄, and N₂O, among others, is generating evident modifications in the patterns of climatic conditions in different places in the world, one of the affected zones being the South American region [1,2]. One of the main causes of the generation of greenhouse gasses is the contemporary model of life of human beings in cities or large cities, where some of the ways of life of people mainly demand (i) the use of mass transport vehicles with internal combustion engines, (ii) the burning of fossil fuels in industrial/commercial processes for the manufacturing/generation of goods and services, and (iii) the generation of electrical energy using coal, oil, and natural gas, among others [3–5].

Considering this contemporary societal development model and population growth, the countries of South America have based their economy on activities linked to the extraction of natural resources, the generation of goods and services, and tourism [6]. These activities demand large amounts of electrical energy in the different cities where people require housing, heating/ventilation, education, health, transportation, entertainment, and food, among others. Also, the territories of each of the countries in the South American region demand energy, where activities related to mining, fishing, agriculture, livestock, the manufacturing industry, the forestry industry, and tourism, among others, are carried out [7]. The demands for electrical energy in the region have historically been satisfied mainly by fossil energy sources based on coal, oil, and natural gas, as well as by conventional renewable energy sources linked to the natural energy of the movement of water produced from river beds and waterfalls in different basins [8].

The South American region has taken advantage of its natural attributes and the potential of the presence of large quantities of fossil as well as renewable resources linked to hydropower, which, due to the low investment and operation cost, has allowed the design, construction, and implementation of different electric power generation plants [9–11]. In this context, we consider the extraordinary and unique geographical, meteorological, hydrological, and hydraulic characteristics of some rivers in South America, where the majority of the basins are located east of the Andes and flow towards the Atlantic Ocean. These characteristics have allowed enormous hydroelectric projects to materialize, highlighting the following among some of them: (i) the Itaipú hydroelectric plant on the Paraná River with an installed capacity of 14,000 MW (Brazil/Paraguay), (ii) the Belo Monte hydroelectric plant on the Xingu River with an installed capacity of 11,200 MW (Brazil), (iii) the Guri hydroelectric plant on the Caroni River with an installed capacity of 10,200 MW (Venezuela), (iv) the Tucuruí hydroelectric plant on the Tocantins River with an installed capacity of 8370 MW (Brazil), (v) the Paulo Afonso hydroelectric plant on the São Francisco River with an installed capacity of 4279 MW (Brazil), and (vi) the Yacyretá hydroelectric plant on the Paraná River with an installed capacity of 4050 MW (Paraguay/Argentina), among others [7]. With this, Brazil has become the country with the second largest installed capacity in the world, with 104 GW, behind China, which has 352 GW, as China currently has the largest hydroelectric plant in the world, called 3 Gorges, on the Yangtze River, with an installed capacity of 22,500 MW. On the other hand, in addition to providing energy and energy storage, hydroelectric plants can provide water for irrigation, drinking water, and flood control [6].

Hydroelectric energy is the main source of electricity generation in most South American countries [7]. It accounts for 45% of the region's total electricity needs, significantly higher than the global average of 16%, and numerous new projects are being developed.

According to the International Renewable Energy Agency (IRENA), in 2018, hydroelectric plants continued to be a cost-effective source of electricity supply, cheaper than fossil energy and wind/solar energy (as of 2018) [7]. This is of particular relevance in South America, where less than 50% of the hydroelectric potential has been exploited, and where there is a growing demand for energy from emerging countries in full development [8]. Although hydroelectricity is indeed a cost-efficient technology, the construction of new hydroelectric plants generates controversies due to both their investments and their environmental and social impacts on the territory of the basins [12,13]. Hydro energy projects have many negative impacts that are a detriment to its sustainability, including the destruction of river ecosystems and deforestation. Therefore, the need for new reservoirs, dams, and electric turbine installations must be carefully evaluated, case by case, strategically evaluating their benefits and impacts [14–16].

But hydropower is not a foolproof source: climate change hazards could have important adverse impacts. For example, extreme weather effects such as (i) rising temperatures, (ii) melting glaciers, and (iii) fluctuating rainfall, among other consequences of the climate crisis, can negatively impact hydroelectric energy production [10,17,18]. South American countries such as Chile, Argentina, Colombia, Ecuador, Uruguay, and part of Brazil

have registered extreme drought phenomena in recent years (Figure 1), thus reducing the generation of electrical energy and leading to energy rationing in the population that lives in its main cities [10–12,16,18]. This should change the position of governments and investors in coping with some of the already noticeable effects to consider the best case and worst case climate scenarios when assessing the reliability and profitability of new hydropower projects.



Figure 1. Negative impacts of climate change considering the droughts that condition the water storage volume in the reservoirs available to generate energy in the South American hydroelectrical facilities. (a) Normal situation without drought, (b) start of drought season, (c) drought season record, and (d) noticeable decrease in the volume of water in the reservoir.

Figure 1 shows the state of the reservoir of the Mazar hydroelectric plant in Ecuador, where in 2022, 2023, and 2024, low levels of water storage have been recorded due to the lack of precipitation in the basin to which it belongs. This has resulted in a low level of electric energy generation in said country, even leading to rationing of the use of electric energy in the population for different cities [19,20]. This situation has been recorded in several countries in the South American region in recent years such as Chile, Colombia, and Argentina, among others.

The higher concentration of greenhouse gas (GHG) emissions produces a greater negative impact on global hydropower generation. However, these changes depending on the particular territory within South America. The Andean region is expected to see a slight increase in hydro power production, while the rest of South America is expected to see a decrease [6]. Like other types of infrastructure, the hydroelectric industry is expected to experience the negative effects of climate change. Water availability and hydropower production can be affected by alterations in hydrological patterns and extreme drought events [7].

1.2. The Implementation of Alternative Renewables Energies as a Solution to Cope with Climate Change Impacts in South America

Although hydroelectric energy is by far the number one renewable source around the world and in the countries of South America, according to the latest report from the International Hydroelectric Energy Association (IHA), installed hydroelectric capacity increased by 1.6 percent to 1330 GW in 2020, a year in which the sector generated a record 4370 TWh of clean electricity, compared to the previous record of 4306 TWh reached in 2019 [7]. This is, for example, approximately equivalent to the entire annual electricity consumption of the United States. However, unfortunately, this source of renewable energy is threatened; it is susceptible and vulnerable to the effects of climate change, which does not guarantee a safe and permanent offer or supply to satisfy the growing demands of modern society [8].

Looking to the future, and in terms of planning the supply systems and energy matrix of the South American countries, it is necessary to think about and visualize the sustainable development of the territory in a comprehensive and strategic way [21]. In this sense, the countries of the region are committed to complying with the sustainable development goals (SDGs) of the UN agenda for the year 2030 [22]. Likewise, South American countries have also committed to comply with the global agreements reached at COP 25 to reduce the generation of greenhouse gasses (GHGs) as much as possible, eliminate energy sources that use fossil fuels, and promote the implementation of renewable energies to achieve carbon-neutral economies by the year 2050 [6].

In this way, it is possible to focus on finding an optimal combination of technologies that have reduced greenhouse gas (GHG) emissions, low cost, and minimal negative socio-environmental impact, to maximize the benefits for society. In this current context, under the threat of global climate change, it is evident that the role of hydroelectricity is changing. In this sense, energy production is evolving from a firm base of generation of electrical energy to flexible and complementary generation. Considering the implementation of renewable energy in the countries of South America, the most promising clean energies are wind energy, solar energy, and geothermal energy [8,23].

Considering the vulnerability of basin territories to the impacts of climate change in many South American countries, hydroelectricity will cease to be the main source of energy supply in the coming decades and will become a facilitator of other renewable energies. The storage capacity of hydroelectric plants, added to their operational flexibility, makes them an ideal technological complement for variable electricity generation [24,25].

In this scenario, wind energy is one of the sources of renewable energy (RER) generation that has had a growing and constant implementation in South American countries [26–28]. The different governments of the countries in the region have decided to commit to its implementation and thus face the vulnerability and uncertainty of hydroelectric energy generation. In this sense, it is important to consider the following comparative advantages of wind energy: (i) more than 20 years of development, innovation, and implementation in countries in Europe, the United States, and China, (ii) a progressive reduction in the initial investment costs and operating costs of infrastructure projects associated with wind farms, and (iii) a considerable reduction in negative impacts on the environment [29–31].

In addition to the above, the enormous and extraordinary wind potential throughout the year in different territories of the countries of the region has allowed the development of engineering studies, the construction of infrastructure, and the operation of various wind farms, supplying electrical energy to cities and industrial and commercial production centers [6,7].

Considering the particular and diverse site-specific conditions of the South American region has meant testing engineering design companies, construction enterprises, contractors, electro-mechanical equipment manufacturers/vendors, government authorities, and communities, among others, to overcome different challenges and complexities, which

makes the experience acquired in recent years in the implementation of wind energy unique and one of the fastest growing worldwide (Figure 2).



Figure 2. Implementation of renewable wind energy in the Andean region of South America. DALL-E-2 image, May 2024, created from [32].

1.3. Aim of the Systematic Review

This systematic review studies the advances in wind energy implementation in South America, considering different territories such as coastal lands, agricultural plains, mountainous areas, and even desert areas, highlighting the state of the practice of these experiences through a review of the scientific publications available on Scopus.

In this sense, a four-phase methodological procedure was implemented: (i) Phase 1: quantitative method considering a bibliometric analysis; (ii) Phase 2: qualitative method considering a systematic review of the literature; (iii) Phase 3: integration method considering a mixed review; and (iv) Phase 4: generation of scientific maps using the VOSviewer software. The name of this method is the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. In this systematic review of scientific publications, the following research questions (RQs) are defined:

- RQ1: What are the main clusters of wind energy concepts applied to insert this technology in South America and how do they evolve over time?
- RQ2: What is the on-shore wind energy installed capacity (MW) and usable potential (MW) in each country of South America?
- RQ3: What is the annual energy production (GWh) of on-shore wind farms and what is the related reduction rate for greenhouse gasses (GHGs) in each country of South America?
- RQ4: Which South American countries have more development of on-shore wind energy considering the quantity of wind farm facilities under operation?
- RQ5: What are the main advances related to climate change mitigation considering the implementation of wind energy in South America?
- RQ6: What main facilities and emerging technologies/initiatives are linked with wind energy considering private investment projects in South America?
- RQ7: What are the universities' main research and development (R&D) studies/projects to insert wind energy in South America?
- RQ8: What are the main sustainability challenges for the future linked with the implementation of wind energy in South America?

Finally, for the adequate development of this systematic review, the following content structure was defined: Section 1: Introduction, Section 2: Resources and Methodology, Section 3: Results and Findings, Section 4: Discussion, and Section 5: Conclusions.

2. Resources and Methodology of Literature Review

2.1. Resources

2.1.1. Scopus Scientific Databases

To implement this study, the Scopus database was considered a source of information as it contains some of the most important scientific information in the world, with scientific journals related to renewable energy from wind resources. For the interpretation of this research, different scientific publications, mainly considering articles and review-type documents, were studied, all of which were published in English from 1987 to 2024.

2.1.2. Use of Software

To carry out the systematization, processing, and interpretation of data, the software MS Excel version 21 and VOSviewer version 1.6.20 were used. The first is to systematize and process the data through tables and graphs, while the second is to interpretate the information through scientific maps.

2.2. Methodology

2.2.1. Bibliometric Analysis and Systematic Content Review

The method applied in this systematic review considered the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [33] and the production of scientific maps using the VOSviewer software [34].

Considering the PRISMA method, a flowchart must be developed to show the elimination steps: “identification, screening, eligibility, and final inclusion”. The study removal process is shown in Figure 3.

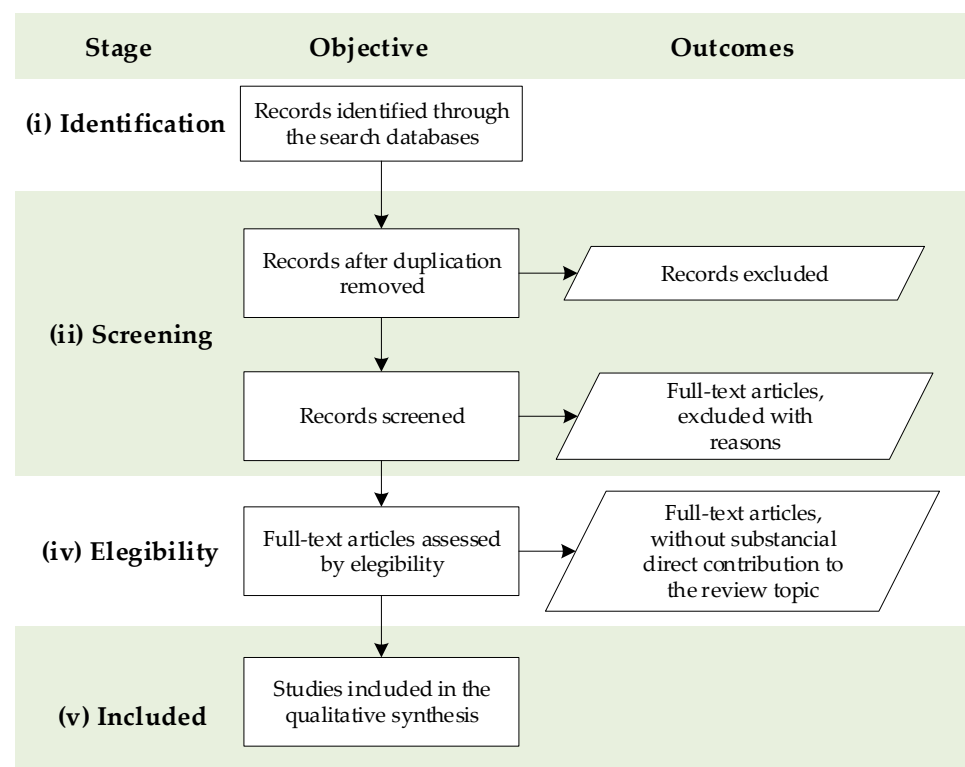


Figure 3. The PRISMA flow diagram of the search process for the highlighted and reviewed articles from the Scopus database. Adapted from [35].

The PRISMA statement is a methodological procedure that researchers can consider to report systematic reviews and meta-analyses [36]. The PRISMA guidelines provide recommendations that help address the interpretation of research by helping systematic reviewers to inform the review in a precise, accurate, and direct form [36,37].

In this sense, a 4-phase methodological procedure was implemented: (i) Phase 1: quantitative method considering a bibliometric analysis, (ii) Phase 2: qualitative method considering a systematic review of literature, (iii) Phase 3: integration method considering a mixed review, and (iv) Phase 4: generation of scientific maps using the VOSviewer soft-ware. Figure 4 shows a summary of the methodology implemented in this systematic review. In this study, the 8 research questions mentioned above are considered.

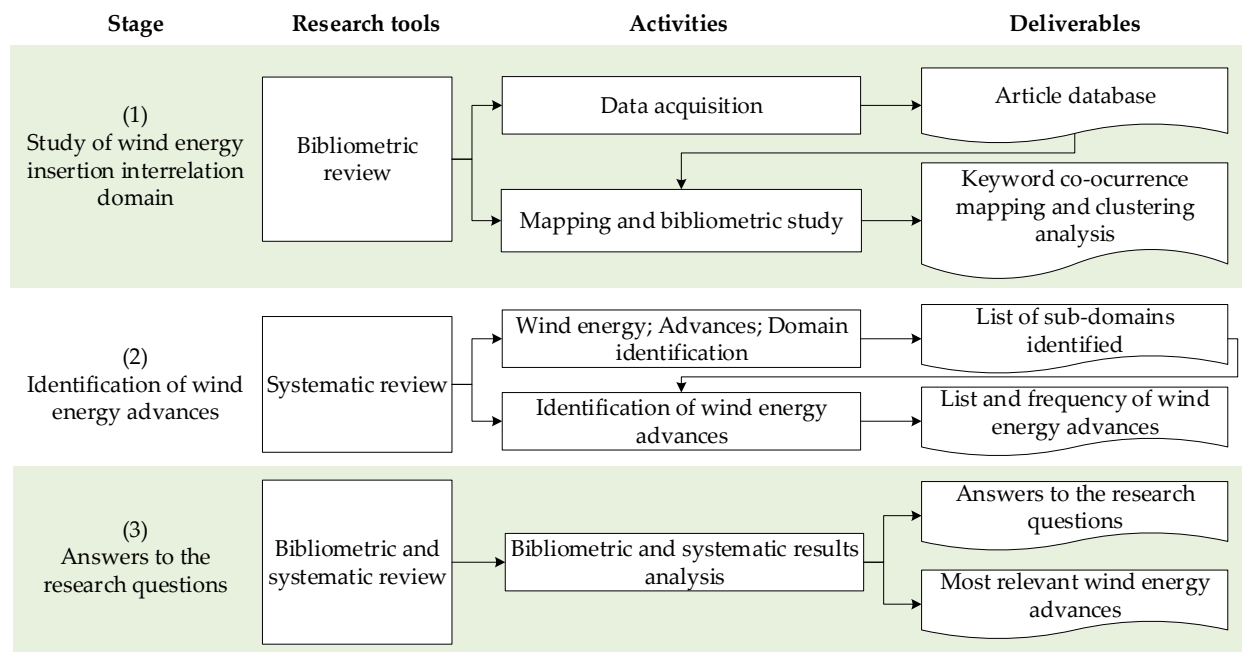


Figure 4. Summary of the methodology implemented in this systematic review. Adapted from [38].

Figure 4 shows the phases, research tools, actions, and deliverables utilized in the method used in this research. Three major stages of the method applied in this systematic review are (i) interrelated renewable energy from wind resources in the South America domain, through data acquisition and bibliometric analysis, to later obtain the maps of co-occurrence of keywords and cluster analysis; (ii) the identification of wind energy implementation in South America, a systematic review, the identification of advanced domains of wind energy, and obtaining a list of identified subdomains; and (iii) answers to the research questions, through an analysis of the integrated systematic review of bibliometrics, to finally find the most relevant scopes of wind energy implementation in South America.

2.2.2. Processing of Articles Selected

To implement the selection process of scientific publications to be studied in this systematic review, a search was developed considering a set of keywords using Boolean operators. Therefore, a definition of a series of keywords was carried out within the topic to be analyzed. The relevant words selected for this research were (i) wind, (ii) energy, (iii) Argentina, (iv) Bolivia, (v) Brazil, (vi) Chile, (vii) Colombia, (viii) Ecuador, (ix) Paraguay, (x) Peru, (xi) Venezuela, (xii) Uruguay, and (xiii) South America. The countries of Suriname, Guyana, and French Guyana were not considered due to a lack of available publications. Once the keywords were chosen, it was possible to create eleven combinations of keywords using the Boolean AND operator, as shown below in Table 1:

Table 1. Keywords and Boolean operators are used to search scientific publications.

Keywords	Boolean Operator	Keywords	Boolean Operator	Keywords
Wind	AND	Energy	AND	Argentina
				Bolivia
				Brazil
				Chile
				Colombia
				Ecuador
				Paraguay
				Peru
				Venezuela
				Uruguay
				South America

The results were obtained by selecting and classifying the scientific publications by carrying out the search strategies considering the study criteria. Finally, the data extraction form was evaluated considering the documents selected, obtaining information from the metadata analysis perspective DEM (data extracted from metadata) and from the content analysis perspective DEC (data extracted from content), as shown in Table 2.

Table 2. Data extraction form implemented in this research. Adapted from [38].

Id.	Criteria	Field	Question	Data
DEM 1	Metadata perspective	Keywords	What are the keywords?	Keywords
DEM 2	Metadata perspective	Title	What is the name?	Name
DEM 3	Metadata perspective	Authors	Who are the authors?	Authors List
DEM 4	Metadata perspective	Year	What is the publication year?	Year
DEM 5	Metadata perspective	Country	What is the country of the first author?	Country
DEM 6	Metadata perspective	Citation count	How many citations does the document have?	Number
DEM 7	Metadata perspective	Document Type	What is the name of the type of document?	Conference paper or Article or Review or Other
DEC8	Content-based perspective	Popular Clusters	RQ1: What are the main clusters of wind energy concepts applied for implementation of this technology in South America and how do they evolve over time?	e.g., on-shore wind energy, off-shore wind energy, green hydrogen, among others
DEC9	Content-based perspective	On-shore Wind Energy Potential and Installed Capacity	RQ2: What is the on-shore wind energy installed capacity (MW) and usable potential (MW) in each country of South America?	e.g., 9000 MW installed capacity and 12,000 MW energy potential, among others
DEC10	Content-based perspective	On-shore Wind Annual Energy Production and Reduction Rate of GHGs	RQ3: What is the annual energy production (GWh) from on-shore wind farms and what is the related reduction rate of greenhouse gasses (GHGs) in each country of South America?	e.g., 50,000 MWh, 2.5 Mt eq CO ₂ , among others

Table 2. Cont.

Id.	Criteria	Field	Question	Data
DEC11	Content-based perspective	Quantity of Wind Farm Facilities	RQ4: Which South American countries have more development of on-shore wind energy considering the quantity of wind farm facilities under operation?	e.g., 10, 33, 120, among others
DEC12	Content-based perspective	Climate Change Mitigation Advances	RQ5: What are the main advances related to climate change mitigation considering the implementation of wind energy in South America?	e.g., low-carbon economy incentives and clean energy transition, among others
DEC13	Content-based perspective	Emerging technologies/initiatives	RQ6: What are the main facilities and emerging technologies/initiatives linked with wind energy considering private investment projects in South America?	e.g., green hydrogen produced with wind energy, and hybridization with solar PV, among others
DEC14	Content-based perspective	Research and development (R&D) studies/projects	RQ7: What are the universities' main research and development (R&D) studies/projects to insert wind energy in South America?	e.g., improving wind turbine efficiency, integration of wind energy to smart grids, among others
DEC15	Content-based perspective	Sustainability challenges	RQ8: What are the main sustainability challenges for the future linked with the implementation of wind energy in South America?	e.g., stability of wind energy generation, and decrease in environmental impacts on local fauna and landscape, among others

3. Results

The following paragraphs show the results obtained in this research:

3.1. Process of Article Screening

To carry out the selection process of scientific publications to be studied, an analysis was developed in phases considering exclusion criteria (EC) to select scientific publications. Figure 5 shows the steps applied together with the results.

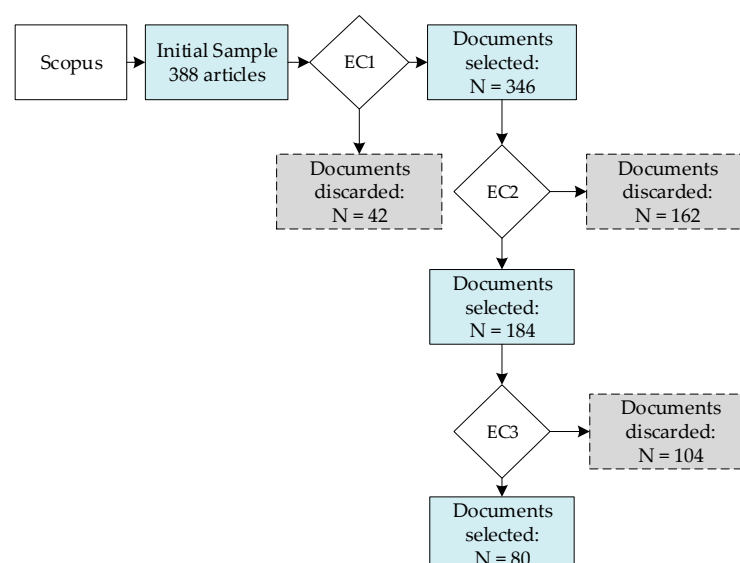


Figure 5. Scientific publication selection flowchart.

Figure 5 presents the extraction of documents from the Scopus database considering the combinations of relevant concepts mentioned above, where 388 publications were obtained. Exclusion criterion 1 (EC1) was used for these documents to eliminate duplicate articles, leaving 346 documents. Then, exclusion criterion 2 (EC2) was used, which analyzed the title of the documents to study which ones are related to wind energy implementation in South America, giving a result of 184 documents. Finally, exclusion criterion 3 (EC3) was considered, reading the abstract, finally leaving 80 documents. These 80 selected publications deal specifically with advances in the implementation of wind energy in South America, which will be subject to a specific study described in the following pages of this research.

3.2. Bibliometric Analysis Results for Wind Energy Implementation in South America

Considering RQ1, ‘What are the main clusters of wind energy concepts applied for implementation of this technology in South America and how do they evolve over time?’, the following answer is presented in the following figures and tables:

3.2.1. Study Distribution Published per Year

Figure 6 shows the results obtained for study distribution published per year of scientific publications according to the 80 articles selected.

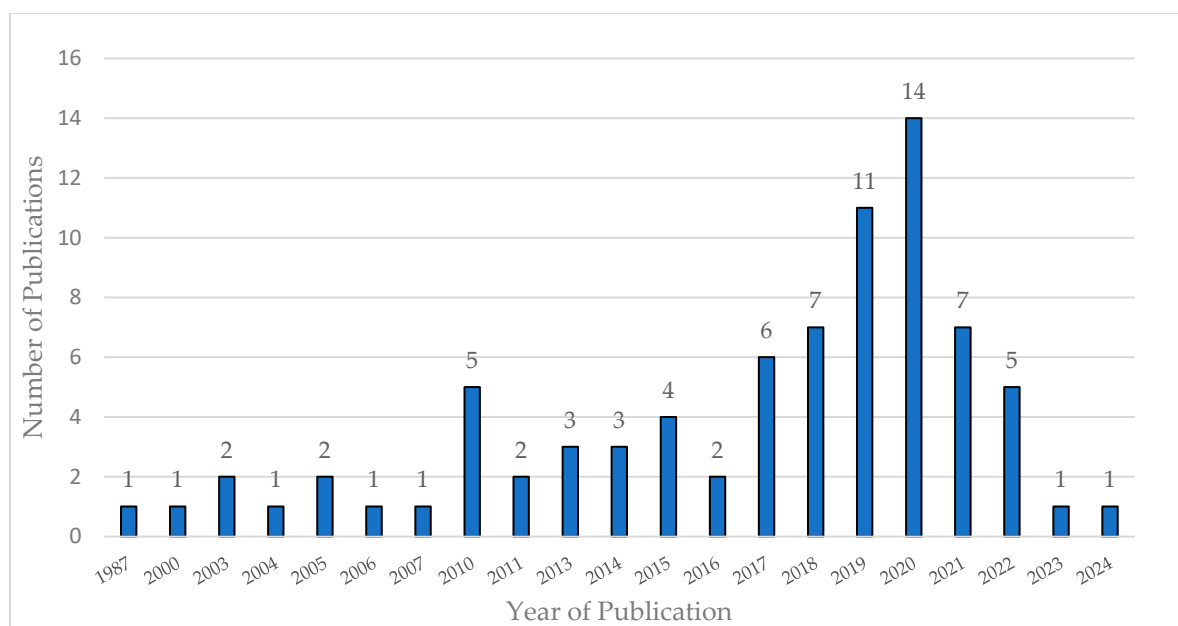


Figure 6. Results considering a number of 80 scientific publications selected from 1987 to 2024.

Figure 6 shows the number of scientific publications related to wind energy implementation in South America published per year, considering a sample of 80; this figure shows that the year with the most articles was 2020, while the least published were several years with zero publications. Despite some variations, it can be observed that over the years, the number of articles and interest in the topic have increased. It should be considered that the sample was taken in January 2024; therefore, said year does not include all the articles generated.

3.2.2. Distribution of Selected Publications Considering Different Countries

Figure 7 shows the distribution of selected publications considering different nations for the 80 scientific publications.

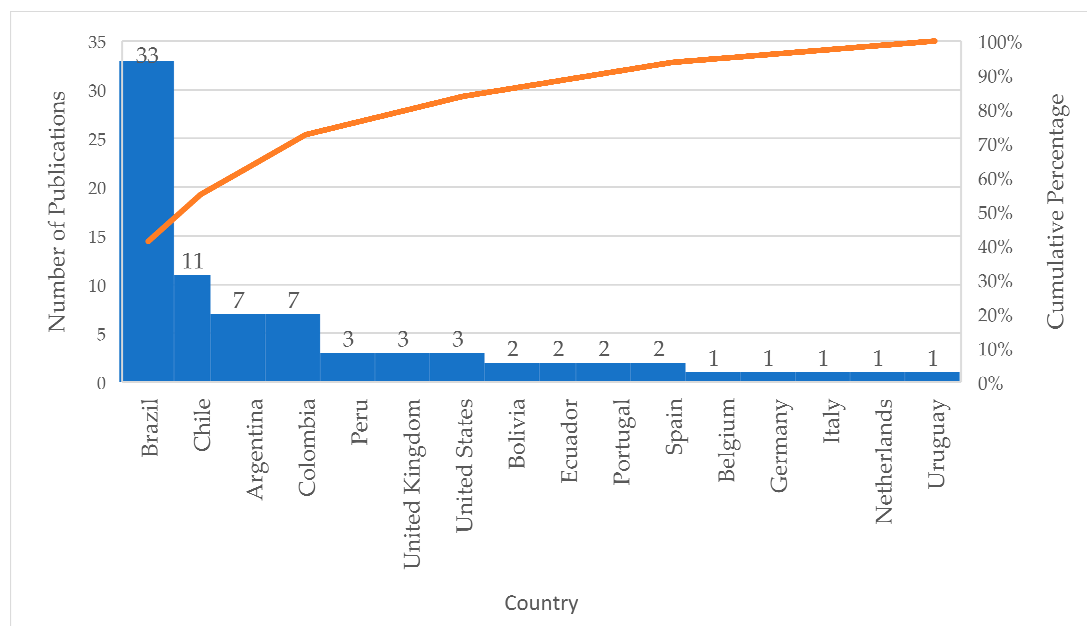


Figure 7. First author distribution by country considering the 80 scientific publications selected.

Figure 7 shows the sample of the 16 nations with the largest number of articles on the topic. The greatest quantity of publications generated by nation is mainly localized in Brazil, Chile, Argentina, and Colombia, which represent approximately 70% of the 80 scientific publications, while Peru, the United Kingdom, the United States, Bolivia, Ecuador, Portugal, and Spain also stand out in percentage of publications. Finally, Belgium, Germany, Italy, the Netherlands, and Uruguay have a minor percentage of publications.

3.2.3. Distribution of Citations Considering Different Countries

The results considering the quantity of citations about scientific publications by nation in recent years are shown in Figure 8, according to the 80 selected scientific publications.

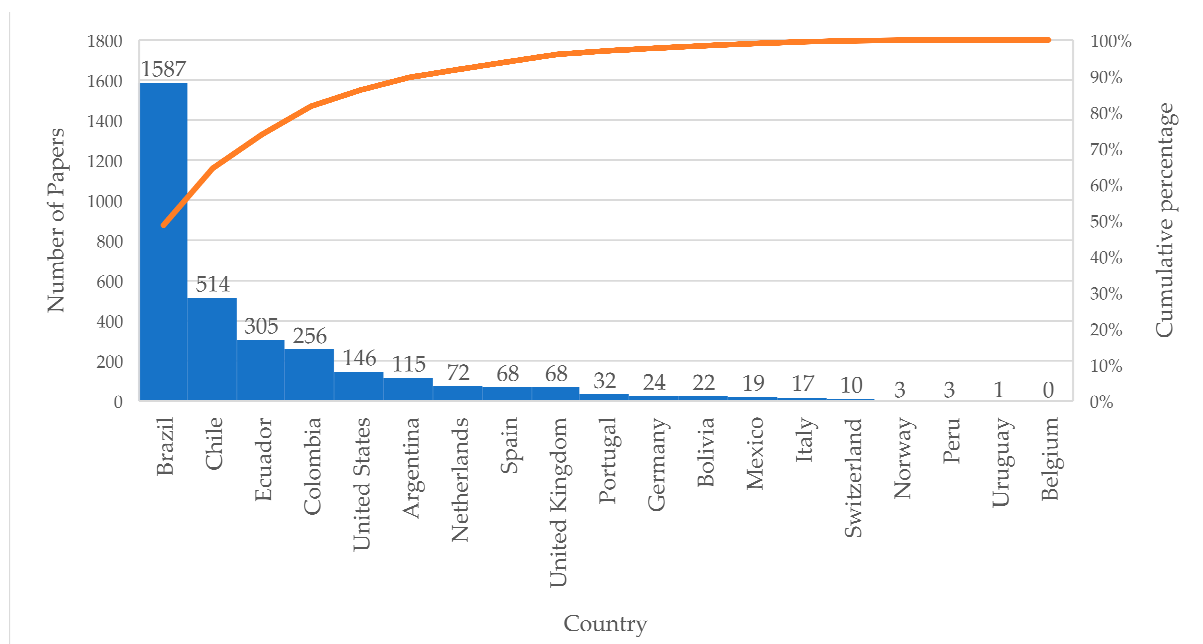


Figure 8. Number of citations and distribution by country considering 80 scientific publications selected.

Figure 8 presents the number of citations by country, where Brazil stands out with approximately 50% of the total citations, followed by Chile with 15% of the citations. The nations with 80% of the accumulated citations are Ecuador and Colombia. The graph in Figure 8 shows that some countries in South America such as Brazil, Chile, Ecuador, Colombia, and Argentina, as well as the United States, are the ones that cite the 80 selected articles the most. There are some European countries with a significant number of citations; they are the Netherlands, Spain, and the UK. Then, to a lesser extent, other South American countries such as Bolivia, Peru, and Uruguay, as well as some European countries such as Portugal, Germany, Italy, Switzerland, and Belgium, also cite the 80 selected articles.

3.2.4. Document Type Distribution Considering Articles Selected

Figure 9 presents the results obtained for document type distribution in recent years, considering the 80 selected scientific publications.

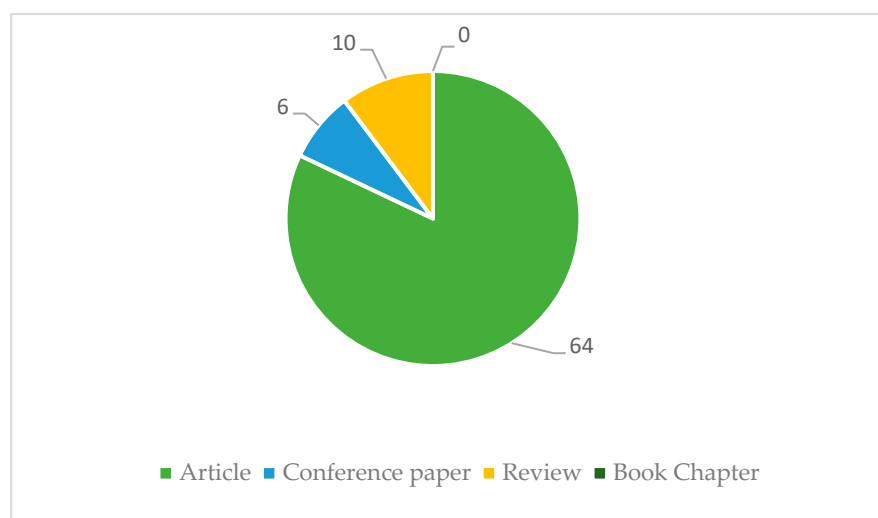


Figure 9. Distribution by type of the 80 scientific publications selected.

The pie chart shown in Figure 9 indicates the types of scientific publications found in the Scopus database, of which articles predominate with 64, followed by reviews with 10, a total of 6 conference papers, and 0 book chapters. This means that the data on progress in the implementation of wind energy in South America are being studied by universities and are less promoted in terms of experience in renewable energy by technical conferences.

3.2.5. Keyword Co-Occurrence Analysis

Considering that the search for the 80 selected scientific publications obtained bibliometric metadata, these data were analyzed in VOSviewer software to generate a co-occurrence map without considering the time dimension [39]. A criterion was defined considering a minimum occurrence value of two keywords, which means that a keyword appears on the map when two scientific publications cite it [34]. A map considering four clusters (represented in blue, yellow, green, and red) is shown in Figure 10.

Considering the co-occurrence map presented in Figure 10, four clusters were produced, which are shown by different colors. Within the keywords, the ones that stand out the most are renewable energy, wind power, and wind energy. Table 3 shows an interpretative summary of Figure 10, one can observe the topics applied by cluster and prominent keywords of the co-occurrence analysis.

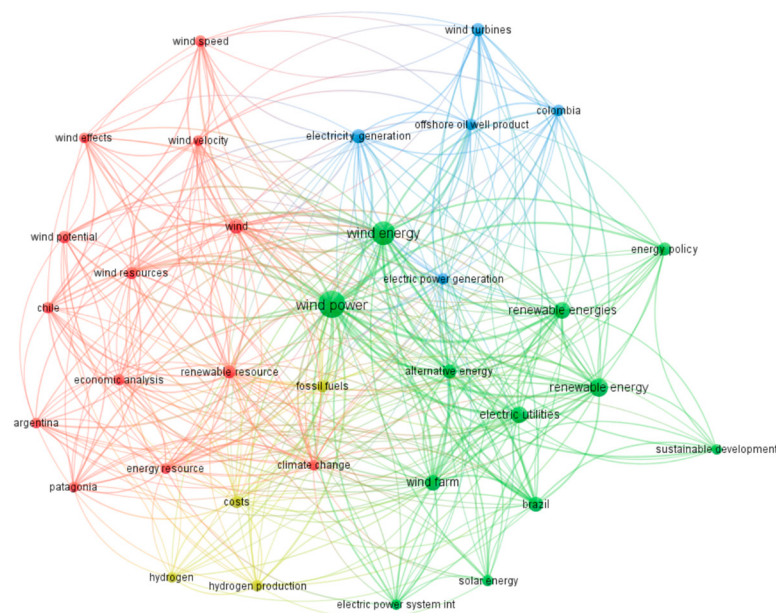


Figure 10. Results of keyword co-occurrence map considering 80 scientific publications selected using VOSviewer without time dimension.

Table 3. VOSviewer clusters without time dimension considering 80 scientific publications selected.

Cluster Name	Keywords	Cluster Definition
Cluster “Yellow”	Hydrogen, costs, fossil fuels, climate change	Hydrogen production
Cluster “Blue”	Wind turbines, off-shore oil well production, electricity generation	Off-shore wind energy
Cluster “Red”	Renewable resources, wind speed, energy resource	Wind potential
Cluster “Green”	Wind energy, wind farm, energy policy, sustainable development	Renewable energy

According to the cluster interpretation of Table 3, it is possible to find that the implementation of wind energy has a strong application trend in clean energy, focused on sustainable development.

Additionally, the resulting map using VOSviewer with the time dimension shows three clusters (represented in yellow, blue, and green) in terms of the year in which the selected scientific publications were published, as shown in Figure 11.

According to the co-occurrence map presented in Figure 11, it is possible to observe the time dimension in which these concepts were generated, the most recent being renewable energy, wind farms, and sustainable development, while the oldest are wind potential, wind resources, and wind turbines, among others. Finally, Table 4 shows an interpretative summary of Figure 11, where one can observe the topics applied by cluster and prominent keywords of the co-occurrence analysis.

Table 4. VOSviewer clusters with time evolution considering 80 scientific publications selected.

Cluster Name	Keywords	Period of Publication	Cluster Definition
Cluster “Blue”	Wind potential, wind resources, wind turbines	2012–2014	Wind energy potential
Cluster “Green”	Wind energy, wind power, renewable resources	2014–2016	Renewable energy technology
Cluster “Yellow”	Renewable energy, energy policy, sustainable development	2016–2018	Sustainability

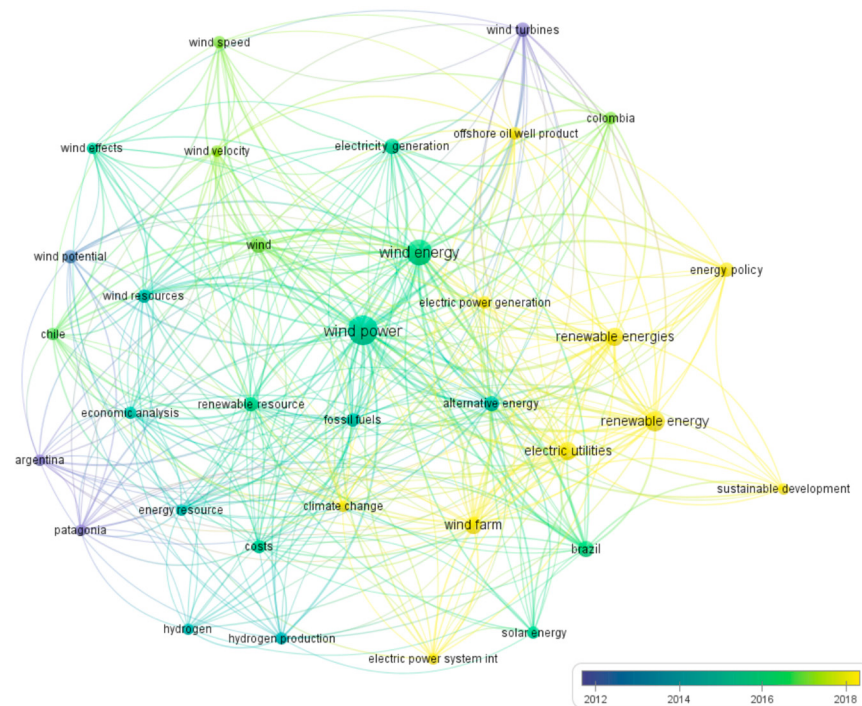


Figure 11. Results of keyword co-occurrence map considering 80 scientific publications selected using VOSviewer with time dimension.

According to the cluster analysis of Table 4, it is observed that the evolution over time of the implementation of wind energy in South America tends to start with aspects of the study of wind energy potential, then evolves and implements renewable energy technology, and finally develops the concept of sustainability considering the planning tools of renewable energy.

3.3. Systematic Content Review Results for Advances in the Implementation of Wind Energy in South America

3.3.1. Content-Based Data Perspective Analysis

Content-based data perspective analysis is presented in this chapter of the article, showing the answers to the research questions considering the 80 selected articles.

Considering RQ2, ‘What is the on-shore wind energy installed capacity (MW) and usable potential (MW) in each country of South America?’, the following answer is presented in Table 5, compilation based on the following sources of information: [6,40,41].

According to the results shown in Table 5 concerning the year 2023, for the South American region, the percentage of use of the usable wind potential goes from 0 in the case of Paraguay to 15% in the case of Chile. The countries with the greatest installed capacity of on-shore wind energy are (i) Brazil, (ii) Chile, (iii) Argentina, and (iv) Uruguay. On the contrary, the countries with the lowest installed on-shore wind capacity are (i) Paraguay, (ii) Ecuador, and (iii) Bolivia. In addition, Table 5 shows the installed capacity and potential of the on-shore wind resources of Mexico, the United States, and China. This way, it is possible to compare the different economies and implementation of this form of clean energy in each country. Although compared to Mexico, the United States and China, the development and implementation of wind energy has not been as rapid in the South American region, each country therein has been contributing in its fair measure to the mitigation of climate change. Finally, considering the South American region in 2023, it had an installed capacity of terrestrial wind energy equivalent to 39,298 MW and a used percentage of its potential equivalent to 3.1%.

Figure 12 is shown below, which illustrates a map of operating utility-scale wind capacity in Latin America, specifying the installed capacity for each country.

Table 5. Summary of on-shore wind energy installed capacity (MW) and usable potential (MW) in countries of South America considering the data from the year 2023.

Country	Installed Capacity (MW)	Usable Potential (MW)	Percentage Used of Potential (%)
Argentina	4363	300,000	1.5
Bolivia	135	100,000	0.1
Brazil	25,055	700,000	3.6
Chile	5993	40,000	15.0
Colombia	913	30,000	3.0
Ecuador	78	4000	2.0
Paraguay	0	2000	0.0
Peru	978	20,500	4.8
Uruguay	1645	40,000	4.1
Venezuela	138	45,000	0.3
South America	39,298	1,281,500	3.1
Mexico	7318	50,000	14.6
USA	144,429	10,640,080	1.4
China	335,504	2,968,000	11.0



Figure 12. Mapping of operating utility-scale wind capacity in Latin America. Adapted from [6].

According to Figure 12, it is possible to see that Brazil stands out in the region with an installed capacity of over 18 GW, followed by Chile and Argentina with an installed capacity in the range of 6–9 GW, and then the rest of the countries with installed capacities of less than 3 GW.

Considering RQ3, ‘What is the annual energy production (GWh) from on-shore wind farms and what is the related reduction rate of greenhouse gasses (GHGs) in each country of South America?’, the following answer considering the data from the year 2020 are presented in Table 6, compilation based on the following source of information: [7].

Data from the countries of Mexico, the USA, and China are considered to compare the orders of magnitude of the South American countries with those other countries, and thus interpret the relationship between the implementation of wind energy and the size of each economy and level of development. In this sense, considering the results of Table 6, it appears that Brazil is the country that generates the most electrical energy based on wind energy with 57,050 GWh. Then, there is Argentina with 9412 GWh and Chile and Uruguay with 5602 GWh and 5476 GWh, respectively. For comparison, the values of annual electrical energy production for Mexico, the USA, and China are shown, revealing the degree of implementation of wind energy in those parts of the world concerning the South American region. South America as a whole generates annual electricity based on land-based wind energy equivalent to 79,593 GWh, which corresponds to 23% of what the USA generates and 17% of what China generates.

For the generation of greenhouse gas emissions from wind farms, as seen in Table 6 and indicated in millions of tons of CO₂ equivalent, these are lower for each of the countries in the South American region, but for the USA and China, due to the large number of wind farms in operation, these values are higher.

Table 6. Summary of annual energy production (GWh) from on-shore wind farms and related reduction rate of greenhouse gasses (GHGs) in each country of South America considering the data from the year 2020.

Parameters (Year 2020)	Units	Argentina	Brazil	Bolivia	Chile	Colombia	Ecuador	Paraguay	Peru	Uruguay	Venezuela	Mexico	USA	China
Electricity generated from on-shore wind energy	GWh	9412	57,050	64.21	5602	10.12	77.1	N/A	1814	5476	88	19,701	341,818	467,037
GHG emissions generated from on-shore wind energy	Mt CO ₂ eq	0.1	0.7	0	0.1	0	0	N/A	0	0.1	0	0.2	4.1	5.6
Avoided GHG emissions from on-shore wind energy	Mt CO ₂ eq	4.10	29.30	0.03	4.5	0.01	0.06	N/A	0.9	4.5	0.04	9.67	164.20	417.40

In addition, Table 6 shows that the greenhouse gas emissions, indicated in millions of tons of CO₂ equivalent (Mt eq CO₂), were avoided by implementing wind energy instead of using fossil energy sources. Considering all the countries in the South American region under study, there is a contribution to the mitigation of climate change considering the annual reduction of 43.5 million tons of CO₂ equivalents.

Finally, in the case of Paraguay, as there are no large-scale on-shore wind energy projects to date, it is not possible to show results.

Considering RQ4, ‘Which South American countries have more development of on-shore wind energy considering the quantity of wind farm facilities under operation?’, the

following answer is presented according to Table 7 and Figure 13, compilation based on the following source of information: [41].

Table 7 shows the result of the registry of the number of on-shore wind farms under operation in each of the countries in the South American region. For this estimation, wind turbines at a height of 90 m and an installed capacity of 2.0 MW were considered. The results highlight Brazil, Argentina, Chile, and Uruguay in first place. In addition, it is possible to mention that an estimate has been made of the number of wind turbines installed in each country; for this, it is assumed that wind turbines are 90 m high and have an installed capacity of 2.0 MW. In that sense, the country that has the most wind turbines in operation is Brazil with 12,528, followed by Chile with 2997, Argentina with 2182, and then Uruguay with 823. Finally, we can mention that the South American region as a whole accumulates 694 on-shore wind farms and 19,649 wind turbines. The distribution of the number of on-shore wind farms in the South American region can be seen in Figure 13:

Figure 13 shows the spatial distribution of the number of on-shore wind farms in operation in each of the countries in the South American region. Brazil (476), Argentina (75), Chile (66), and Uruguay (48) stand out in first place. Although Chile has fewer wind farms than Argentina, it has a greater total installed capacity; this is because larger wind turbines are used in the case of Chile.

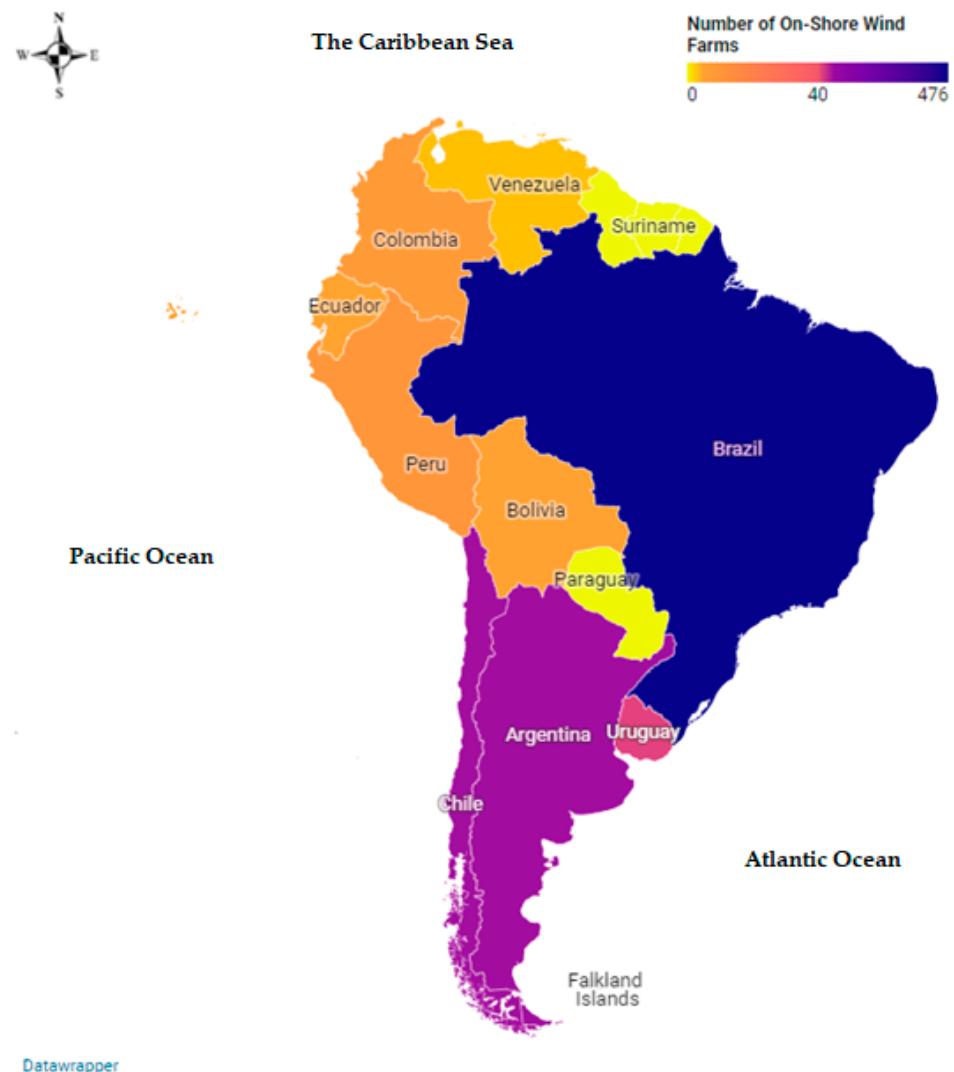
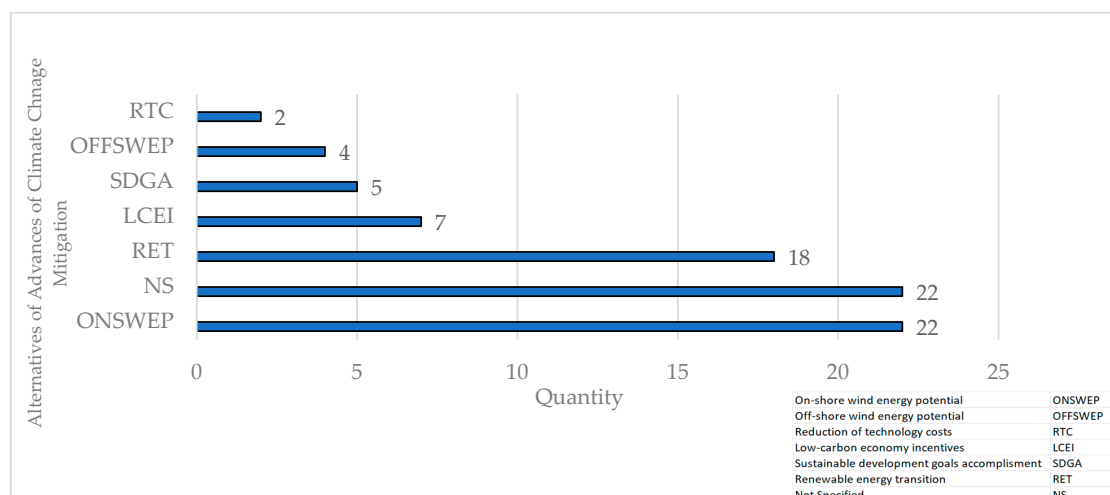


Figure 13. Spatial distribution of on-shore wind farms under operation in the countries of South America—year 2023.

Table 7. Summary of number of on-shore wind farms and the number of wind turbines in each country of South America considering the year 2023.

Country	Number of On-Shore Wind Farms	Number of Wind Turbines
Argentina	75	2182
Bolivia	5	68
Brazil	476	12,528
Chile	66	2997
Colombia	8	457
Ecuador	4	39
Paraguay	0	0
Peru	10	489
Uruguay	48	823
Venezuela	2	69
South America	694	19,649

Considering RQ5, ‘What are the main advances related to climate change mitigation considering the implementation of wind energy in South America?’, the following answer is presented according to Figure 14:

**Figure 14.** Advances related to climate change mitigation considering the implementation of wind energy in South America.

According to Figure 14, it is shown that the main issue linked to the mitigation of climate change is the estimation of the terrestrial wind potential (ONSWEP) through studies of the wind resource in the territory with 22 repetitions. Likewise, when reviewing the scientific literature in 22 cases, thematic issues linked to the mitigation of climate change were not specified (NS); this is due to the development of technical studies linked to wind farms. Then, there are 18 repetitions considering the theme of the transition to renewable energies. Finally, with less than seven repetitions, the following topics are mentioned in the publications: reduction in technological costs (RTC), incentives for low-carbon economies (LCEI), compliance with sustainable development objectives (SDGA), and off-shore wind energy potential (OFFSWEP).

Considering RQ6, ‘What are the main facilities and emerging technologies/initiatives linked with wind energy considering private investment projects in South America?’, the following answer is presented according to Figure 15:

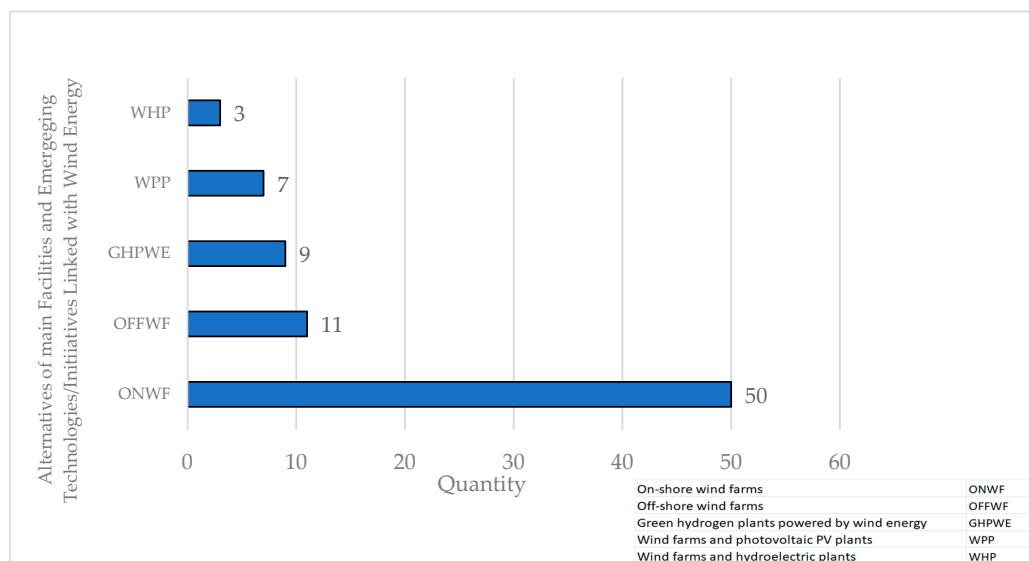


Figure 15. Facilities and Emerging technologies/initiatives linked with wind energy considering private investment projects in South America.

According to Figure 15, it is shown that the main theme of emerging technologies/initiatives linked to wind energy is the construction/operation of on-shore wind farms (ONWFs) with 50 repetitions. Finally, with less than 11 repetitions, the following topics are mentioned in the publications: the construction/operation of off-shore wind farms (OFFWFs), green H₂ plants with the use of wind energy (GHPWE), and hybridization of wind farms with photovoltaic plants (WPP), and hybridization of wind farms with hydroelectric plants (WHP).

Considering RQ7, ‘What are the universities’ main research and development (R&D) studies/projects to insert wind energy in South America?’, the following answer is presented according to Figure 16:

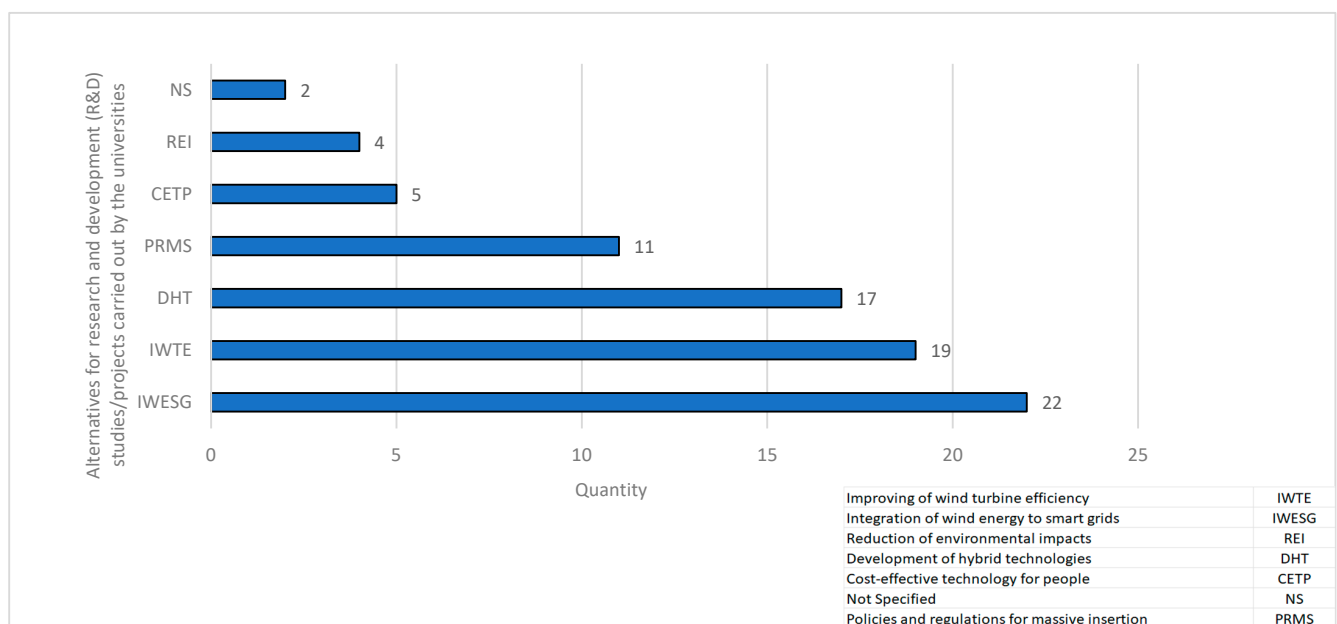


Figure 16. Research and development (R&D) studies/projects carried out by the universities for the implementation of wind energy in South America.

According to Figure 16, it is shown that the main topic linked to the studies/research projects regarding wind energy by universities is the integration of wind energy in smart grids (IWESG) with 22 repetitions. Then, with 19 repetitions, we have the improvement of the efficiency of the wind turbines (IWTE). Furthermore, with 17 repetitions, there is the development of hybrid technologies (DHT). Finally, with less than 11 repetitions, the following topics are mentioned in the publications: massive implementation of policies and regulations (PRMS), cost-effective technologies for people (CETP), reduction in environmental impacts (REI), and not specified (NS).

Considering RQ8, ‘What are the main sustainability challenges for the future linked with the implementation of wind energy in South America?’, the following answer is presented according to Figure 17:

According to Figure 17, it is shown that with 27 repetitions, no sustainability challenges are specified for the future of the implementation of wind energy in South America. Then, with 19 repetitions, we have the diversification of the energy matrix considering renewable energy sources (DMEORES). In addition, with 17 repetitions, there is the theme of political and regulatory aspects that affect the expansion of wind energy (REPWE). Finally, with less than 11 repetitions, the following topics are mentioned in the publications: stability of wind energy generation (SWEG) and reduction in environmental impacts on local fauna and landscapes (DEILFL).

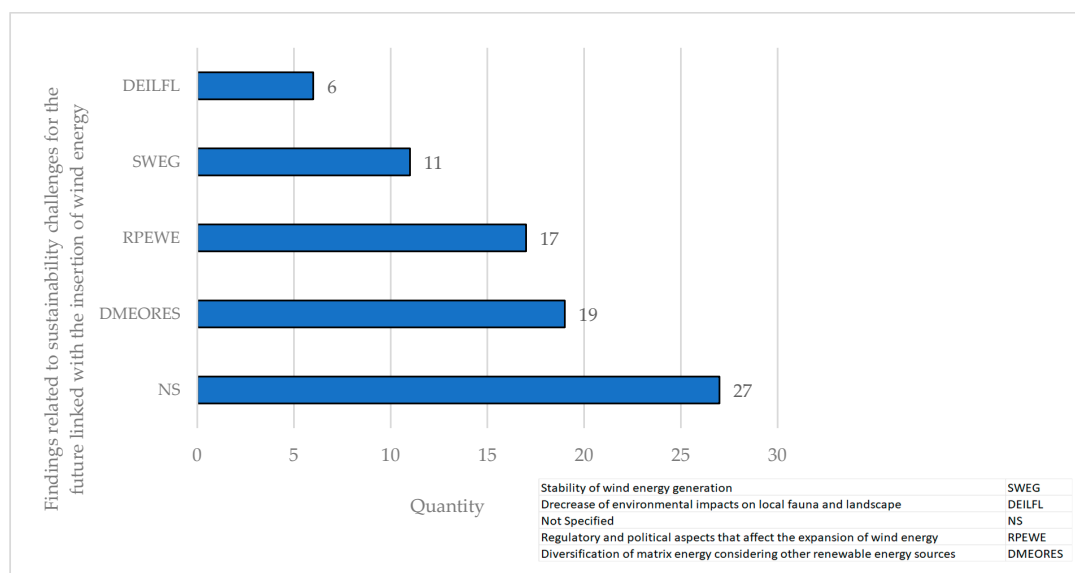


Figure 17. Sustainability challenges for the future linked with the implementation of wind energy in South America.

3.3.2. Comparative Analysis of the Articles Selected Considering Advances in the Implementation of Wind Energy in South America

A comparison of the main characteristics of the selected articles is summarized in Table 8. This table includes (i) advances related to climate change mitigation, (ii) main facilities and emerging technologies/initiatives linked with wind energy, (iii) research and development (R&D) studies/projects carried out by the universities, and (iv) sustainability challenges for the future.

Table 8. Comparative analysis of the articles selected considering advances in the implementation of wind energy in South America. The following abbreviations are considered for (i) advances related to climate change mitigation considering the implementation of wind energy in South America (on-shore wind energy potential, ONSWEP; off-shore wind energy potential, OFFSWEP; reduction in technology costs, RTC; low-carbon economy incentives, LCEI; sustainable development goal accomplishment, SDGA; renewable energy transition, RET; or not specified, NS), (ii) facilities and emerging technologies/initiatives that are linked with wind energy considering private investment projects in the countries of South America (on-shore wind farms, ONWFs; off-shore wind farms, OFFWFs; green hydrogen plants powered by wind energy, GHPWE; wind farms and photovoltaic PV plants, WPP; wind farms and hydroelectric plants, WHP; or not specified, NS), (iii) research and development (R&D) studies/projects carried out by the universities for the implementation of wind energy in South America (improving wind turbine efficiency, IWTE; integration of wind energy to smart grids, IWESG; reduction in environmental impacts, REI; development of hybrid technologies, DHT; cost-effective technology for people, CETP; policies and regulations for massive implementation, PRMS; or not specified, NS), (iv) sustainability challenges for the future linked with the implementation of wind energy in South America (stability of wind energy generation, SWEG; decrease in environmental impacts on local fauna and landscape, DEILFL; regulatory and political aspects that affect the expansion of wind energy, RPEWE; diversification of matrix energy considering other renewable energy sources, DMEORES; not specified, NS).

#	Authors	Year	(i)	(ii)	(iii)	(iv)
1	Mattar and Guzmán-Ibarra [42]	2017	RTC	OFFWF	IWESG	NS
2	Da Silva et al. [43]	2005	RET	GHPWE	DHT	SWEG
3	De Bona et al. [44]	2021	ONSWEP	ONWF	IWTE	NS
4	Dos Santos et al. [45]	2021	NS	WPP	IWESG	DMEORES
5	Rodríguez et al. [46]	2010	LCEI	GHPWE	DHT	SWEG
6	Valença and Bernard [47]	2015	NS	ONWF	REI	DEILFL
7	De Azevedo et al. [48]	2020	OFFSWEP	OFFWF	IWESG	NS
8	Carvajal-Romo et al. [49]	2019	ONSWEP	WPP	DHT	DMEORES
9	Watts et al. (1) [50]	2016	ONSWEP	ONWF	CETP	NS
10	Diógenes et al. [51]	2019	NS	ONWF	PRMS	RPEWE
11	Bernard et al. [52]	2014	NS	ONWF	PRMS	DEILFL
12	Falavigna et al. [53]	2020	NS	ONWF	REI	DEILFL
13	Castillo et al. [54]	2018	NS	WHP	DHT	DMEORES
14	de Medeiros Galvão et al. [55]	2020	ONSWEP	ONWF	CETP	NS
15	Otoni Salles et al. [56]	2019	LCEI	ONWF	IWESG	RPEWE
16	Lozer dos Reis et al. [57]	2021	OFFSWEP	OFFWF	CETP	SWEG
17	Bastidas-Salamanca and Rueda-Bayona [58]	2021	LCEI	OFFWF	IWESG	SWEG
18	Hernandez et al. [59]	2021	NS	OFFWF	REI	RPEWE
19	De Jong et al. [60]	2019	ONSWEP	ONWF	IWTE	DMEORES
20	Tito et al. [61]	2020	ONSWEP	ONWF	IWTE	NS
21	Botero at al. [62]	2010	LCEI	ONWF	IWESG	RPEWE
22	Armijo and Philibert [63]	2020	NS	GHPWE	DHT	DMEORES
23	Neri et al. [64]	2019	SDGA	ONWF	CETP	DEILFL

Table 8. Cont.

#	Authors	Year	(i)	(ii)	(iii)	(iv)
24	Watts et al. (2) [65]	2017	NS	ONWF	IWTE	SWEG
25	Ramos Júnior et al. [66]	2022	SDGA	ONWF	IWESG	NS
26	Edsand [67]	2017	ONSWEP	ONWF	IWESG	DEILFL
27	Vallejos-Romero et al. [68]	2020	RET	WHP	PRMS	RPEWE
28	Nadaleti et al. [69]	2020	ONSWEP	GHPWE	DHT	DMEORES
29	Dalbem et al. [70]	2014	NS	ONWF	PRMS	NS
30	Bianchi et al. [71]	2017	ONSWEP	ONWF	IWTE	SWEG
31	Mönnich et al. [72]	2004	ONSWEP	GHPWE	DHT	DMEORES
32	Zolezzi et al. [73]	2010	ONSWEP	GHPWE	DHT	DMEORES
33	Maximov et al. [74]	2010	RET	ONWF	IWESG	NS
34	Icaza et al. (1) [75]	2020	ONSWEP	ONWF	IWESG	NS
35	Frate-Albuquerque and Caldeira-Pires [76]	2005	RET	ONWF	PRMS	RPEWE
36	Pereira et al. (1) [77]	2022	NS	ONWF	REI	DEILFL
37	Farkat Diógenes et al. [78]	2020	NS	ONWF	PRMS	RPEWE
38	Araújo and Gorayeb [79]	2023	NS	ONWF	PRMS	RPEWE
39	Soares et al. [80]	2021	RET	ONWF	PRMS	RPEWE
40	Levieux et al. [81]	2019	NS	WHP	DHT	DMEORES
41	Icaza et al. (2) [82]	2018	ONSWEP	ONWF	IWTE	NS
42	Rueda-Bayona et al. (1) [83]	2019	LCEI	OFFWF	IWESG	RPEWE
43	Mejía et al. [84]	2006	RET	ONWF	IWTE	NS
44	Spazzafumo [85]	2013	RET	GHPWE	DHT	DMEORES
45	Cevallos-Sierra and Ramos-Martin [86]	2018	RET	WPP	DHT	DMEORES
46	González-Longatt et al. (1) [87]	2015	OFFSWEP	OFFWF	IWTE	NS
47	Weiss et al. [88]	2018	ONSWEP	ONWF	IWTE	SWEG
48	Watts and Jara [89]	2011	RET	ONWF	IWESG	NS
49	Sigal et al. [90]	2015	LCEI	GHPWE	DHT	DMEORES
50	Rego and De Oliveira Ribeiro [91]	2018	LCEI	ONWF	IWESG	NS
51	Riojas-Díaz et al. [92]	2022	RET	ONWF	DHT	DMEORES
52	De Lara Filho et al. [93]	2019	RET	WPP	DHT	DMEORES
53	Candia et al. [94]	2019	RET	WPP	DHT	DMEORES
54	Gonçalves et al. [95]	2020	SDGA	ONWF	CETP	NS
55	Pereira et al. (2) [96]	2013	NS	ONWF	IWTE	NS
56	Nadaleti et al. (1) [97]	2020	ONSWEP	GHPWE	DHT	DMEORES
57	Ardanche et al. [98]	2018	NS	ONWF	PRMS	RPEWE
58	Moraes et al. [99]	2016	RTC	ONWF	IWESG	NS
59	Arroyo and Miguel [100]	2020	RET	ONWF	IWESG	DMEORES
60	Coelho and Pinho [101]	2017	RET	OFFWF	IWTE	RPEWE
61	Mattar et al. [102]	2021	OFFSWEP	OFFWF	PRMS	RPEWE
62	Osorio-Aravena et al. [103]	2020	SDGA	WPP	IWESG	DMEORES

Table 8. Cont.

#	Authors	Year	(i)	(ii)	(iii)	(iv)
63	Mamani and Hendrick (1) [104]	2022	NS	ONWF	IWTE	SWEG
64	Benzo et al. [105]	2020	NS	ONWF	IWTE	SWEG
65	Rueda-Bayona et al. (2) [106]	2019	NS	OFFWF	IWTE	NS
66	Carvalho [107]	2003	RET	ONWF	IWESG	NS
67	Filgueiras and Silva [108]	2003	NS	ONWF	IWESG	RPEWE
68	De Lima Camargo et al. [109]	2019	RET	ONWF	IWESG	RPEWE
69	Silva et al. [110]	2013	NS	ONWF	IWTE	NS
70	Labriola and Palese [111]	2000	ONSWEP	ONWF	NS	NS
71	Becerra et al. [112]	2017	ONSWEP	ONWF	IWTE	NS
72	Labriola [113]	2007	RET	ONWF	IWESG	NS
73	Recalde [114]	2010	ONSWEP	ONWF	PRMS	RPEWE
74	Mamani and Hendrick (2) [115]	2022	ONSWEP	ONWF	IWTE	NS
75	González-Longatt [116]	2015	RET	ONWF	IWESG	NS
76	Nelson and Caldera [117]	1987	ONSWEP	ONWF	NS	RPEWE
77	Love and Garwood [118]	2011	NS	WPP	DHT	DMEORES
78	González-Longatt et al. (2) [119]	2014	ONSWEP	ONWF	IWTE	SWEG
79	Reboita et al. [120]	2018	ONSWEP	ONWF	IWTE	SWEG
80	Cacciuttolo et al. [121]	2024	SDGA	OFFWF	IWESG	NS

The interpretation of Table 8 reveals the following results:

- Regarding the aspects in column (i), 28% of the cases are on-shore wind energy potential, while 28% correspond to not specified and 23% correspond to renewable energy transition, and the remaining 23% correspond to sustainable development goal activities. It is possible to notice that there is a clear tendency considering advances in climate change mitigation linked with the implementation of wind energy in South America.
- When studying the aspects in column (ii), 63% correspond to on-shore wind farms, 14% correspond to off-shore wind farms, 11% correspond to green hydrogen plants powered by wind energy, and finally, the remaining 13% are hybridization modes with solar energy and hydroelectric plants. This teaches us that the current trend in the South America region is to implement emerging technologies/initiatives that are linked with wind energy considering private investment projects.
- Regarding the aspects in column (iii), 22% correspond to the integration of wind energy to smart grids, 19% correspond to improving wind turbine efficiency, 17% involve the development of hybrid technologies, 11% are policies and regulations for massive implementation, and 11% correspond to social and environmental studies. This shows the trend in carried out research and development (R&D) studies/projects by the universities linked with the implementation of wind energy in South America.
- When analyzing the aspects in column (iv), 34% are not specified information, 24% are related to the diversification of matrix energy considering other renewable energy sources, 17% are linked with regulatory and political aspects that affect the expansion of wind energy, 11% correspond to the stability of wind energy generation, and 6% are related to the decrease in environmental impacts on the local fauna and landscape. This tells us that, currently, the emphasis on sustainability challenges for the future is linked with the implementation of wind energy in South America.

- The analysis of the cost (CAPEX and OPEX) reveals that the information documented in the scientific literature does not specify the costs of wind energy infrastructure.

4. Discussion

4.1. Main Developments

4.1.1. Advances in Wind Energy Implementation in Each Country of South America

All countries in the South American region have carried out technical–economic studies to know the wind energy potential they have in their territories. In addition, the countries of the region are aligned with the SDGs and COP 25 agreement, which is why they have been implementing projects, plans, and policies over the last two decades. In this way, the implementation of infrastructure for the generation of electrical energy through alternative renewable energy sources has been developed, with wind energy being one of the most popular alternatives in the region. Table 9 shows a ranking of the countries in the South American region according to the criterion of installed capacity (MW) and also considers their progress in the implementation of wind energy. Table 9 is a compilation based on the following sources of information: [6,7,41].

According to Table 9, in the South American region, Brazil leads the ranking, one of the reasons being the country's high demand for electricity due to the size of its population, which mostly lives in cities, and the large-scale industrial sector. Although Brazil generates a significant amount of electricity through hydroelectric plants, the authorities have decided to diversify its energy matrix through alternative renewable energies such as solar and wind energy due to their high usable potential in the territory [6].

In second place in the ranking is Chile, where one of the reasons why an aggressive implementation of renewable energies has been promoted in the last two decades is to decarbonize and diversify its energy matrix, since in its history, electric energy was generated based on fossil sources (coal and oil). The high demand for electrical energy due mainly to large mining projects linked to the copper industry and the growth of its cities has allowed the implementation of an important number of wind farms in its territory. The enormous potential of wind resources in the Patagonia area offers Chile the opportunity to expand its installed wind energy capacity [6].

Table 9. Ranking of countries of South America considering the implementation of installed capacity of wind energy. Year: 2023.

Ranking	Country	Installed Capacity (MW)	Number of On-Shore Wind Farms	Number of Wind Turbines	Usable Potential (MW)	Percentage Used of Potential (%)
1	Brazil	25,055	476	12,528	700,000	3.6
2	Chile	5993	66	2997	40,000	15.0
3	Argentina	4363	75	2182	300,000	1.5
4	Uruguay	1645	48	823	40,000	4.1
5	Peru	978	10	489	20,500	4.8
6	Colombia	913	8	457	30,000	3.0
7	Venezuela	138	2	69	45,000	0.3
8	Bolivia	135	5	68	100,000	0.1
9	Ecuador	78	4	39	4000	2.0
10	Paraguay	0	0	0	2000	0.0
Total	South America	39,298	694	19,649	1,281,500	3.1

Third place in the ranking belongs to Argentina, a country that has historically generated electrical energy based on fossil fuels such as oil and natural gas, in addition to the implementation of hydroelectric plants. Like Chile, considering the enormous wind

resource potential in the Patagonian area, Argentina is developing technical–economic studies to insert new wind farms in said southern area [6].

In fourth place is Uruguay, where despite being a small country in terms of the number of inhabitants and territorial area, they have decided to diversify their energy matrix and bet on the implementation of wind energy. The country has an important ecological resource potential to be exploited, and this is how the authorities have decided to promote the implementation of this technology. This satisfies the demand for electrical energy for cities and different industries such as agriculture, livestock, and services, among others. In a year of normal rainfall, 97% of Uruguay’s electricity demand is covered by renewable energy through a combination of wind (32%), biomass (17%), and solar (3%), in addition to traditional hydroelectric (45%) [6]. The first stage of the energy transition positioned Uruguay at the forefront of renewable energies, ranking as the second country in the world with the greatest participation of alternative renewable energies (such as solar and wind) in its electricity generation [122].

In fifth place is Peru, a mining, fishing, and agri-food country that has had economic growth and important infrastructure development in recent years, which has translated into an increase in its demand for electrical energy. Although Peru has generated its electrical energy mainly through hydroelectric plants and natural gas, it has decided to diversify its energy matrix by implementing a series of wind farms in territories with abundant wind resources [6].

Next in the ranking are Venezuela, Bolivia, Ecuador, Colombia, and Paraguay, countries that have been characterized by generating their electrical energy based on conventional renewable energy comprising hydroelectric plants, in addition to the use of fossil sources such as coal, oil, and natural gas. It is expected that in the coming years and decades, these countries will promote the development of wind energy infrastructure projects in their territories [6].

4.1.2. The Biggest Wind Farms under Operation in South America

- **(i) Lagoa Dos Ventos Wind Farm Power Plant, Piauí Region, Brazil**

Enel Green Power Brazil began the commercial operation of the Lagoa dos Ventos wind farm in the Piauí region in Brazil. It has an installed capacity of 1063.05 MW from 230 wind turbines and is South America’s largest on-shore wind infrastructure as of the year 2024. This wind farm began its construction phase in 2019 and came into operation in 2022. This facility generates over 3.3 TWh per year, eliminating over 1.6 million tons of CO₂ from the atmosphere. Figure 18 shows a representative photo of the wind farm, and Table 10 provides some information on this on-shore wind farm. Table 10 is a compilation based on the following sources of information: [41].

Table 10. Lagoa dos Ventos on-shore wind farm, Brazil—main characteristics.

Parameter	Value	Units
Location	Piauí region	-
Concession Owner	Enel Green Power Brasil	-
Type of Wind Farm	On-Shore	-
Number of Turbines	230	-
Turbines Manufacturer/Model	Nordex/Acciona AW125	-
Diameter of Turbines	125	m
Hub Height	120	m
Installed Capacity per Turbine	4.6	MW
Total Installed Capacity	1063.05	MW
Capacity Factor	0.50	-



Figure 18. Landscape view of Lagoa Dos Ventos wind turbines, Brazil, year 2024.

Considering Figure 18, it is possible to see that the Lagoa Dos Ventos on-shore wind farm is located close to a geographical zone without mountains, in a rural Brazilian landscape in which no contiguous human settlements are located.

Table 10 shows that this wind farm has a total of 230 wind turbines from the supplier Nordex/ Acciona. This on-shore wind farm has a sweep diameter of the blades equivalent to 125 m. Furthermore, the height of the towers is 120 m. Each wind turbine has an installed capacity of 4.6 MW, so, considering all the wind turbines, the wind farm has a total installed capacity equivalent to 1063.05 MW, with an estimated capacity factor of 0.50.

Lagoa dos Ventos phase III will be a 396 MW on-shore wind power project. It is planned in Piauí, Brazil. The project is expected to generate 1,700,000 MWh of electricity to offset 900,000 tons of carbon dioxide emissions (CO_2) per year. The new wind power project consists of 72 turbines. The project is under construction and is expected to enter into commercial operation by 2024 [41].

- **(ii) Rio Do Vento Wind Farm Power Plant, Rio Do Grande Do Norte Region, Brazil**

Casa Dos Ventos began commercial operation of the Rio do Vento on-shore wind farm in the Brazilian Rio Grande Do Norte region. This wind farm started phase I operating in 2021 with 120 wind turbines and a capacity of 504 MW. Then, in 2023, the operation of another 120 turbines capable of generating 534 MW began. It has an installed capacity of 1038 MW from 240 wind turbines and is South America's second-largest on-shore wind infrastructure as of the year 2024. This facility generates over 3.0 TWh per year, eliminating over 1.3 million tons of CO_2 from the atmosphere. Figure 19 shows a representative photo of the wind farm, and Table 11 provides some information on this on-shore wind energy infrastructure. Table 11 is a compilation based on the following source of information: [41].

Considering Figure 19, it is possible to see that the Rio Do Vento on-shore wind farm is located close to a geographical zone with hills, in a rural Brazilian landscape in which no enormous contiguous human settlements are located.

Table 11 shows that this wind farm has a total of 240 wind turbines from the supplier Nordex/ Acciona. The on-shore wind farm has a sweep diameter of the blades equivalent to 125 m. Furthermore, the height of the towers is 120 m. Each wind turbine has an installed capacity of 4.3 MW, so, considering all the wind turbines, the wind farm has a total installed capacity equivalent to 1032 MW, with an estimated capacity factor of 0.50.



Figure 19. Landscape view of Rio do Vento wind turbines, Brazil—year 2024.

Table 11. Rio do Vento on-shore wind farm, Brazil—main characteristics.

Parameter	Value	Units
Location	Rio Do Grande Do Norte Region	-
Concession Owner	Casa dos Ventos S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	240	-
Turbines Manufacturer/Model	Nordex/Acciona 4.3 MW	-
Diameter of Turbines	125	m
Hub Height	120	m
Installed Capacity per Turbine	4.3	MW
Total Installed Capacity	1038	MW
Capacity Factor	0.50	-

- **(iii) Horizonte Farm Power Plant, Taltal, Antofagasta Region, Chile**

Colbun S.A. began commercial operation of the Horizonte on-shore wind farm in Taltal, Antofagasta, Chile. This wind farm started construction in 2021 and then began operation in March 2024. It has an installed capacity of 816 MW from 140 wind turbines and is South America's third-largest on-shore wind infrastructure as of the year 2024. This facility generates over 2.4 TWh per year, eliminating over 0.7 million tons of CO₂ from the atmosphere. Figure 20 shows a representative photo of the wind farm, and Table 12 provides some specifications on this on-shore wind energy infrastructure. Table 12 is a compilation based on the following source of information: [41].

Table 12. Horizonte on-shore wind farm facility, Chile—main characteristics.

Parameter	Value	Units
Location	Taltal, Antofagasta Region	-
Concession Owner	Colbún S.A.	-
Type of Wind Farm	On-Shore	-
Number of Turbines	140	-
Turbines Manufacturer/Model	Enercon E-160 EP5	-
Diameter of Turbines	160	m
Hub Height	120	m
Installed Capacity per Turbine	5.8	MW
Total Installed Capacity	816	MW
Capacity Factor	0.55	-



Figure 20. Landscape view of Horizonte wind turbines, Chile—year 2024.

Considering Figure 20, it is possible to see that the Horizonte on-shore wind farm is located close to a geographical zone without hills or mountains, in the Atacama desert landscape in which no contiguous human settlements are located.

Table 12 shows that this wind energy facility has a total of 140 wind turbines from the supplier Enercon E-160 EP5. This facility has a sweep diameter of the blades equivalent to 160 m. Furthermore, the height of the towers is 120 m. Each wind turbine has an installed capacity of 5.8 MW, so, considering all the wind turbines, the wind farm has a total installed capacity equivalent to 816 MW, with an estimated capacity factor of 0.55.

Colbun S.A. has submitted an environmental evaluation study for review by the Ministry of the Environment of Chile to obtain the social and environmental license to expand its installed capacity up to 996 MW, which is 20% more than the current one [41].

4.2. Lessons Learned and Gaps

4.2.1. Mitigation of Negative Environmental Impacts

Although wind farms contribute to the mitigation of climate change, this type of infrastructure can cause negative socio-environmental impacts in the territory where they are built and later when they reach full operation [79].

In the case of the construction stage, it is important not to negatively affect the natural environment, considering earthworks related to the excavation of trenches for electrical cables and the construction of wind turbine foundations. Thus, another relevant and very careful topic in the construction stage is the discovery of archaeological remains of ancient cultures that inhabited the place where the wind farm is located. In these cases, construction activities must be stopped and archaeologists from the country's Ministry of Archaeology must be summoned, so that they can examine, study, and safely remove the archaeological finds and remains to be taken for study or conservation in conservation research centers and/or museums, respectively.

On the other hand, during the operation stage of the wind farm, there is evidence of some situations that have been recorded in several projects, where some negative socio-environmental impacts are generated. For example, the mortality of different species of birds has been recorded in some cases, which accidentally collide with the blades of wind turbines [53]. Something similar happens at night, where a mortality rate of bat species has been recorded, with the evidence remaining at the base of the wind turbine towers [47,52]. In this sense, it is necessary to implement alternative solutions with the help of advanced

technologies that keep fauna away from the place, thus avoiding the mortality of bird and bat populations and not altering the functioning of ecosystems.

To mitigate the negative impact on bird species (birds, seagulls, and condors, among others), a new technology has been developed that will allow these animals to be protected in wind farms through a system that turns off the turbines. This is done through a sensor system that detects flying objects and through artificial intelligence algorithms that identify the species of birdlife and its possible trajectory. These sensors have an area of one kilometer and act in a matter of seconds, so if the sensor determines that there may be a risk of collision, the blades stop almost immediately. Among artificial intelligence techniques, neural networks improve detectability (including detection between blades), classify detections, and reduce the number of false positives (confusion of other flying elements with birds).

In addition, systems are being implemented using ultrasound to reduce the negative impact of wind turbines on bats, which works by detecting the presence of bats in real-time and has the option of activating the automatic stop of the wind turbine based on the presence of bats or in combination with environmental variables. There are currently two ways of implementing the system available: Detection and Stop. The detection system makes it possible to identify the species of bat that is near the wind turbine. On the other hand, the Stop system allows the wind turbine to be kept stopped when a defined bat activity threshold is exceeded.

In addition, there are other negative socio-environmental impacts of wind farms that affect humans; these are (i) alteration of sunlight patterns during part of the day in homes adjacent to wind farms, producing pulses of intermittent times with shadows (time-variable shadow cast by a wind turbine) that bother residents of the site, and (ii) noise or slight but permanent sound from the movement of the blades of the wind turbines during the day and night in homes adjacent to wind farms [79,88]. Considering these aspects, it is recommended not to build on-shore wind farms at a distance of less than 500 m from homes. This means, in other words, creating a buffer zone with a width of 500 m between areas populated with homes and the wind turbines in the wind farms.

Although negative socio-environmental impacts are less severe than those for hydroelectric large dams, the best locations for wind farms may be in indigenous lands, or farmers/livestock lands; transmission lines may need to cross such lands or other environmentally sensitive areas. In this context, policy makers, private energy developers, and communities must be aware of this broader context and develop appropriate protocols and regulatory frameworks to engage all territory stakeholders to everyone's satisfaction.

Finally, as an important gap recorded in the scientific literature studied in this research, although there is sufficient information on technical aspects of the operation of wind farms in the South American region, there is not a sufficient number of publications and studies linked to sustainability aspects measuring the effectiveness of climate change mitigation measures with indicators.

4.2.2. Implementation of Off-Shore Wind Energy in Coastal Zones and the Sea: A Pending Issue

Off-shore wind facilities have evolved rapidly over time, after slow growth since the first wind turbines were installed in Denmark in 1991. Considering the strong implementation of off-shore wind energy in Europe and China, approximately 56 GW of power capacity has been installed around the world [7]. In this sense, three decades after the first off-shore wind farm was built, South America currently does not have this kind of clean energy facility [23]. These experiences have showed that scalability that can bring positive impacts to South America, because larger wind turbines can be used in the marine environment than in on-shore wind farms.

Countries of the South America region using this energy can predictably produce electricity and increase its generation in autumn and winter—seasons of lower solar radiation and higher energy consumption by industries and people [123]. Chile, Colombia, and Brazil are currently the most advanced countries in their off-shore wind legislation:

Brazilian industry developers, for example, have proposed more than 130 GW of off-shore wind capacity across 55 facilities [48]. The Brazilian oil and gas industry needs energy to produce these fossil fuels, where it operates off-shore and has a well-established supply chain that can use off-shore wind [57]. In fact, the largest off-shore wind project is also expected to come into operation in this country: Ventos do Sul off-shore wind farm will have a 6507 MW installed capacity. It will be located in the South Atlantic Ocean, Rio Grande do Sul region, Brazil. The off-shore facility is currently in the announcement stage. It will be developed in a single phase. The infrastructure construction is likely to commence in 2025 and it is expected to enter into commercial operation in 2029 [41].

Figure 21 shows a panoramic view generated with artificial intelligence of the future Ventos Do Sul off-shore wind farm.



Figure 21. Future off-shore wind farm in the Atlantic Ocean on Brazilian coast. DALL-E-2 image, May 2024, created from [32].

In Colombia, an off-shore wind energy road map was launched recently. Off-shore wind energy technical studies, environmental impact assessment (EIA) studies, and benefits for energy companies are promoted by the Ministry of Mines and Energy [58]. On the other hand, Chile has begun planning a long-term strategy to implement off-shore wind energy infrastructure projects considering more than 6000 km of coastal zones [102].

Some complexities for the implementation of off-shore wind energy in the region of South America are the following:

- (i) The difficulty of installation of off-shore wind energy is a main challenge. This kind of technology needs the use of highly specialized equipment in the construction and maintenance phases. Many off-shore wind facilities exist in northern Europe, including turbines with fixed foundations and those on floating platforms. These off-shore wind farms require complex assembly due to wind turbine towers that can be more than 200 m high, needing adequate logistical issues and port infrastructure [23].
- (ii) Environmental impact assessment (EIA) studies are needed to install an off-shore wind farm. In this sense, it is necessary to study the compatibility of the wind energy infrastructure with navigation, marine fauna, and migration routes, among others [23].
- (iii) Many components of wind turbines are made in northern Europe. In this sense, the distance from established suppliers presents logistical and transport challenges, for example for turbine nacelles, the central hubs that house generators, gearboxes, and drive trains. Therefore, more off-shore wind components must be produced locally in South America, avoiding the need to be imported [23].

4.3. Future Sustainable Prospects

4.3.1. Green Hydrogen (GH₂) and Synthetic e-fuel Production from Patagonia Region, Chile

From Magallanes, Patagonia, Chile, “The End of the World” and one of the southernmost points in the world, humanity begins the journey towards decarbonization. The first green hydrogen (GH₂) and synthetic e-fuel production demonstration plant in the world is called Haru Oni or “land of wind”, in the language spoken by the Selk’nam and

Tehuelches native peoples from Chile [124]. The sustainable facility project entails building a green hydrogen-based fuel production plant, a 3.4 MW wind turbine, and a 13 kV backup transmission line. The plant was built on a 3.7 Ha site within Tehuel Aike site, Cabo Negro, North of Punta Arenas, Magallanes Region. The construction work had a duration of around eleven months. This facility is the world's first integrated industrial-scale plant for synthetic e-fuels [124].

The operation of the demonstration plant started in December 2022 considering a consortium consisting of Highly Innovative Fuels (HIF), Siemens Energy, Porsche, Enel, ExxonMobil, Enap, Empresas Gasco, and Johnson and Matthey, among others. This demonstration plant potentially represents a key mitigation action to cope with climate change. It can use wind resources to generate green hydrogen (GH₂) and then turn that GH₂ into a synthetic e-fuel that is chemically identical to gasoline [125].

The Haru Oni project uses wind power considering 5000 equivalent operating hours (EOHs) to generate green hydrogen (GH₂) from water. Then, GH₂ is combined with biogenic CO₂ captured from the atmosphere to produce e-methanol. Finally, this process produce e-gasoline, which can be used in conventional vehicles, with no modifications required. This would make transportation systems carbon-neutral [126–128]. Figure 22 shows a schematical view of the process of generating green hydrogen (GH₂) and synthetic e-fuels.

Observing Figure 22, the Haru Oni facility is the first demonstration plant of green hydrogen (GH₂) production in Chile and is the first operating e-fuel infrastructure worldwide. In a first stage, the demonstration plant uses wind and water resources. With wind, it is possible to generate electricity, and then water and electricity are considered in an electrolysis process to produce green hydrogen (GH₂). In a second stage, the demonstration plant captures CO₂ from a biogenic source and use a process of synthesis to combine the CO₂ and GH₂ to produce e-fuels, including carbon-neutral gasoline (e-gasoline) and carbon neutral liquefied gas (eLG). The e-fuel can create a way for existing infrastructure to become carbon-neutral by continuously reusing and recycling CO₂ [124,125,129]. Figure 23 shows a panoramic view of the Haru Oni demonstration plant.

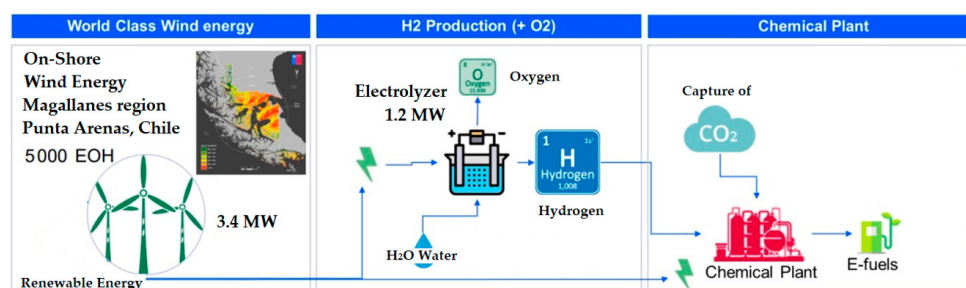


Figure 22. Example of innovation in the region of South America: Haru Oni green H₂ and green e-fuel demonstration plant using wind energy—Magallanes region, Chile. Adapted from [129].



Figure 23. Panoramic view of Chile's Haru Oni wind turbine and green H₂ demonstration plant—year 2024 Data from [125].

The demonstration plant annually produces 600 tons of crude e-methanol and 130,000 L of e-gasoline. Both e-fuels are stored in tanks and transported by truck 35 km to Puerto Mardones. In the port, e-fuels are prepared for export. The demonstration plant will allow Chile to transform in a Green Hydrogen Industrial Cluster (GHIC) and to play a crucial role in providing the world with an environmentally friendly, competitive e-fuel that does not generate CO₂ emissions [127,130]. Table 13 shows the main technical specifications of the Haru Oni demonstration plant. Table 13 is a compilation based on the following sources of information: [124,125,129].

Haru Oni demonstration plant is in phase I of the project, which produces green hydrogen (GH₂), methanol, and synthetic e-fuels. For example, one wind turbine at Haru Oni can create the same amount of e-fuel as around six wind turbines in Germany. The facility “Haru Oni” is carrying out pioneering work and is expected to produce up to 550 million liters of e-fuel in the coming years, which can serve as an example for many other countries worldwide. Synthetic fuel is a liquid energy carrier that creates about 90% less CO₂ emissions than fossil fuels. In the case of e-gasoline, it is simultaneously compatible with existing liquid fuel infrastructure [124,125,129].

Table 13. Haru Oni wind turbine, green hydrogen (GH₂), and e-fuel production demonstration plant, Magallanes, Chile—main specifications.

Parameter	Value	Units
Location	Tehuel Aike site, Cabo Negro, North of Punta Arenas, Magallanes Region	-
Concession Owner	HIF	-
Phase of the Project	Industrial Demonstration Plant	-
Type of Wind Farm	On-Shore	-
Number of Turbines	1	-
Turbines Manufacturer/Model	Siemens-Gamesa SG 3.4-132	-
Diameter of Turbines	132	m
Hub Height	100	m
Installed Capacity per Turbine	3.4	MW
Total Installed Capacity	3.4	MW
Capacity Factor	0.57	-
Equivalent Operating Hours (EOH)	5000	Hours
Plant Surface	3.7	Ha
Electrolyzer Capacity	1.2	MW
e-fuel Production	130,000	L/year
e-methanol Production	600	Tons/year

Finally, it is possible to mention that the company HIF is planning phase II of the project, a 325 MW on-shore wind farm, which would ultimately help it reach its goal of producing up to 140,000 tons of synthetic methanol per year [124,125,129].

4.3.2. Prospective Utility-Scale On-Shore and Off-Shore Wind Capacity in South America Region

The South American region offers the opportunity for the development of both terrestrial and marine wind energy thanks to its enormous wind generation potential. In that sense, it offers the conditions to design, build, and implement wind farms with the use of wind turbines of different sizes and spans. This way, the region has the opportunity to transform itself into a center of technological development and innovation, where each country can acquire experience and share it with the rest of the world [6,7]. Figure 24 shows the technological evolution of wind turbines over time.

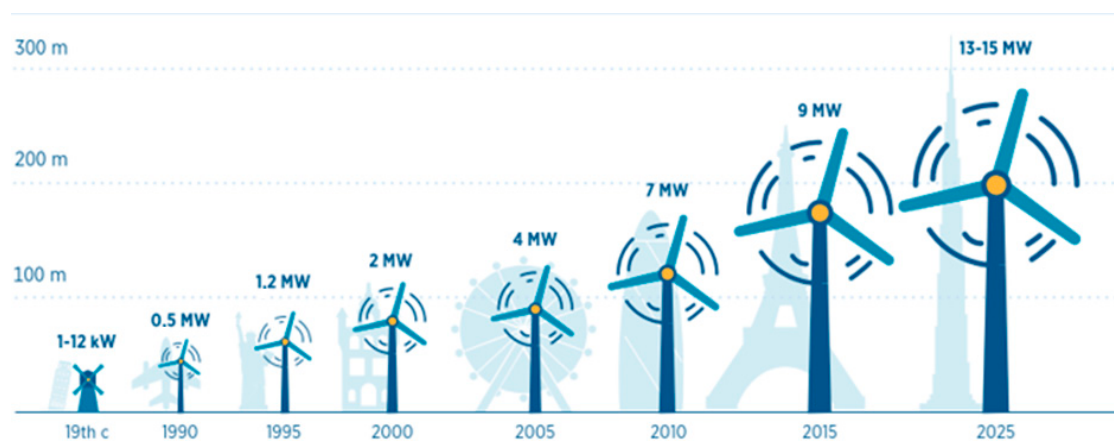


Figure 24. The technological evolution of wind turbines considering different installed capacities, sizes, and heights—year 2024. Adapted from [131].

Considering Figure 24, it is possible to mention that in South American countries, wind turbines have been implemented in on-shore wind farms of the following installed power sizes: (i) 1–12 kW, (ii) 0.5 MW, (iii) 1.2 MW, (iv) 2.0 MW, and (v) 4.0 MW. On the other hand, the construction and operation of off-shore wind farms are expected in the coming years and decades in the South American region, mainly in Brazil, Chile, and Colombia, where the following sizes of installed power will be considered: (i) 7.0 MW, (ii) 9.0 MW, and (iii) 13–15 MW. The latter is because the wind speeds at sea are much higher than the wind speeds inland areas; this is mainly due to the difference in the friction of the moving air masses, either with the water of the sea or vegetation, as well as the topography and urbanization of on-shore territory.

Wind turbines are evolving continuously, considering the technological advances and the increasing size and power of installed capacity. In this sense, competitive advantages of wind energy are reached, contributing to the reduction in costs. The average capacity of newly installed wind turbines grew by 7% from 2021 to 2022, to 3.2 MW, while the height increased by 4% from 2021 by 2022, at 98.1 m. Taller wind turbines can produce more electric energy by obtaining the highest velocities of wind resources and avoiding roughness from the land or sea surface.

Figure 25 shows a map of the expected prospective installed capacity for each of the countries in the Latin American region and also specifically in the South American region.

It is possible to see considering Figure 25 that the countries with the greatest wind potential and opportunity to insert wind farm infrastructure are (i) Brazil, (ii) Chile, (iii) Argentina, and (iv) Uruguay. In the case of Brazil, a high potential is observed in the northern coastal zone equivalent to 7.5 GW, in the central coastal zone equivalent to 6.5 GW, and in the southern coastal zone of the country equivalent to 8.0 GW. On the other hand, Chile has a high wind potential in the southern region of Patagonia. Research by the Chilean Ministries of Energy shows that Magallanes possesses some of Chile's best wind resources and could yield 12.5 GW. Argentina is another country with territory in the Patagonia area where high-speed winds are generated, with projects for on-shore wind farms being planned with an installed power equivalent to 8.0 GW. Finally, Uruguay has a high wind resource potential, where an installed capacity equivalent to 6.0 GW is projected.

Although other countries in the region have the opportunity to use wind resources as a renewable energy source, their potential to implement large-scale wind farms is lower; this is the case of (i) Peru, equivalent to 2.5 GW, (ii) Colombia, equivalent to 3.0 GW, (iii) Venezuela, equivalent to 1.5 GW, (iv) Ecuador, equivalent to 0.5 GW, (v) Paraguay, equivalent to 0 GW, and (vi) Bolivia, equivalent to 0 MW.



Figure 25. Mapping of prospective utility-scale wind capacity in Latin America. Adapted from [6].

4.3.3. Emerging Technologies Linked with Wind Energy and Industry 4.0 Paradigm with Application in the South American Region

Wind energy faces significant challenges in terms of efficiency, scaling, and costs. It is in this sense that the paradigm of Industry 4.0 and its technologies are linked, for example, with the implementation of improvement tools in the estimation of electrical energy generation based on wind energy [132,133].

Changes in wind speed can occur in periods of less than 10 min, which is the aspect that most increases the intermittency of wind energy and is the most difficult to predict. Figure 26 shows the production of five wind power plants that currently operate in Peru. Finding a common pattern of energy production on the same day is impossible. Even the same plant can vary from one day to the next, for example, the Wayra wind farm located in Peru, on 24 June 2019, from 04:00 p.m. to 09:30 p.m. It achieved almost constant energy production; however, on the other two days analyzed, the production was different at the same time of day.

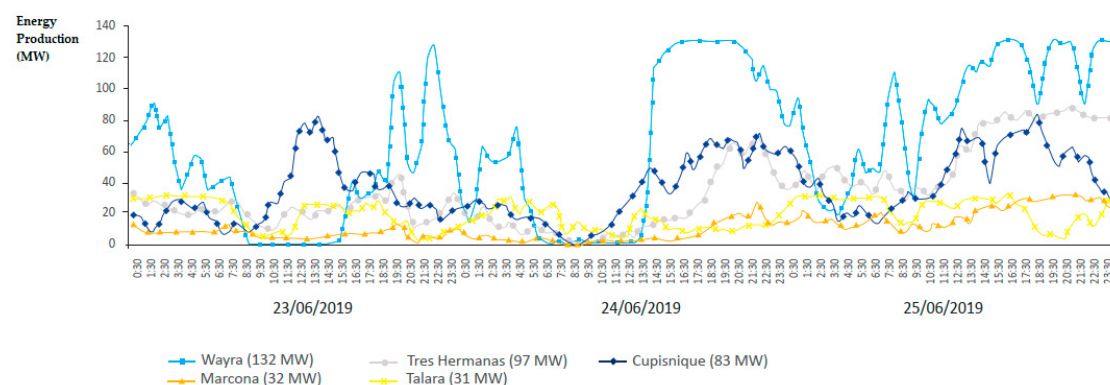


Figure 26. An example that shows the variability in wind energy production in wind farms in Peru. Adapted from [134].

This is why there are already tools that allow us to reduce this uncertainty due to the variable behavior of the wind that occurs in nature, and thus estimate the generation of electricity more accurately through an adequate weather forecast and the analysis of the spatiotemporal behavior of the direction and speeds of the winds. Considering the technology of artificial intelligence (AI), mathematical and statistical algorithms make it possible to collect large amounts of environmental data on weather forecast information and analyze them together with the historical record of spatiotemporal behavior data of the direction and speeds of the wind. By studying, interpreting, and fusing this information, wind turbines are able to optimize their operation in advance in order to generate the maximum possible energy. With this type of technology, artificial intelligence (AI) algorithms linked to wind farms can also make an approximate calculation of the electrical energy they would be able to generate in the next 36 h. This is an advantage that can help prepare an energy generation schedule to know how necessary it will be to complement wind energy with other types of energy resources [135–137].

During recent years, artificial intelligence algorithms have been improved until very satisfactory results have been achieved. Although the effects of variable wind behavior cannot be eliminated, the forecast has resulted in wind farms improving their generation figures by 20% [137].

Artificial intelligence (AI) can assist in feasibility engineering studies to select more favorable sites for wind farms and turbine locations. It can analyze large amounts of geographic and environmental data to identify sites with the best wind resources. This saves valuable time and resources that would have been spent analyzing these locations manually [136].

Furthermore, artificial intelligence (AI) not only serves to improve the generation process, but its main characteristic is its capacity for autonomous learning. It can also be applied to other aspects, such as predictive maintenance and monitoring of the performance/efficiency of wind turbines. Several wind farms in the South American region are applying a tool that saves money on their repairs and reduces their downtime. This technology, which works through artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT), is capable of detecting breakdowns or failures before they occur. In this way, it is possible to reduce the repair times of wind turbines, in addition to extending their useful life [138,139].

In addition, contracting companies specialized in the construction of wind farms (EPC) are using a wide variety of innovative tools and methods to build their wind farms, which include (i) proximity sensors in machinery to increase the safety of the work with the use of the Internet of Things (IoT), (ii) the use of unmanned aerial vehicles or drones (UAVs) to carry out topographic surveys and inspection of wind turbines, and (iii) software solutions to remotely monitor and support the different activities of the start-up and normal operation of wind farms, among others. These processes and tools have allowed data to be collected more quickly, accurately, and reliably, thus improving the quality of construction and efficiency of the operation stage and also facilitating communication between teams of engineers in the field and in remote offices [140,141].

On the other hand, the operation of wind farms in their operational stage in remote places that are difficult to access, whether on-shore or off-shore, also benefits enormously from artificial intelligence (AI). This is how artificial intelligence (AI) can improve remote monitoring of these difficult-to-access locations, increasing their availability. This reduces the need for supervision or human personnel on site, which in turn decreases operating costs and increases human safety by reducing accident risks [135].

5. Conclusions

All countries in the South American region considered in this study, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, and Venezuela, have implemented infrastructure linked to wind energy, except Paraguay. This is because Paraguay has

emphasized the generation of electricity through conventional renewable energy sources such as hydroelectricity.

Brazil, Chile, Argentina, and Uruguay are at the forefront as of 2023 considering the study, design, construction, and operation of large-scale on-shore wind farms in the South American region, with a collective installed capacity that exceeds 37 GW. Brazil leads with a total installed capacity equivalent to 25 GW considering on-shore wind farms.

As of 2023, considering the countries of the South American region under study, there are 694 large-scale on-shore wind farms in operation, with a total estimated number of 19,649 wind turbines installed. As of 2023, there are no off-shore wind farms in operation in the South American region.

Additionally, countries such as Colombia and Peru are experiencing a promising scenario regarding the implementation of wind energy in their territories, considering the portfolio of infrastructure projects under the feasibility study stage, under the processing of environmental impact studies (EIAs), and in the construction stage.

It is noteworthy to mention that the introduction of wind energy in the countries of the South American region has made it possible to reduce greenhouse gas (GHG) emissions, transforming the energy matrix from fossil energy sources to clean and renewable energy sources. In that sense, the contribution of each country in the region to the mitigation of climate change can be appreciated. Considering all the countries in the South American region under study, there is a contribution to the mitigation of climate change with an annual reduction of 43.5 million tons of CO₂ equivalents.

Wind energy is still a relatively underexploited resource across the South American region, particularly concerning its vast potential. For this potential to be realized, energy policy needs to overcome the mindset that has dominated the sector throughout its history in South America: the preference for hydroelectric generation.

Wind energy adequately complements the region's hydro power generation because hydroelectricity can adapt to the intermittence of winds. In some places of the South American region, the wind resources are strongest during the summer season, precisely when hydro power production is most limited. Climate change is affecting hydroelectricity, altering hydrological patterns, and making this renewable energy less stable and less predictable.

On the other hand, considering the experiences in other regions of the world, off-shore wind energy costs are becoming more competitive, while the availability of on-shore lands is decreasing. In this context, considering the off-shore potential of some countries in South America, the region has the opportunity to take advantage of its full potential and create an attractive financing environment and develop off-shore wind policies. The development of off-shore wind energy can bring opportunities to local economies, with the potential for local job creation, particularly in the operations and maintenance phase.

The Haru Oni green hydrogen (GH₂) plant in Chile is fully operating considering the use of renewable energy in the Patagonia region, producing e-fuel from wind and water. The facility was commissioned in 2022, making it the first plant of its kind to produce green hydrogen (GH₂) in Chile as well as one of the largest in Latin America. As a lighthouse project of hydrogen for development (H4D) at the southern tip of Chile, production has started at the world's first industrial-scale facility for carbon-neutral fuel. In this sense, implementing emerging technologies linked with carbon neutrality, like the generation of green hydrogen and synthetic e-fuels, looks like a synergetic clean energy solution combined with wind energy, and considering the high potential of natural resources may transform the region into a world-class sustainable territory.

This systematic review on renewable wind energy implementation in South America illuminates several dimensions of the energy transition from theoretical, practical, and policy-related perspectives. Theoretically, this research enriches the renewable energy literature by elaborating on the unique challenges and opportunities presented by the South American context, which is marked by its diverse ecological and socio-economic landscape. Practically, the findings reveal significant progress in the adoption of on-shore

and off-shore wind energy, emphasizing the role of governmental policies and private investments in shaping the energy infrastructure.

The practical contributions of this study are particularly evident in the detailed analysis of wind energy capacity and production across different South American countries. This has significant implications for stakeholders involved in energy planning and development, offering a nuanced understanding of regional disparities and potential areas for growth.

However, this study is not without its limitations. One of the primary constraints is the variability in data availability and quality across the countries studied, which may affect the generalizability of the findings. Additionally, the focus on wind energy alone does not account for the interplay with other forms of renewable energy, which could provide a more comprehensive view of the renewable energy ecosystem.

Future studies should aim to integrate multi-energy system analyses that include solar, hydro, and bioenergy to provide a holistic view of renewable transitions. Furthermore, exploring the socio-economic impacts of renewable energy adoption on local communities would provide deeper insights into the sustainability of such initiatives.

Finally, it is possible to mention that the vast majority of South American countries have promoted the implementation of wind energy to diversify their energy matrix and not depend on conventional renewable energy from hydroelectric plants, due to droughts and changes in patterns of precipitation in the region due to climate change. It is expected that by 2050, all countries in the region will have on-shore wind energy infrastructures and some countries will implement off-shore wind farm infrastructures.

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Abbreviations

GWEC	Global Wind Energy Council
GHG	Greenhouse Gasses
CO ₂ eq	Carbon Dioxide equivalent
NDCs	Nationally Determined Contributions
GWA	Global Wind Atlas
IRENA	International Renewable Energy Agency
ESMAP	Energy Sector Management Assistance Program
PF	Plant Factor
H ₂	Hydrogen
GH ₂	Green Hydrogen
GHIC	Green Hydrogen Industrial Clusters
H4D	Hydrogen for Development
e-fuels	Electrofuels
e-gasoline	Carbon-neutral gasoline
e-LG	Carbon-neutral liquefied gas
R&D	Research and Development
AI	Artificial Intelligence
ML	Machine Learning
IoT	Internet of Things
CC	Cloud Computing
UAVs	Unmanned Aerial Vehicles

EIA	Environmental Impact Assessment
DEM	Data Extraction from Metadata
DEC	Data Extraction from Content
EC	Exclusion Criteria
CAPEX	Capital Costs
OPEX	Operational Costs
SDGs	Sustainable Development Goals
UN	United Nations
EPC	Engineering, Procurement and Construction
RER	Renewable Energy Resource
MW	Megawatts
GW	Gigawatts
MWh	MegawattsHour
GWh	GigawattsHour
TWh	TerawattsHour
Mt	Millions of tons
masl	Meters above sea level

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