energies

Systematic Review

Renewable Solar Energy Facilities in South America—The Road to a Low-Carbon Sustainable Energy Matrix: A Systematic Review

Carlos Cacciuttolo [1,2,*], Valentina Guzmán [1] and Patricio Catriñir [1]

[1] Department of Civil Works and Geology, Catholic University of Temuco, Temuco 4780000, Chile; vguzman2015@alu.uct.cl (V.G.); pcatrinir2016@alu.uct.cl (P.C.)
[2] Department of Civil Engineering, Universidad de Castilla-La Mancha, Av. Camilo Jose Cela s/n, 13071 Ciudad Real, Spain
* Correspondence: carlos.cacciuttolo@gmail.com or ccacciuttolo@uct.cl

Abstract: South America is a place on the planet that stands out with enormous potential linked to renewable energies. Countries in this region have developed private investment projects to carry out an energy transition from fossil energies to clean energies and contribute to climate change mitigation. The sun resource is one of the more abundant sources of renewable energies that stands out in South America, especially in the Atacama Desert. In this context, South American countries are developing sustainable actions/strategies linked to implementing solar photovoltaic (PV) and concentrated solar power (CSP) facilities and achieving carbon neutrality for the year 2050. As a result, this systematic review presents the progress, new trends, and the road to a sustainable paradigm with disruptive innovations like artificial intelligence, robots, and unmanned aerial vehicles (UAVs) for solar energy facilities in the region. According to the findings, solar energy infrastructure was applied in South America during the global climate change crisis era. Different levels of implementation in solar photovoltaic (PV) facilities have been reached in each country, with the region being a worldwide research and development (R&D) hotspot. Also, high potential exists for concentrated solar power (CSP) facilities considering the technology evolution, and for the implementation of the hybridization of solar photovoltaic (PV) facilities with onshore wind farm infrastructures, decreasing the capital/operation costs of the projects. Finally, synergy between solar energy infrastructures with emerging technologies linked with low-carbon economies like battery energy storage systems (BESSs) and the use of floating solar PV plants looks like a promising sustainable solution.

Keywords: solar energy; photovoltaic (PV) facilities; concentrated solar power (CSP) facilities; battery energy storage systems (BESSs); hybrid renewable energy facility; climate change; sustainability

check for updates

Citation: Cacciuttolo, C.; Guzmán, V.; Catriñir, P. Renewable Solar Energy Facilities in South America—The Road to a Low-Carbon Sustainable Energy Matrix: A Systematic Review. *Energies* **2024**, *17*, 5532. https://doi.org/10.3390/en17225532

Academic Editors: Yuhan Huang, Jianye Chen, Wenting Lin and Xuehui Wang

Received: 8 September 2024
Revised: 14 October 2024
Accepted: 18 October 2024
Published: 6 November 2024

1. Introduction

1.1. Implementation of Renewables Energies in South America Towards a Low-Carbon Sustainable Energy Matrix

Renewable energy is energy that is not consumed or exhausted on a human scale in the processes of transformation and use of useful energy and generates significantly lower adverse environmental impacts than those produced by conventional or fossil energy sources [1–3]. This type of energy is classified as conventional and non-conventional, depending on the degree of development of the technologies for its use and the penetration in the present energy markets [4–6].

In South America, large hydroelectric installations (greater than 20 MW) are recognized as conventional renewable energy, and the following are recognized as non-conventional renewable energy: mini hydroelectric (less than 20 MW), solar, wind, waves/tidal, bioenergy, biogas, and geothermal [7,8]. Implementing these renewable energy sources to a greater or lesser extent is gradually transforming the region's energy matrix from being based on fossil fuels to being low-carbon and sustainable [9,10]. In this context, the South American region is making efforts to mitigate the impacts of global climate change by promoting private investment projects and public policies for the inclusion of clean energy [11,12].

In South America, there is still an incipient development of renewable energies such as geothermal, waves/tidal, biogas, and bioenergy, and since the technologies are in a research and development stage, they have not managed to be scalable, and the costs are not yet competitive with other alternatives [13]. In this sense, the region's most popular and widely implemented renewable energies have been hydroelectric energy, wind energy, and solar energy [14].

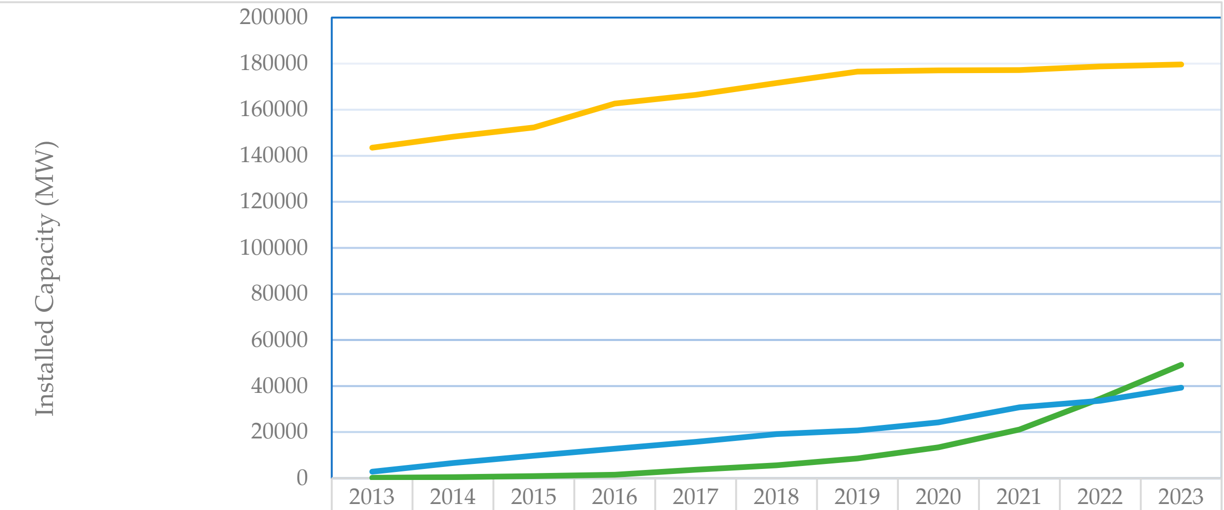
Hydroelectric energy is obtained by transforming water's potential and kinetic energy to move turbines that feed generating equipment to produce electricity. Because of the water resource that gives rise to it, it is considered a renewable and clean source of energy, which is unfortunately threatened by the negative effects of climate change [15]. In this sense, the generation of this type of energy depends on the existence of an appropriate runoff flow and an elevation difference (height) that allows the speed of the falling water to be sufficient for the operation of the turbines. South America has these hydrological characteristics in its hydrographic basins on both the Pacific and Atlantic oceans [13,15]. Although this type of renewable energy has been very popular in the region in the last 10 decades, communities are currently complaining about negative environmental impacts, which has led to less implementation of this type of project in recent years, with countries such as Brazil, Venezuela, Colombia, Peru, and Paraguay standing out [15,16]. In this regard, the application of two types of hydroelectric energy is being evaluated: (i) reservoir hydroelectricity (impoundment), in which it accumulates a sufficient volume of water to then circulate it through narrower conduits and at high pressures to the turbines, where part of the mechanical energy is transformed into electrical energy, and then the water is returned to the source of origin (mainly rivers); and (ii) run-of-the-river hydroelectricity (diversion), in which it diverts a portion of the water from the rivers to operate the turbines and generate electricity, and then return the flow to the river in a lower area, after having used it to produce energy [14,16].

In this sense, South American countries have implemented other renewable energy alternatives, meeting the Sustainable Development Goals (SDGs) of the UN agenda for 2030 and achieving decarbonization by 2050 [4,17]. These renewable energy alternatives such as onshore wind energy and photovoltaic solar energy have been strongly implemented in the last decade [18–20].

Wind energy is a source resulting from the transformation of the movement of air masses generated by the wind into usable energy, preferably electrical [21]. The technologies developed for the use of wind movement as an energy source produce zero greenhouse gas emissions during their operation and consist of wind turbines or wind generators that transform the kinetic energy of the wind into mechanical energy and then the electric generator converts it into electrical energy [22]. This type of renewable energy has had a large-scale industrial implementation of onshore wind farms in countries in the region with high potential that are mainly located near the ocean on the coastal edge; among those included are Brazil, Chile, Argentina, Uruguay, and Peru [13,15]. Although there is a high potential for offshore wind energy, to date, this type of infrastructure does not exist in the region yet [14]. Some of the limitations of this energy source in the region have been (i) its remoteness from population centers or industrial centers located far from the ocean and (ii) intermittency in its generation due to the variability of wind speed during the hours of the day [15].

Given this background, photovoltaic solar energy has positioned itself in the last decade as a reliable, massive, and scalable source in the region, experiencing strong growth after the COVID-19 pandemic [13,23]. The sun is one of South America's most constant sources of energy due to the abundance and high irradiation it generates in the outer layer of the atmosphere [24]. The energy received on the Earth's surface is called irradiance, and it depends on the time of day, the inclination of the sun's rays, and the cloud cover. One of its main barriers is that it is only received during the day, so it needs to be combined with other energy sources or associated with storage systems [25,26]. Northern Chile, southern Peru, southern Bolivia, and northwestern Argentina are among the countries with the most solar radiation globally, mainly due to their northern sector: the “Sun Belt” [27–29]. Chile stands out from the rest thanks to the geography of the Atacama Desert, with virtually unlimited resource potential [30,31]. In addition, the vast expanses of desert land provide ample and available physical space [32,33].

Figure 1 shows the evolution of the implementation of renewable energy (hydroelectric, onshore wind, and solar photovoltaic) in the last decade within the South American region, highlighting the growth rate of these technologies in the study area.



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Solar PV Energy South America	163	409	842	1468	3647	5586	8507	13346	21075	34510	49202
On-Shore Wind Energy South America	2787	6523	9726	12729	15705	19118	20671	24203	30733	33574	39298
Hydro Energy South America	143543	148243	152295	162648	166388	171567	176495	177036	177205	178741	179685

Figure 1. Comparative evolution between solar PV energy, wind energy, and hydroelectric energy implementation in South America.

The graph above shows that among the renewable energies implemented in South America in the last 10 years, hydroelectric energy is the one that has the advantage, increasing its installed capacity from 143,543 MW in 2013 to 179,685 MW in 2023. This is followed by photovoltaic solar energy, which, in the last 10 years, has had a strong increase in the region, having 163 MW of installed capacity in 2013 and reaching 49,202 MW of installed capacity by 2023. In the case of onshore wind energy, its installed capacity has increased in recent years from 2787 MW in 2013 to 39,298 MW in 2023.

It is possible to see in the graphs above that the growth rate of hydroelectric energy has decreased and stabilized in recent years since 2019 when the global COVID-19 pandemic occurred. The opposite happens with onshore wind energy and solar photovoltaic energy, where both show a high growth rate. In the case of onshore wind energy, stronger implementation began in the first years compared to solar photovoltaic energy, but this has been reversed in recent years starting in 2021, where currently solar photovoltaic energy has a more massive implementation than onshore wind energy.

In this sense, solar energy can be transformed directly into electrical energy through photovoltaic systems, and indirectly through concentrated solar power, and can be used to heat water or salts through solar collectors [34]. One of the characteristics of solar energy is that its technologies are scalable and modular (see Figure 2), meaning they can be used both in large industrial installations and in small systems for domestic use [35].

Figure 2. Implementation of renewable solar PV energy in the Atacama Desert, Chile, South America.

1.2. Scope of the Article

This systematic review studies the progress in solar energy facility implementation in South America, considering different countries in this region, highlighting the state of solar energy generation on a large scale through a review of the scientific publications available on Scopus.

In this systematic review, the following research questions (RQs) are defined:

- RQ1: What are the main clusters of solar energy concepts applied to implement this infrastructure in South America and how do they evolve?
- RQ2: What is the solar energy installed capacity (MW), solar average theoretical potential considering global horizontal irradiance (GHI) (kWh/m^2), and solar average practical potential (kWh/kW) in each country of South America?
- RQ3: What is the annual energy production (GWh) from solar energy infrastructures and what is the related reduction rate of greenhouse gases (GHGs) in each country of South America?
- RQ4: Which South American countries have more advances in solar energy considering the quantity of solar energy infrastructures under operation?
- RQ5: What are the main policies related to climate change mitigation considering the implementation of solar energy in South America?
- RQ6: What are the main cutting-edge technologies linked with solar energy infrastructures in South America?
- RQ7: What are the main challenges facing the implementation of solar energy in South America?
- RQ8: What are the main types of energy storage systems used in solar energy production in South America?

This study provides a general overview of the advancements and shortcomings of solar energy across the entire South American territory, focusing on gathering pertinent information to illustrate how these energy solutions have been implemented or progressed in the vast territorial and social diversity that characterizes South America. The aim is to conduct an analysis that integrates all the identified features, revealing the overall progress in the implementation of solar energy, not just in a specific area, whether social, geographical, technological, etc. The study also highlights the progression over time, based on the analyzed documentation, with particular attention to the evolution of the technologies used, the territorial expansion of solar energy implementation, the increase in energy currently supplied to the grid, and its impact on the population.

Finally, to communicate the main ideas of this article adequately, the following content structure was defined: Section 1: Introduction; Section 2: Resources and Methodology; Section 3: Results; Section 4: Discussion of Results; and Section 5: Conclusions.

2. Methodology Applied

2.1. Resources

2.1.1. Publications from Scopus

The Scopus database was considered to carry out this systematic review because it contains scientific journals related to solar renewable energy, all of which were published in English from 1989 to 2024.

2.1.2. Use of Software

For systematizing and processing the data, MS Excel version 21 was used, and for interpreting the information, VOSviewer 1.6.20 was used.

2.2. Method Applied

2.2.1. Bibliometric Analysis and Systematic Content Review

The methodological tool applied in this publication considered the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [36] and the creation of scientific graphs using the VOSviewer software [37].

Using the PRISMA tool, a methodological procedure shows the elimination steps: "identification, screening, eligibility, and final inclusion" (Figure 3).

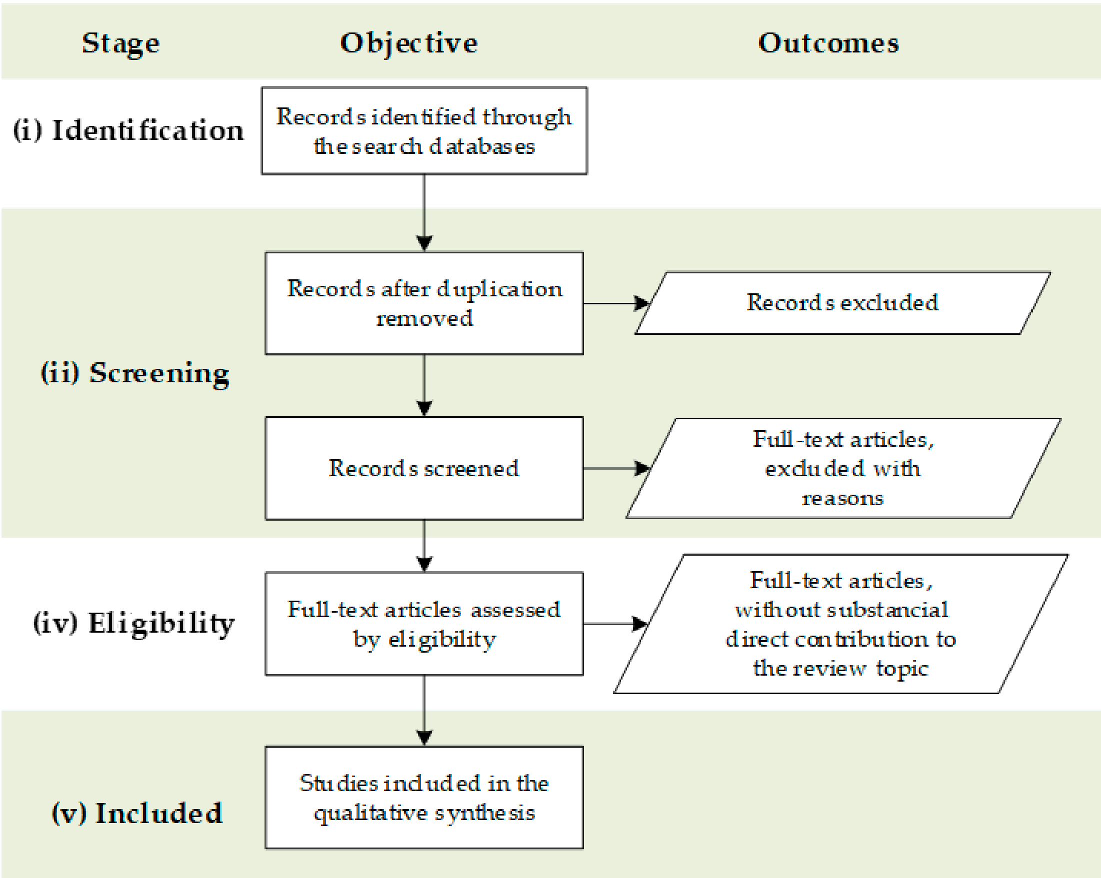


Figure 3. Methodological procedure applied.

The PRISMA statement is a methodological procedure that researchers can consider when reporting systematic reviews and meta-analyses [38]. The PRISMA guidelines provide recommendations that help address the interpretation of research by assisting systematic reviewers to inform the review; in this sense, a 4-phase methodological procedure was implemented: (i) Phase 1: quantitative method for a bibliometric analysis; (ii) Phase 2: qualitative method for a systematic review of the literature; (iii) Phase 3: integration method for a mixed review; and (iv) Phase 4: generation of scientific maps using the VOSviewer software (see Figure 4). In this study, the 8 research questions mentioned above are considered.

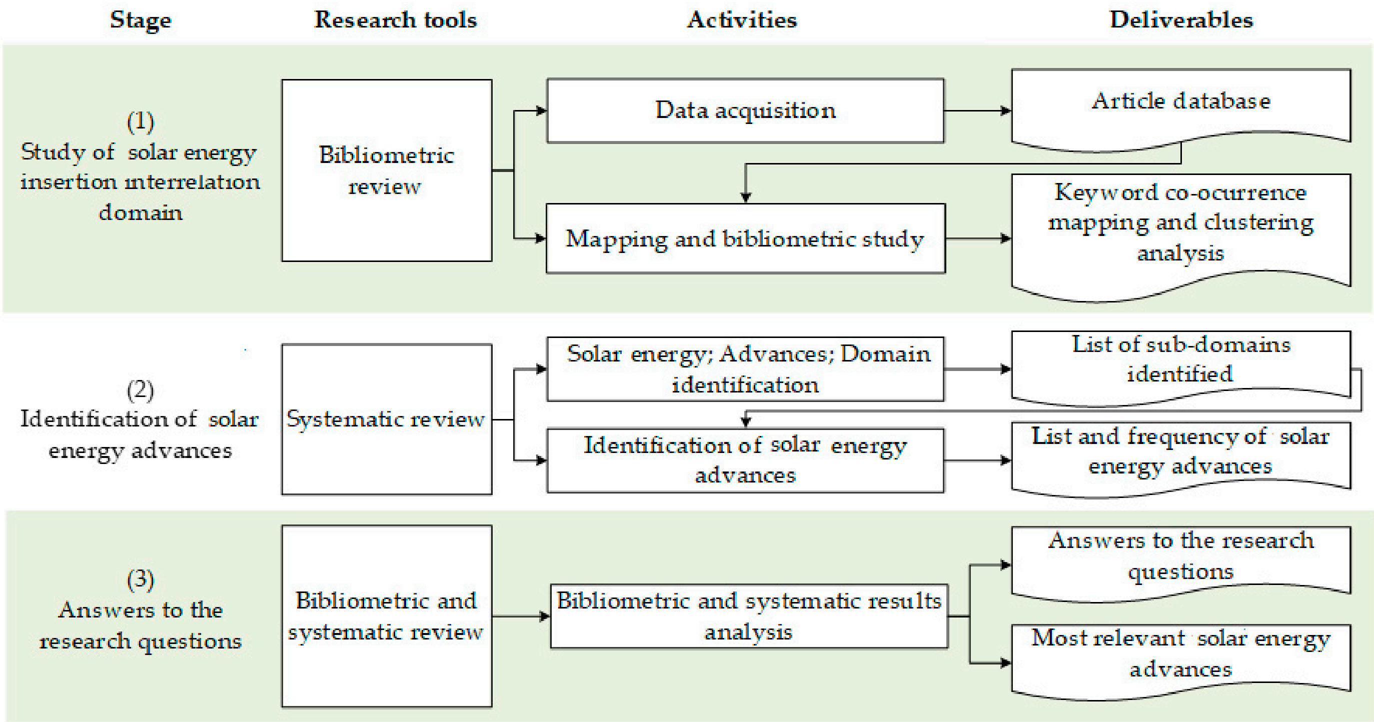


Figure 4. Summary of the methodology implemented in this systematic review.

Figure 4 shows a summary of the methodological procedure applied in this systematic review.

2.2.2. Analysis of Publications Selected

A definition of keywords was carried out within the topic to be analyzed. The relevant words selected for this research were (i) solar, (ii) energy, (iii) Argentina, (iv) Bolivia, (v) Brazil, (vi) Chile, (vii) Colombia, (viii) Ecuador, (ix) Paraguay, (x) Peru, (xi) Uruguay, (xii) Venezuela, 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.

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

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

Table 2. Data extraction form implemented in this research.

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?	author 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 solar energy concepts applied to implement this infrastructure in South America and how do they evolve?	e.g., solar PV energy, and solar CSP energy, among others
DEC9	Content-based perspective	Solar Energy Potential and Installed Capacity	RQ2: What is the solar energy installed capacity (MW), solar average theoretical potential considering global horizontal irradiance (GHI) (kWh/m^2), and solar average practical potential (kWh/kW) in each country of South America?	e.g., 5000 MW installed capacity and 4.654 solar average practical potential (kWh/kW), among others
DEC10	Content-based perspective	Solar Annual Energy Production and Reduction Rate of GHGs	RQ3: What is the annual energy production (GWh) from solar energy infrastructures and what is the related reduction rate of greenhouse gases (GHGs) in each country of South America?	e.g., 20,000 MWh, 1.2 Mt eq CO_2, among others
DEC11	Content-based perspective	Quantity of Solar Farm Facilities	RQ4: Which South American countries have more advances in solar energy considering the quantity of solar energy infrastructures under operation?	e.g., 12, 22, 90, among others
DEC12	Content-based perspective	Climate Change Mitigation Progress	RQ5: What are the main policies related to climate change mitigation considering the implementation of solar energy in South America?	e.g., rural electrification and clean energy for remote places, among others

Table 2. *Cont.*

Id.	Criteria	Field	Question	Data
DEC13	Content-based perspective	Cutting-Edge technologies	RQ6: What are the main cutting-edge technologies linked with solar energy infrastructures in South America?	e.g., bifacial panel utilization, battery energy storage system (BESS) application, and floating solar PV farms, among others
DEC14	Content-based perspective	Challenges	RQ7: What are the main challenges facing the implementation of solar energy in South America?	e.g., economic and political, intermittent power supply, and sustainable and resilient infrastructures, among others
DEC15	Content-based perspective	Energy Storage Systems	RQ8: What are the main types of energy storage systems used in solar energy production in South America?	e.g., lithium BESS, hydrogen, and hydraulic storage, among others

3. Results and Findings

3.1. Analysis of Publication Screening

An analysis was developed in phases considering exclusion criteria (ECs) to select scientific publications. Figure 5 shows the steps applied together with the results.

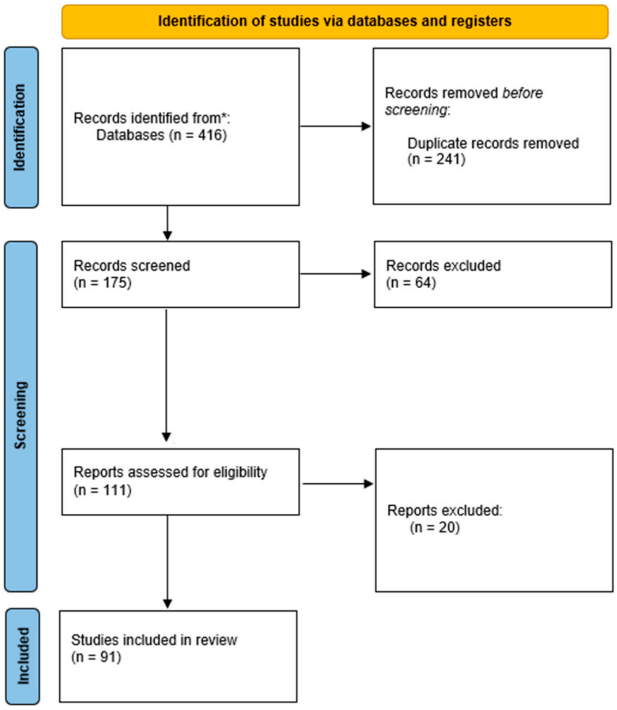


Figure 5. PRISMA flow diagram of the procedure for article screening and selection. * Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).

Figure 5 presents the extraction of documents from the Scopus database considering the combinations of relevant concepts mentioned above, where 416 publications were obtained. Exclusion criterion 1 (EC1) was used to eliminate these documents according to an analysis of the title of the articles, leaving 346 documents. Then, exclusion criterion 2 (EC2) was used, reading the abstract of the documents to study which ones were related to solar energy implementation in South America, giving a result of 111 documents. Finally, exclusion criterion 3 (EC3) was considered, eliminating articles without a substantial direct contribution to the systematic review, leaving 91 documents. These 91 selected publications deal specifically with advances in the implementation of solar energy in South America, which will be subject to a specific study described in the following pages of this research.

3.2. Results and Findings Using Bibliometric Analysis

The following paragraphs present the response to the following research question RQ1, "What are the main clusters of solar energy concepts applied for implementation of this technology in South America and how do they evolve?".

3.2.1. Articles Published per Year

Articles published per year related to solar energy in South America are presented in Figure 6 according to the 91 articles selected.

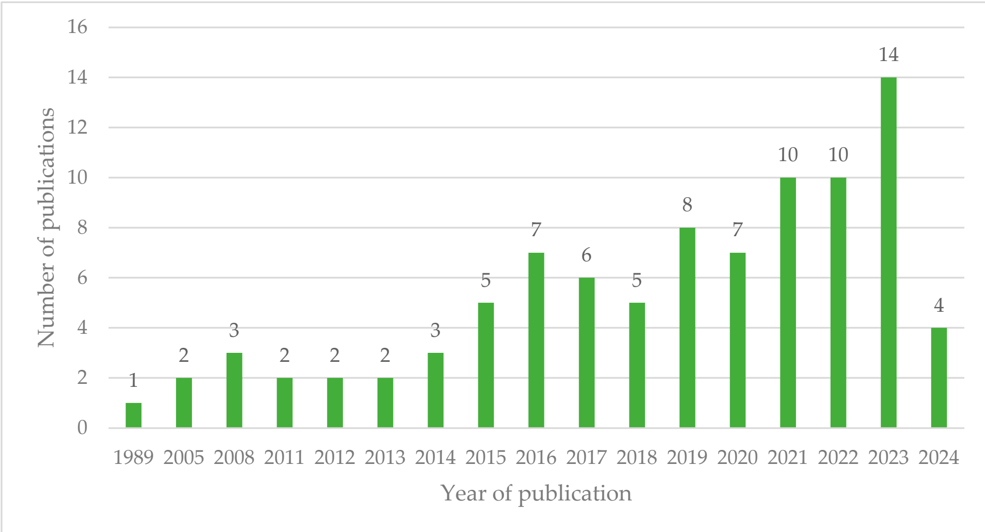


Figure 6. Findings considering 91 articles selected from 1989 to 2024.

Figure 6 shows that the year with the most articles was 2023, 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 has increased. It should be considered that the sample was taken in July 2024; therefore, said year does not include all the articles generated.

3.2.2. Production of Selected Articles from Different Countries

The production of 91 selected articles from different countries is shown in Figure 7.

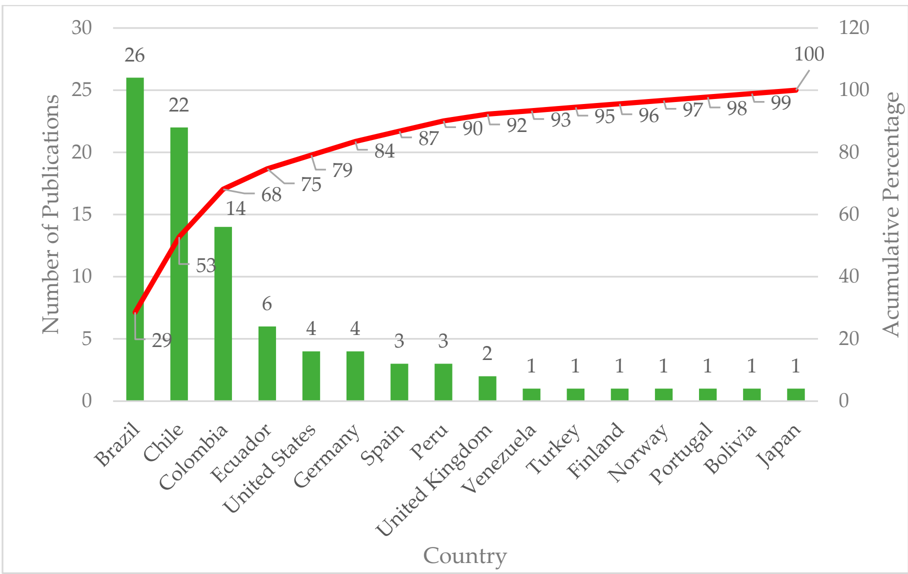


Figure 7. Production of 91 selected articles from different countries.

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 the nation is mainly localized in Brazil, Chile, Colombia, and Ecuador, which represent approximately 75% of the 91 publications, while the United States, Germany, Spain, Peru, and the United Kingdom also stand out in the percentage of publications. Finally, Venezuela, Turkey, Finland, Norway, Portugal, Bolivia, and Japan have a minor percentage of publications.

3.2.3. Production of Citations of Selected Articles from Different Nations

Figure 8 shows the findings considering the production of citations for 91 selected articles by nation.

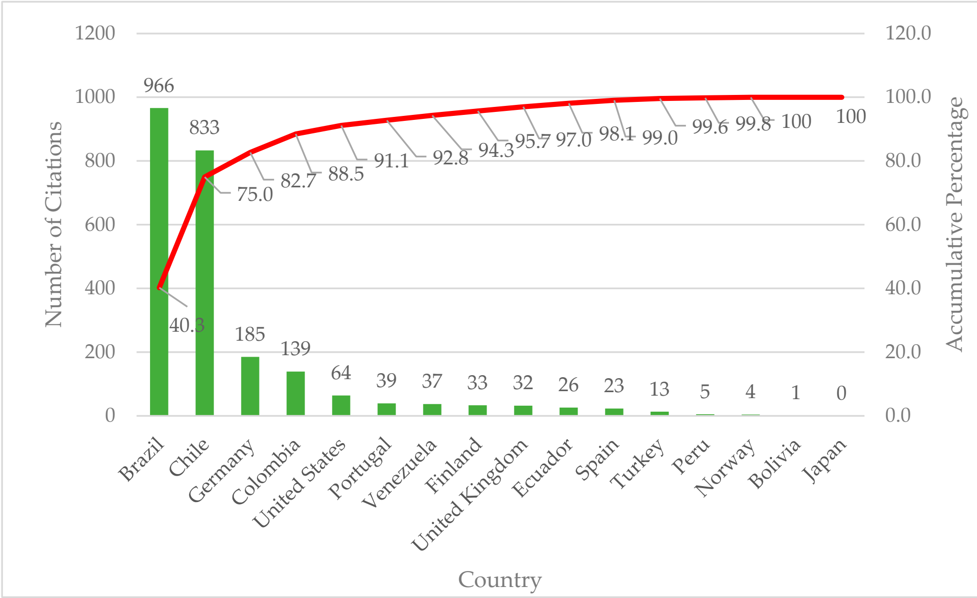


Figure 8. Production of citations of 91 selected articles by nation.

Figure 8 presents the number of citations by nation, where Brazil stands out with approximately 40% of the total citations, followed by Chile with 35% of the citations. The nations with 88% of the accumulated citations are Brazil, Chile, Germany, and Colombia. The graph in Figure 8 shows that some countries in South America such as Brazil, Chile, Colombia, Venezuela, and Ecuador, as well as the United States, are the ones that cite the 91 selected articles the most. There are some European countries with a significant number of citations; they are Germany, Portugal, Finland, and the UK. Then, to a lesser extent, other South American countries such as Bolivia, and Peru, as well as some European countries such as Spain, Turkey, and Norway, as well as Japan, also cite the 91 selected articles.

3.2.4. Document Classification Considering 91 Publications Selected

The document classification (review or article) considering the 91 publications selected is shown in Figure 9.

The pie chart shown in Figure 9 indicates the types of publications found in the Scopus database, of which articles predominate with 83, followed by reviews with 8.

3.2.5. Findings Considering Keyword Co-Occurrence Study

Considering the 91 selected articles, these were analyzed in VOSviewer software to generate a co-occurrence map without considering the time dimension. A criterion was defined considering the minimum occurrence value of two keywords, which means that a keyword appears on the map when two scientific publications cite it [39]. A map comprising seven clusters (represented in blue, yellow, green, red, orange, purple, and sky blue) is shown in Figure 10.

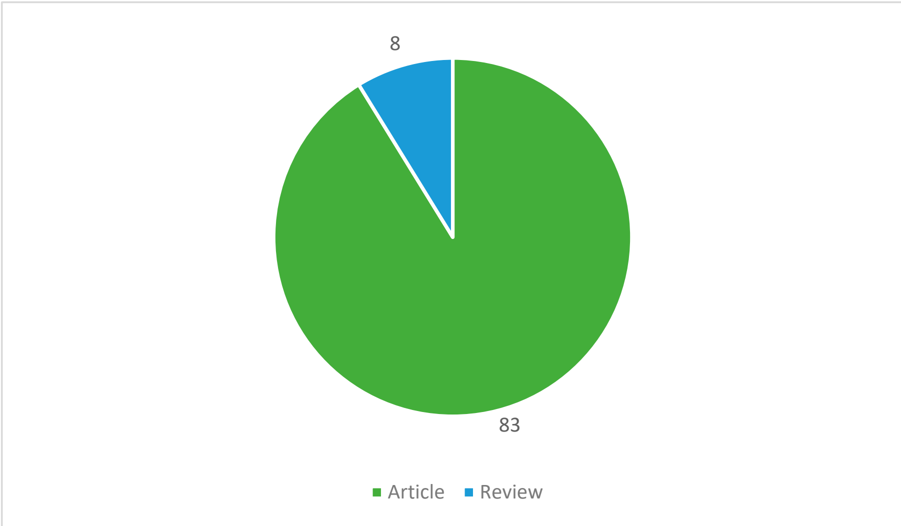


Figure 9. Document classification by type of the 91 scientific publications selected.

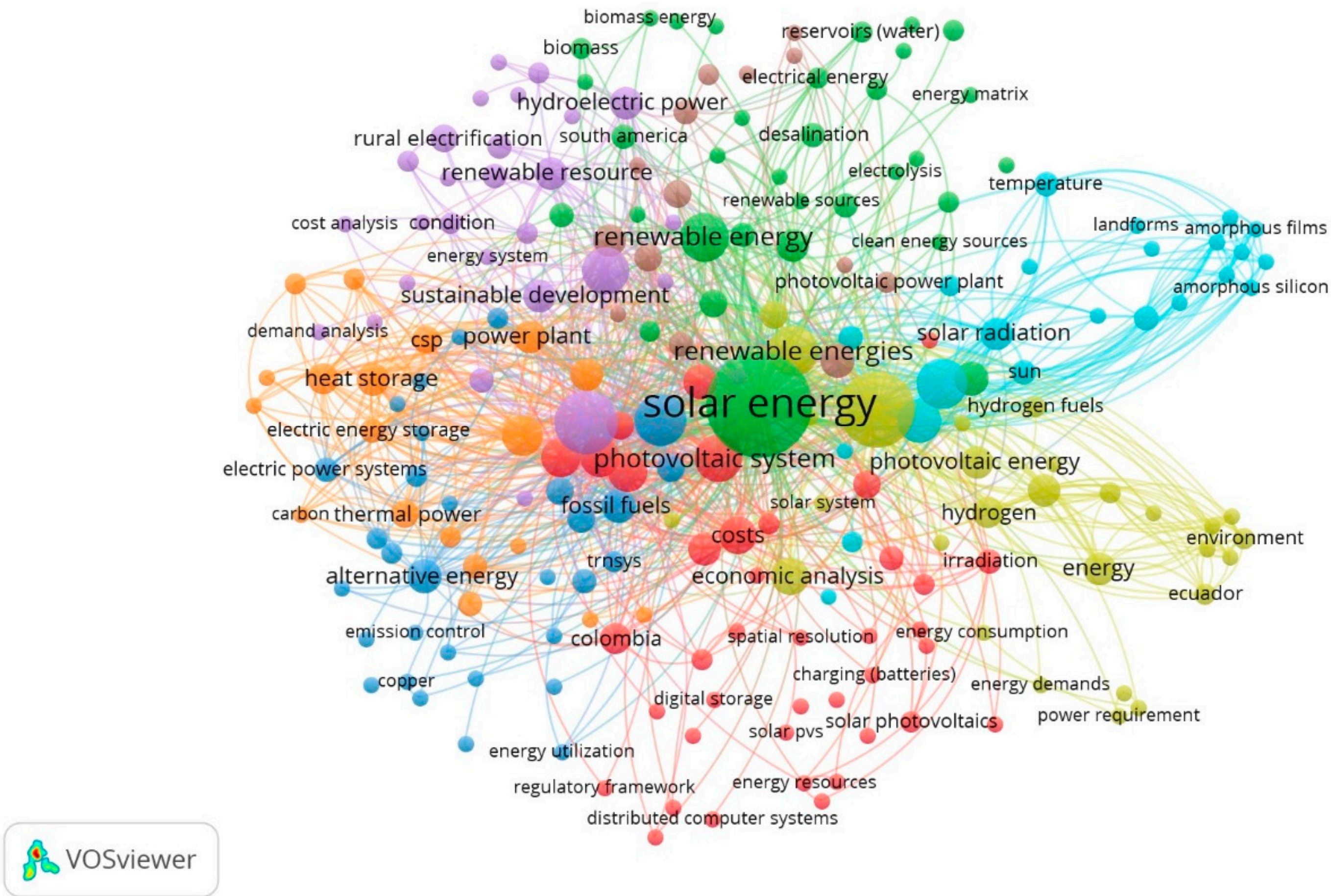


Figure 10. Findings of keyword co-occurrence study using VOSviewer without time dimension.

Considering the co-occurrence map presented in Figure 10, seven clusters were produced, which are shown in different colors. Within the keywords, the ones that stand out the most are renewable energy, solar energy, and photovoltaic systems. 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.

Table 3. VOSviewer clusters without time dimension.

Cluster Name	Keywords	Cluster Definition
Cluster "Yellow"	Hydrogen fuels, hydrogen, PV energy, environment	Green hydrogen production
Cluster "Blue"	Fossil fuels, emission control, electric power systems	Decarbonatization
Cluster "Red"	PV systems, digital storage, distributed computer system	Energy digitalization
Cluster "Green"	Solar energy, renewable energy, energy matrix, South America	Renewable energy
Cluster "Orange"	CSP, heat storage, electric energy storage	Energy storage
Cluster "Purple"	Sustainable development, hydroelectric power, energy system	Hybridization
Cluster "Sky Blue"	Solar radiation, amorphous silicon, amorphous films	New PV cells

According to the cluster interpretation of Table 3, it is possible to find that the implementation of solar energy has a strong application trend in sustainable sources of energy.

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 publications were published, as shown in Figure 11.

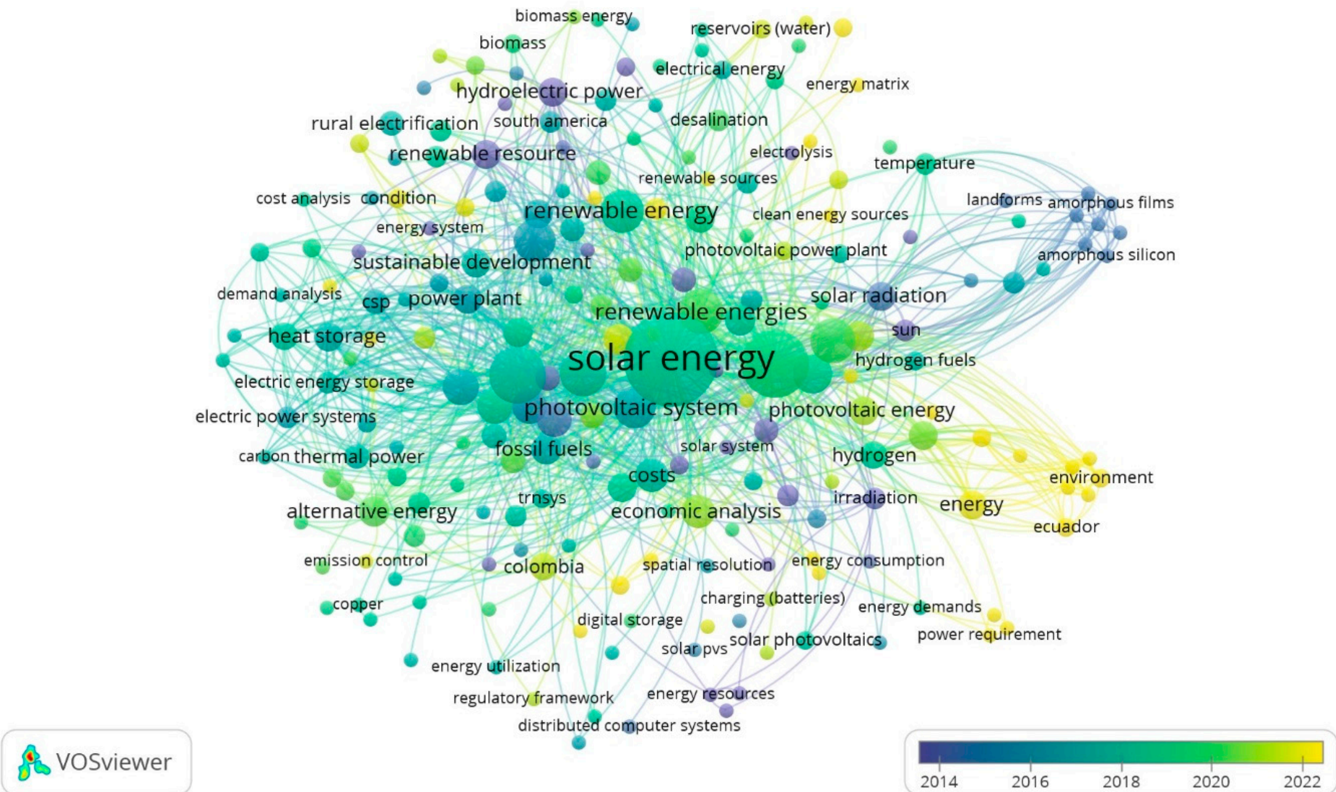


Figure 11. Findings of keyword co-occurrence study using VOSviewer with time dimension.

According to the co-occurrence map presented in Figure 11, it is possible to observe the time dimension in which these concepts were generated, with the most recent being solar energy, environment, and water reservoirs, while the oldest are PV system, solar radiation, and amorphous silicon, 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.

Cluster Name	Keywords	Period of Publication	Cluster Definition
Cluster "Blue"	PV system, solar radiation, amorphous silicon	2014–2016	New PV cells
Cluster "Green"	Solar energy, renewable energy, heat storage	2016–2020	Solar energy storage
Cluster "Yellow"	Solar energy, environment, water reservoirs	2020–2022	Green hydrogen production

According to the cluster analysis of Table 4, it is observed that the evolution over time of the implementation of solar energy in South America tends to start with aspects of the study of new PV cells, then evolves into the analysis of solar energy storage technology, and finally develops into green hydrogen production.

3.3. Systematic Content Review Findings

3.3.1. Content Analysis

Content analysis is presented in this chapter of the systematic review, showing the answers to the research questions considering the 91 selected articles.

Considering RQ2, "What is the solar energy installed capacity (MW), solar average theoretical potential considering global horizontal irradiance (GHI) (kWh/m^2), and solar average practical potential (kWh/kW) in each country of South America?", the following answer is presented in Table 5, a compilation based on the following sources of information.

Table 5. A summary of the solar energy installed capacity (MW), solar average theoretical potential considering global horizontal irradiance (GHI) (kWh/m^2), and solar average practical potential (kWh/kW) in each country of South America according to the data from the year 2023.

Country	Installed Capacity (MW)	Average Theoretical Potential (GHI) (kWh/m^2)	Average Practical Potential (kWh/kW)
Argentina	1408	5.124	4.599
Bolivia	172	5.424	4.942
Brazil	37,449	5.276	4.404
Chile	8790	5.758	5.365
Colombia	716	4.867	4.049
Ecuador	31	4.305	3.402
Paraguay	1	5.077	4.281
Peru	398	5.146	4.901
Uruguay	297	4.790	4.304
Venezuela	5	5.350	4.355
South America	**49,267**	**5.112**	**4.460**
Mexico	10,893	5.728	4.924
USA	137,725	4.498	4.358
China	609,350	4.127	3.883

According to Table 5, the following findings are presented: (i) the South American region had an installed capacity of solar PV energy equivalent to 49,267 MW; (ii) if comparing the installed capacity of the South American region with large economies such as Mexico, USA, and China, the insertion of solar PV energy has not been as rapid; (iii) the countries with the lowest installed capacity of solar PV energy are Paraguay, Venezuela, and Ecuador; (iv) the countries with the greatest installed capacity of solar PV energy are Brazil, Chile, Argentina, and Colombia; and finally (v), the installed capacity of the usable solar potential changes from 1 MW in the case of Paraguay to 37,449 MW in the case of Brazil.

Figure 12 is shown below, which illustrates a map of the average simulated solar PV capacity factors in Latin America.

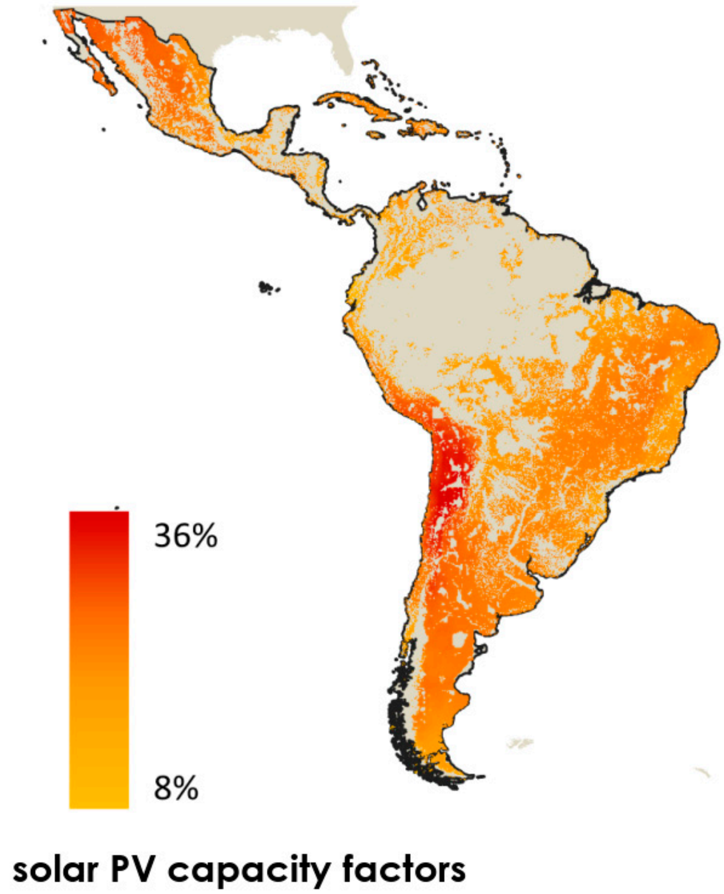


Figure 12. Mapping of average simulated solar PV capacity factors in Latin America. Adapted from [13].

Figure 12 shows that the highest capacity factors are in the area of the Atacama Desert. In this case, solar PV capacity factors were calculated assuming utility-scale solar PV plants with polycrystalline silicon modules (the best available technology (BAT) in 2023), single-axis tracking, and site-adapted tilt angle.

A map of solar PV facilities in Latin America specifying the installed capacity for each country is shown in Figure 13.

According to Figure 13, Chile stands out in the region with an installed capacity of over 6 GW. In second place is Brazil with an installed capacity in the range of 4–6 GW, and finally, the rest of the countries have installed capacities of less than 2 GW.

The following paragraphs present the response to the following research question RQ3, "What is the annual energy production (GWh) from solar energy infrastructures and what is the related reduction rate of greenhouse gases (GHGs) in each country of South America?"

Figure 13. Mapping of solar PV facilities in Latin America specifying the installed capacity for each country. Adapted from [14].

According to Table 6, the following findings are presented: (i) Brazil is the country that generates the most electrical energy based on solar energy with 10,759 GWh. Then, there is Chile with 8141 GWh and Argentina with 1346 GWh; (ii) South America generates annual electricity based on solar PV energy equivalent to 22,048 GWh, which corresponds to 19% of what the USA generates and 8% of what China generates; (iii) the generation of greenhouse gas emissions from solar PV farms indicated in millions of tons of CO_2 equivalent are lower for the South American countries in comparison with Mexico, USA, and China; and (iv) considering all the countries in the South American region, there is a contribution to the mitigation of climate change due to the annual reduction of 12.9 million tons of CO_2 equivalents.

Table 6. A summary of annual energy production (GWh) from solar infrastructures and the related reduction rate of greenhouse gases (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 solar PV energy	GWh	1346	10,759	250	8141	206	38	0.01	838	462	8	13,528	115,902	261,369
GHG emissions generated from solar PV energy	Mt CO_2eq	0.1	0.5	0	0.4	0	0	0	0	0	0	0.6	5.3	12
Avoided GHG emissions from solar PV energy	Mt CO_2eq	0.545	5.157	0.110	6.210	0.136	0.028	0	0.398	0.367	0.004	6.182	51.73	225

Considering RQ4, "Which South American countries have more advances of solar energy considering the quantity of solar energy infrastructures under operation?", the following answer is presented according to Table 7 and Figure 14.

Table 7. A summary of the total installed capacity (MW), the number of solar PV farms, and the average installed capacity per solar PV farm (MW) in each country of South America in the year 2023.

Country	Total Installed Capacity (MW)	Number of Solar PV Farms	Average Installed Capacity per Solar PV Farm (MW)
Argentina	1408	39	36
Bolivia	172	8	22
Brazil	37,449	218	172
Chile	8790	335	26
Colombia	716	30	24
Ecuador	31	3	10
Paraguay	1	1	1
Peru	398	9	44
Uruguay	297	15	20
Venezuela	5	5	1
South America	**49,267**	**663**	**74**

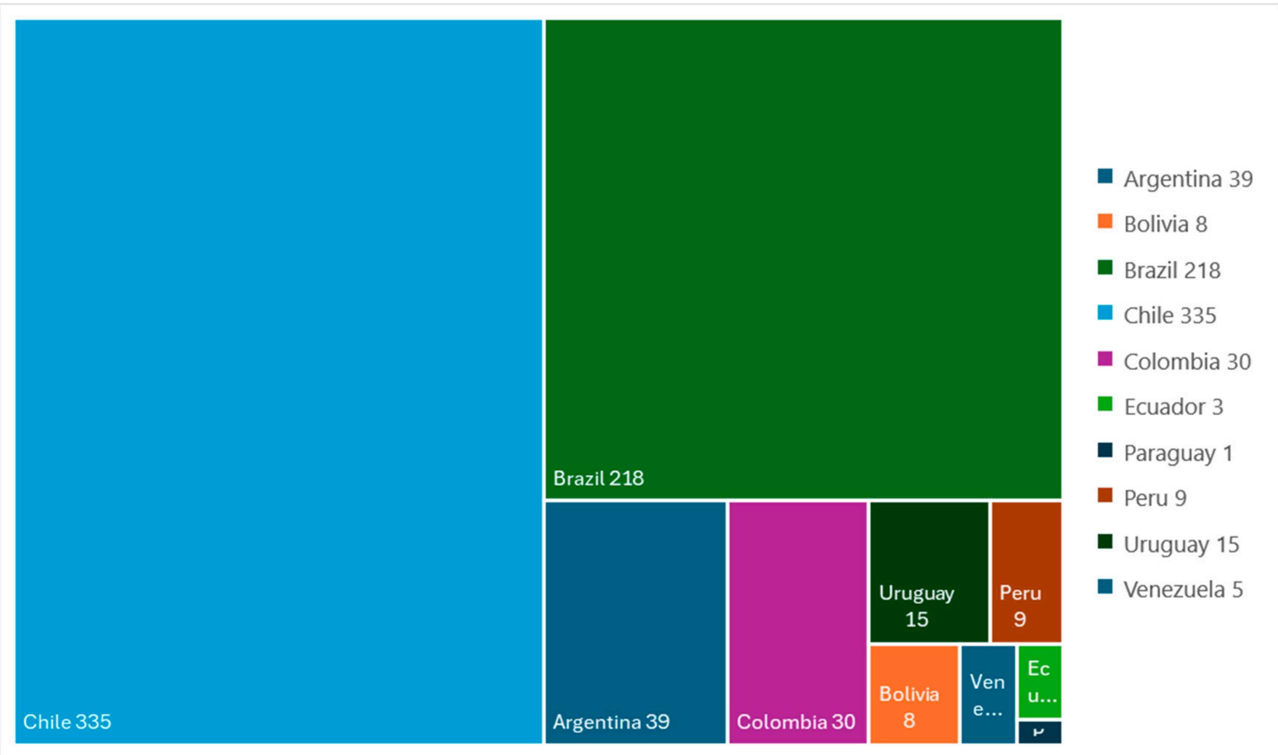


Figure 14. Spatial distribution of the number of solar PV farms under operation in the countries of South America in the year 2023.

According to Table 7, the following findings are presented: (i) Brazil, Chile, Argentina, and Colombia have the highest number of solar PV farms; (ii) the country that has the most solar PV farms in operation is Chile with 335, followed by Brazil with 218, Argentina with 39, and then Colombia with 30; and finally (iii), considering the year 2023, the South American region has 663 solar PV farms.

The distribution of the number of solar PV farms in the South American region can be seen in Figure 14.

Figure 14 shows the spatial distribution of the number of solar PV farms in operation in each of the South American region's countries. Chile (335), Brazil (218), Argentina (39), and Colombia (30) stand out in first place. Chile has more solar PV farms than Brazil because this country has a greater number of small-scale solar PV farms.

The following paragraphs present the response to the following research question RQ5, "What are the main policies related to climate change mitigation considering the implementation of solar energy in South America?"

According to Figure 15, it is shown that the main policy related to climate change mitigation considering the implementation of solar energy in South America is the reduction in fossil fuel energy facilities (RFFEF) with 22% of the 91 publications. In second place, implementation in residential facilities appears in 21% of the 91 publications. Likewise, when reviewing the scientific literature, in 18% of the 91 publications, four categories exist such as clean energy for remote places (CERP), rural electrification (RE), and implementation in industries (II). Finally, with fewer repetitions, the following topics are mentioned in the publications: not specified (N/S) with 2%.

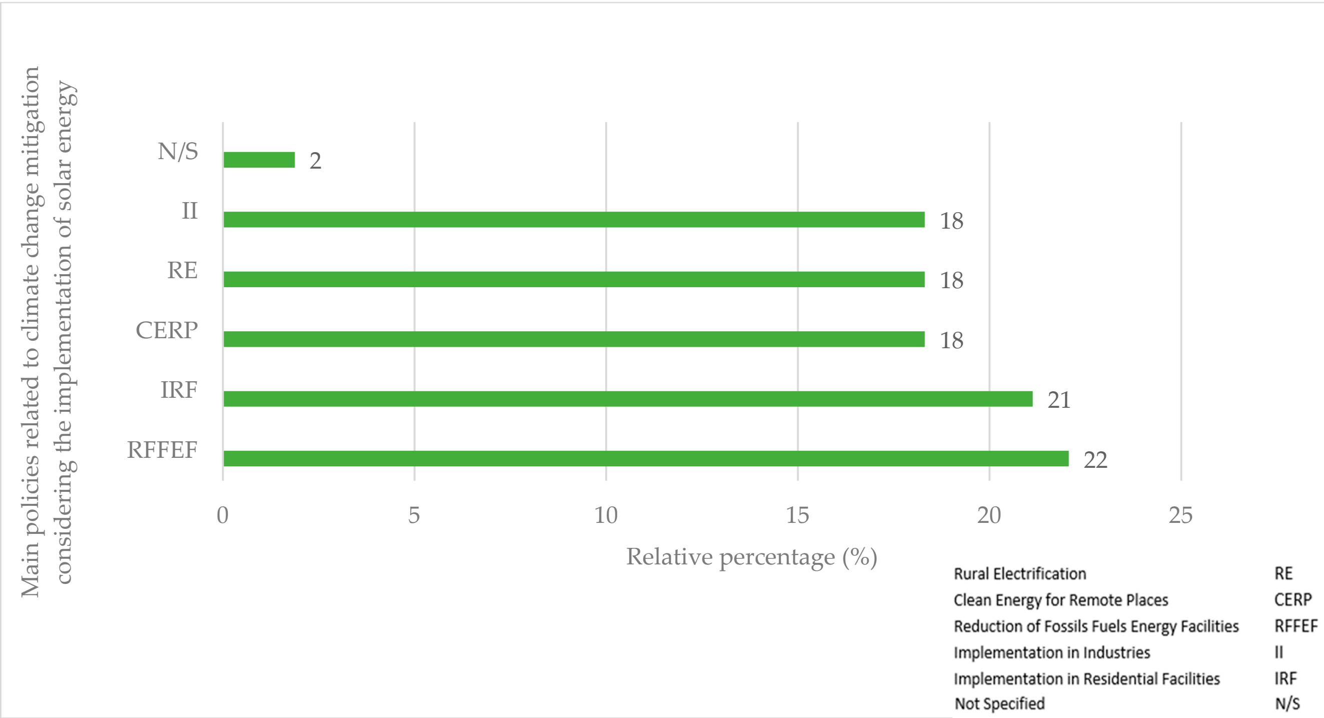


Figure 15. Main policies related to climate change mitigation considering the implementation of solar energy in South America.

The following paragraphs present the response to the following research question RQ6, "What are the main cutting-edge technologies linked with solar energy infrastructures in South America?"

According to Figure 16, it is shown that the main cutting-edge technologies linked with solar energy infrastructures in South America fall under not specified (N/S) information in 35% of the 91 publications. Next, in second place appears to be hybridization with onshore wind energy and floating PV farms (HWEFPV) with 29% of the 91 publications.

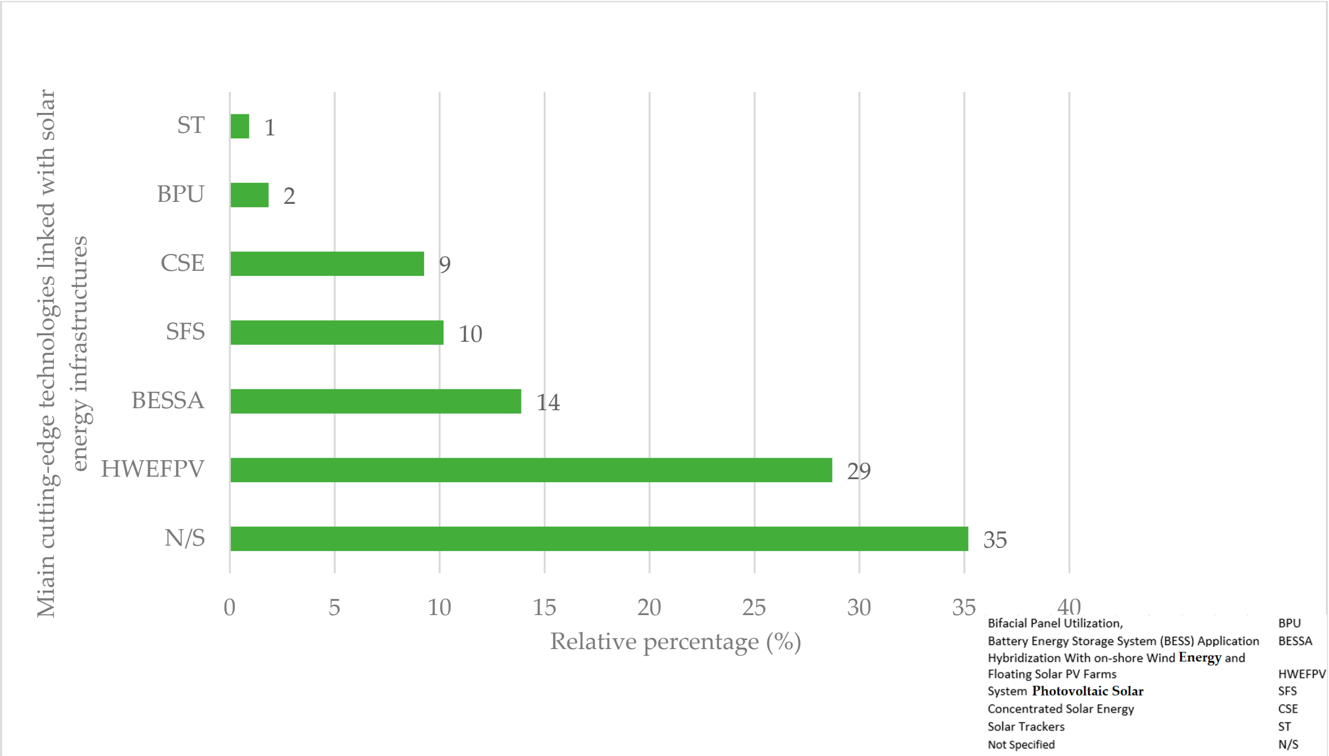


Figure 16. Main cutting-edge technologies linked with solar energy infrastructures in South America.

In the middle part of the graph, it is possible to find three categories: battery energy storage system applications (BESSAs) with 14% of repetitions, system photovoltaic solar (SFS) with 10% of repetitions, and concentrated solar energy (CSE) with 9% of repetitions.

Finally, with fewer repetitions, the following topics are mentioned in the publications: the bifacial panel utilization (BPU) with 2% of repetitions and solar trackers (STs) with 1% of repetitions.

The following paragraphs present the response to the following research question RQ7, "What are the main challenges facing the implementation of solar energy in South America?".

According to Figure 17, it is shown that the main challenges facing the implementation of solar energy in South America are economic and political (EP) topics with 29% of repetitions. Then, with 26% of repetitions, we have the intermittent power supply (IPS). Furthermore, with 19% of repetitions, there is a sustainable and resilient infrastructure (SRI). Next, with 12% of repetitions is the training of human and technological resources (THTR). Finally, with 7% of repetitions, the following topics are mentioned in the publications: awareness and environmental education (AEE), and not specified (N/S).

The following paragraphs present the response to the following research question RQ8, "What are the main types of energy storage systems used in solar energy production in South America?"

According to Figure 18, it is shown that with 23% of repetitions, no types of energy storage systems are specified for use in solar energy production in South America. Then, with 22% of repetitions, we have the lithium-ion batteries (LIBs). In addition, with 20% of repetitions, there is the technology of lead-acid batteries (LABs). Next, with 18% of repetitions is the technology of thermal storage (TS). Next, with 8% of repetitions is the technology of hydraulic storage (HS). Next, with 7% of repetitions is the technology of hydrogen (H). Finally, with fewer repetitions, the following topics are mentioned in the publications: flywheel technology (F) and compressed air storage (CAS).

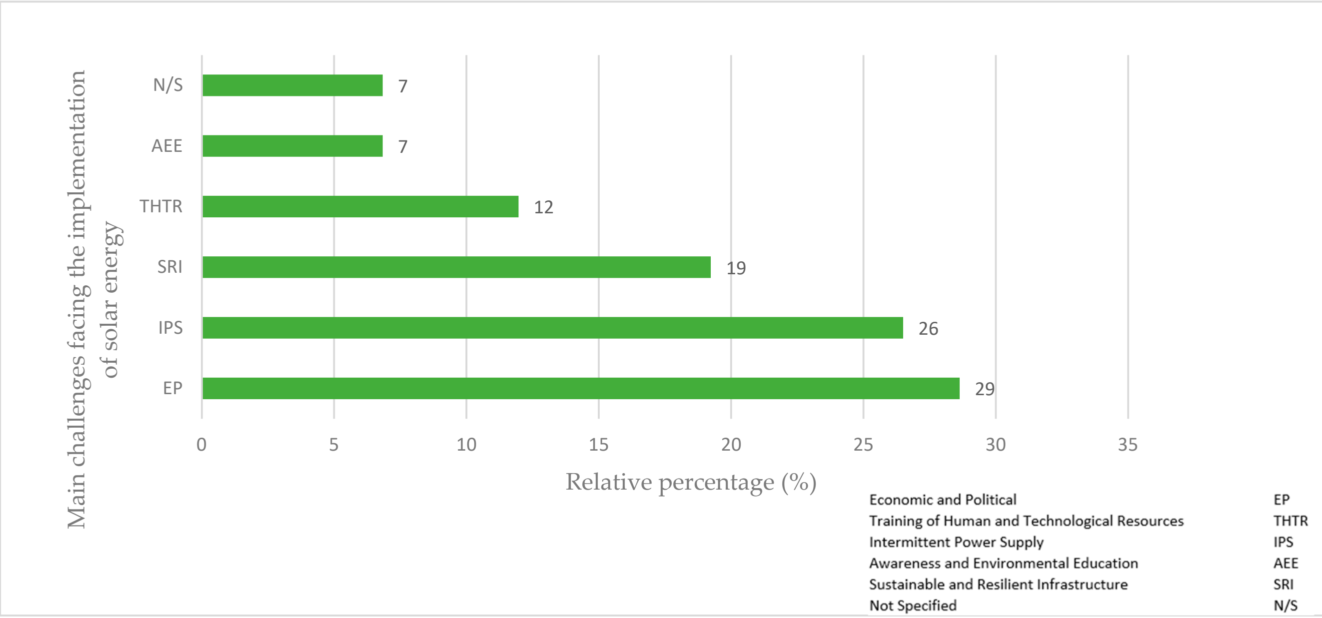


Figure 17. Main challenges facing the implementation of solar energy in South America.

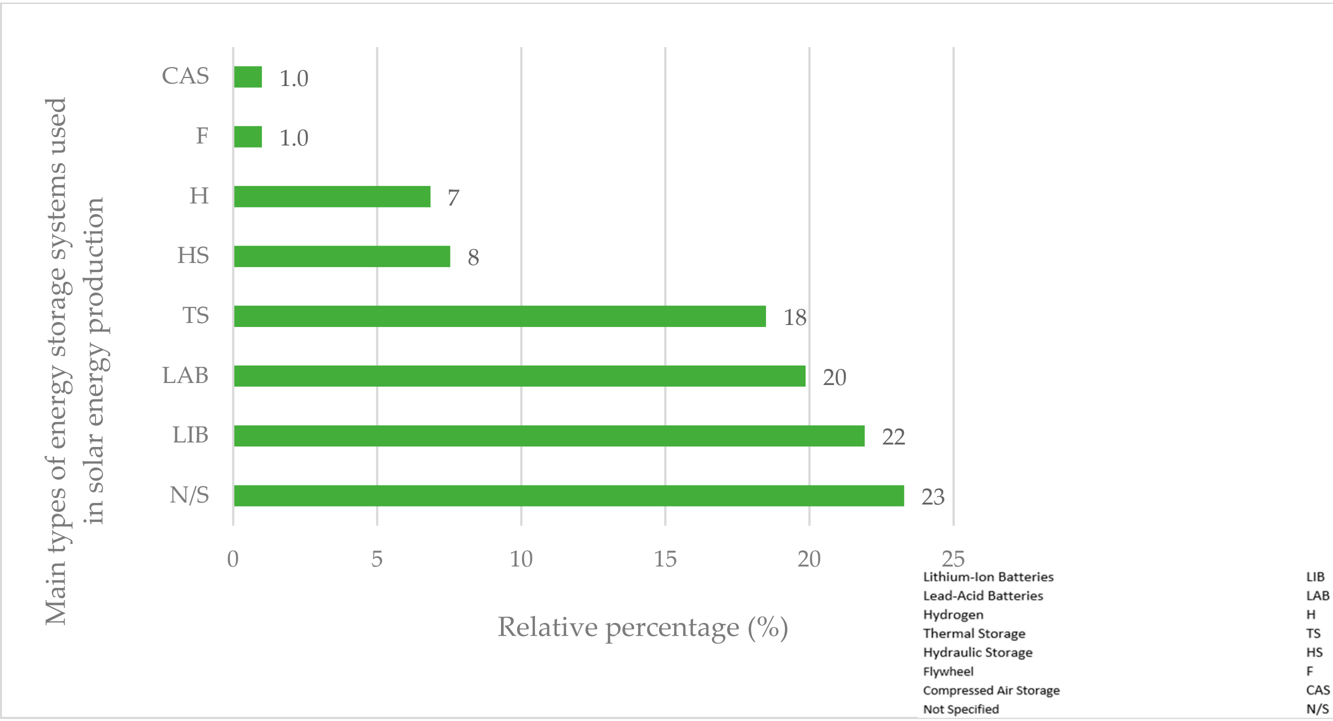


Figure 18. Main types of energy storage systems used in solar energy production in South America.

3.3.2. Comparative Analysis of the Publications Selected

A comparative analysis is carried out considering the selected articles linked with solar energy, which is summarized in Table 8. This table includes (i) main policies related to climate change mitigation, (ii) main cutting-edge technologies, (iii) main challenges, and (iv) main types of energy storage systems.

Table 8. Comparison of the main characteristics of the articles selected dealing with the insertion of solar energy in South America. The following abbreviations are considered for (i) main policies related to climate change mitigation considering the implementation of solar energy in South America (rural electrification, RE; clean energy for remote places, CERP; reduction in fossil fuel energy facilities, RFFEF; implementation in industries, II; implementation in residential facilities, IRF; not specified, N/S), (ii) main cutting-edge technologies linked with solar energy infrastructures applied in South America (bifacial panel utilization, BPU; battery energy storage system (BESS) application, BESSA; hybridization with onshore wind energy and PV, HWEFPV; system PV solar, SFS; concentrated solar energy, CSE; solar trackers, STs; not specified, N/S), (iii) main challenges facing the implementation of solar energy in South America (economic and political, EP; training of human and technological resources, THTR; intermittent power supply, IPS; awareness and environmental education, AEE; sustainable and resilient infrastructure, SRI; not specified, N/S), and (iv) main types of energy storage systems used in solar energy production in South America (lithium-ion batteries, LIBs; lead-acid batteries, LABs; hydrogen, H; thermal storage, TS; hydraulic storage, HS; flywheel, F; compressed air storage, CAS; not specified, N/S).

#	Authors	Year	(i)	(ii)	(iii)	(iv)
1	Galván et al. [40]	2022	RE-CERP-RFFEF	BESSA-HWEFPV	EP-THTR-IPS-AEE-SRI	LIB-H-HS
2	Dei et al. [41]	2005	RE-CERP	BESSA-HWEFPV	N/E	HS
3	Buch and Filho [42]	2012	RE	SFS	EP-THTR-IPS-AEE-SRI	N/E
4	Silva et al. [43]	2023	RFFEF-IRF-II	HWEFPV	EP-THTR-IPS-SRI	LIB-TS-HS
5	De Sousa et al. [44]	2023	RFFEF-IRF	N/E	EP-THTR-IPS-AEE-SRI	LAB
6	David et al. [45]	2024	RE-FM-DPPM	BPU-BESSA-HWEFPV	EP-THTR-IPS-AEE-SRI	LIB-LAB
7	Matos et al. [46]	2022	RFFEF-IRF-II	CSE	EP-IPS	LIB-LAB-TS-HS
8	Barbosa de Melo et al. [47]	2022	IRF-II	BPU-ST	EP	LIB-LAB
9	Carpio [48]	2021	RFFEF-IRF	N/E	IPS-SRI	HS
10	Nadaleti et al. [49]	2022	II-IRF	SFS	SRI	H
11	de Souza et al. [50]	2022	RE-CERP-II-IRF	N/E	N/E	LIB
12	Torres et al. [51]	2021	RFFEF-II-IRF	SFS-CSE	EP-IPS-SRI	N/E
13	Martelli et al. [52]	2020	RFFEF-II-IRF	N/E	EP-IPS	LIB-LAB
14	Viviescas et al. [53]	2019	RFFEF-II-IRF	N/E	N/E	N/E
15	Sulaeman et al. [54]	2021	RFFEF-RE	HWEFPV	N/E	N/E
16	da Rocha Santos et al. [55]	2019	II-IRF	HWEFPV	EP-AEE	LIB-LAB
17	Vilaça Gomes et al. [56]	2018	II-IRF	N/E	EP-IPS-SRI	N/E
18	Urbanetz et al. [57]	2019	II-IRF	SFS	EP-THTR-IPS-AEE-SRI	LIB-TS
19	Soria et al. [58]	2016	RFFEF-II-IRF	BESSA-HWEFPV	EP-THTR-IPS-AEE-SRI	LIB-LAB-TS-HS
20	Fichter et al. [59]	2017	RFFEF-II-IRF	HWEFPV	EP-IPS-THTR	LIB-LAB-TS
21	Ferreira et al. [60]	2018	RE-CERP	CSE	EP-THTR-IPS-AEE-SRI	N/E
22	Malagueta et al. [61]	2014	RFFEF-II-IRF	CSE	EP-THTR-IPS-SRI	TS
23	Nogueira et al. [62]	2014	RE-CERP	HWEFPV	EP-IPS	LIB-LAB-HS
24	Jannuzzi and de Melo [63]	2013	RE-IRF	SFS	EP-SRI	N/E
25	Viana et al. [64]	2011	RE-CERP	CSE	IPS	LIB-LAB-TS
26	do Sacramento et al. [65]	2008	RFFEF-CERP	HWEFPV	N/E	H
27	Martins et al. (1) [66]	2008	RE-CERP	HWEFPV	EP-IPS-SRI	LIB-LAB-TS
28	Martins et al. (2) [67]	2008	RE-CERP	HWEFPV	EP-IPS-AEE	N/E
29	Dhere [68]	1989	RE-CERP	N/E	EP-THTR-SRI	N/E
30	Da Silva et al. [69]	2005	RE-CERP	HWEFPV	N/E	H-HS
31	Quiñones et al. [70]	2020	RFFEF-II	HWEFPV	EP-THTR-IPS-AEE-SRI	N/E
32	Maximov et al. [71]	2021	RFFEF-IRF	N/E	EP-IPS-SRI	TS
33	Viole et al. [72]	2023	RE-CERP	BESSA-SFS	EP-IPS-SRI	LIB-H
34	Vargas Gil et al. [73]	2020	RFFEF-IRF	BESSA	EP-IPS-SRI	LIB-LAB
35	León et al. [74]	2023	CERP	N/E	N/E	N/E
36	Cornejo-Ponce et al. [75]	2022	RE-CERP	N/E	EP-IPS-AEE-SRI	LIB-LAB-TS

Table 8. *Cont.*

#	Authors	Year	(i)	(ii)	(iii)	(iv)
37	Behar et al. [76]	2021	II-RFFEF-CERP	SFS	EP-IPS-SRI	LIB-LAB-TS
38	Haas et al. [77]	2020	RFFEF-II-IRF	HWEFPV	EP-THTR-IPS-AEE-SRI	N/E
39	Bayo-Besteiro et al. [78]	2023	RFFEF-II-IRF	SFS-CSE	IPS	TS
40	Hernández et al. [79]	2020	RFFEF-II	CSE	EP-THTR-SRI	TS-LIB-LAB-H-F
41	Cardemil et al. [80]	2016	RFFEF-II	HWEFPV	N/E	N/E
42	Suuronen et al. [81]	2017	RE-RFFEF	N/E	EP-IPS-SRI	N/E
43	Starke et al. [82]	2016	RFFEF-II	HWEFPV	EP-IPS-SRI	TS
44	Mena et al. [83]	2019	CERP-RFFEF	CSE	EP-IPS-SRI	LIB-LAB-TS
45	Grágeda et al. [84]	2016	RFFEF-II-IRF	SFS	EP-SRI	N/E
46	Girard et al. [85]	2019	RFFEF-II-IRF	N/E	EP-IPS-SRI	N/E
47	Agostini et al. [86]	2016	RFFEF-CERP	N/E	EP-SRI	N/E
48	Moreno-Leiva et al. [87]	2017	II	SFS-CSE	N/E	TS
49	Vega and Zaror [88]	2018	II	SFS	EP-IPS-SRI	N/E
50	Valenzuela et al. [89]	2017	RFFEF-II	HWEFPV	IPS-SRI	LIB-LAB-TS
51	Ferrada et al. [90]	2015	II-IRF	N/E	N/E	LIB-LAB-H-TS-F
52	Jiménez-Estévez et al. [91]	2015	RFFEF-II-IRF	HWEFPV	EP-THTR-IPS-SRI	TS
53	Escobar et al. [92]	2015	RFFEF-II-IRF	N/E	EP-SRI	N/E
54	Cáceres et al. [93]	2013	RFFEF-II-IRF	CSE	EP-IPS-SRI	TS
55	Fuentealba et al. [94]	2015	II-IRF	N/E	AEE-SRI	LIB-LAB-TS
56	Marcher et al. [95]	2015	RFFEF-CERP	N/E	IPS	HS
57	Larraín and Escobar [96]	2012	IRF-II	N/E	EP-IPS-SRI	N/E
58	Parrado et al. [97]	2016	RE-CERP-IRF	HWEFPV	EP-IPS	LIB-LAB-TS
59	Betancur et al. [98]	2024	RE-RFFEF-IRF-II	HWEFPV	REP-THTR-IPS-AEE	TS
60	Villamizar et al. [99]	2023	RE-CERP	N/E	EP-THTR	N/E
61	López et al. [100]	2020	RE-CERP	BESSA-HWEFPV	EP-THTR-IPS	LIB
62	Abril et al. [101]	2021	RE-CERP-RFFEF	N/E	EP-THTR-IPS	LIB-LAB
63	Carvajal-Romo et al. [102]	2019	RE-CERP-IRF	BESSA-HWEFPV	EP-IPS-SRI	LAB-TS
64	Mulcué-Nieto et al. [103]	2020	RE-CERP-RFFEF	N/E	N/E	N/E
65	Aristizabal et al. [104]	2019	RFFEF-IRF	N/E	EP-IPS	N/E
66	Sandoval-Rodriguez et al. [105]	2023	N/E	N/E	N/E	N/E
67	Orjuela-Abril et al. [106]	2023	RE-CERP-II-IRF	N/E	N/E	H
68	Moreno et al. [107]	2022	RE-CERP-RFFEF	N/E	EP-THTR-IPS	N/E
69	Becerra-Fernandez et al. [108]	2023	RE-CERP-RFFEF	N/E	EP-THTR	LIB
70	Pedraza-Yepes et al. [109]	2023	CERP-RFFEF	BESSA	EP-THTR-IPS	LIB
71	Murillo et al. [110]	2023	RE-CERP-RFFEF	BESSA	EP-IPS	LAB
72	Rodríguez-Urrego et al. [111]	2018	RE-CERP	HWEFPV	EP-THTR-IPS	N/E
73	Ariza Taba et al. [112]	2017	RE-CERP-RFFEF	N/E	EP-IPS-SRI	N/E
74	Domenech et al. [113]	2022	RE-CERP-IRF	N/E	EP-IPS-AEE	LIB-LAB
75	Boero and Agyenim [114]	2019	IRF-II	N/E	EP-IPS	TS
76	Lata-Garcia et al. [115]	2018	RE-CERP	HWEFPV	IPS-SRI	LAB
77	Tian et al. [116]	2021	CERP-RFFEF-IRF	N/E	EP-AEE-SRI	N/E
78	Zalamea-Leon et al. [117]	2023	IRF-II	N/E	EP-IPS-SRI	N/E
79	Cevallos Escandón et al. (1) [118]	2022	RFFEF-IRF	N/E	EP-THTR-IPS	H
80	Cevallos-Escandón et al. (2) [119]	2023	RFFEF-II	BESSA-HWEFPV	EP-THTR-IPS	HS
81	Bermeo et al. [120]	2021	N/E	N/E	EP-THTR-IPS	N/E
82	Becker Pessolani [121]	2016	RE-CERP-RFFEF	N/E	EP-THTR-IPS	N/E
83	Love and Garwood [122]	2011	RE	N/E	EP-IPS-SRI	LAB
84	Canziani et al. (1) [123]	2021	RE-RFFEF-IRF	BESSA-HWEFPV	EP-IPS-SRI	LIB-LAB
85	Delgadillo et al. [124]	2022	RE-CERP	BESSA-HWEFPV	EP-THTR-IPS	LIB-TS
86	Canziani et al. (2) [125]	2021	RE-CERP	BESSA-HWEFPV	EP-IPS	LAB
87	Caravantes et al. [126]	2024	N/E	N/E	N/E	N/E

Table 8. *Cont.*

#	Authors	Year	(i)	(ii)	(iii)	(iv)
88	Narvaez et al. [127]	2023	N/E	N/E	N/E	N/E
89	De Barbosa et al. [128]	2017	RFFEF-II-IRF	BESSA-HWEFPV	EP-IPS	LIB-LAB-HS-CAS
90	Posso and Zambrano [129]	2014	RE-CERP-	N/E	N/E	N/E
91	Cacciuttolo et al. [130]	2024	RE-CERP-II	HWEFPV	EP-IPS-SRI	TS-H

The interpretation of Table 8 reveals the following results:

- Regarding the aspects in column (i), there is a relatively even distribution between the different policies implemented in South America to promote the development of solar energy, with all options achieving a repetition percentage of around 20%.
- When studying the aspects in column (ii), there is a percentage of around 35% where the scientific literature does not specify what type of cutting-edge technologies are being implemented in South America for the development of solar energy.
- Regarding the aspects in column (iii), more than 55% of the scientific literature considers political/economic issues and the intermittency of energy production as challenges for the implementation of solar energy in South America. In this sense, this means that the community demands a solar energy production/transmission/distribution system that is accessible to all citizens in an equitable, fair, and efficient manner.
- When analyzing the aspects in column (iv), nearly 23% of the publications analyzed in this research do not specify any type of technology for storing energy from solar sources; however, the most popular technologies used to date in South America are lithium batteries and lead-acid batteries.
- In the scientific literature reviewed exists a gap considering the implementation of Industry 4.0 technologies in the solar energy industry in South America, such as (i) sensors, (ii) IoT, (iii) cloud computing, (iv) data analytics, (v) artificial intelligence, and (vi) digital twins, among others.
- Also, in the scientific literature reviewed exists a gap considering the application of circular economy principles linked with solar energy facilities in South America, such as the recycling and reuse of solar PV panels.
- 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. Advances and Progress

4.1.1. Advances in Solar Energy Insertion of the Countries in South America

The countries in South America have carried out studies to determine solar energy potential. In addition, the countries are aligned with sustainability, which is why they have been implementing public and private investment projects over the last decade. In this way, the implementation of facilities for the generation of electrical energy through clean energy sources has been developed, with solar energy being one of the most attractive alternatives in the region. Table 9 shows a ranking of the countries in South America according to the criterion of installed capacity (MW).

According to Table 9, in South America, Brazil leads the ranking, with 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. Brazil has the biggest solar PV farms, and in some cases, the solar PV facilities reach 1000 MW of installed capacity.

In second place in the ranking is Chile, and one of the reasons why an aggressive implementation of renewable energies has been promoted in the last decade 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 is mainly due to large mining projects linked to the copper and lithium industry. The enormous potential of solar resources in the Atacama Desert offers Chile the opportunity to expand its installed solar energy capacity.

Table 9. Ranking of countries of South America for the insertion of solar PV energy considering installed capacity. Year: 2023.

Ranking	Country	Installed Capacity MW	Number of Solar PV Farms	Average Theoretical Potential (GHI) kWh/m^2	Average Practical Potential kWh/kW
1	Brazil	37,449	218	5.760	4.404
2	Chile	8790	335	5.758	5.365
3	Argentina	1408	39	5.124	4.599
4	Colombia	716	30	4.867	4.049
5	Peru	398	9	5.146	4.901
6	Uruguay	297	15	4.790	4.304
7	Bolivia	172	8	5.424	4.942
8	Ecuador	31	3	4.305	3.402
9	Venezuela	5	5	5.350	4.355
10	Paraguay	1	1	5.077	4.281
Total	**South America**	**49,267**	**663**	**5.112**	**4.460**

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. Argentina requires the diversification of the energy matrix, and considering the enormous solar resource potential in the northern area, Argentina is developing technical–economic studies to insert new solar PV farms.

In fourth place is Colombia; it has decided to diversify its energy matrix and bet on the implementation of solar energy. This satisfies the demand for electrical energy for cities and different industries such as agriculture, livestock, and services, among others.

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. Peru has decided to diversify its energy matrix by implementing a series of solar PV farms in the southern territory with abundant solar resources.

Next in the ranking are Uruguay, Bolivia, Ecuador, Venezuela, and Paraguay, countries that have been characterized by generating their electrical energy based on hydroelectric plants.

Table 10 shows the biggest solar PV farms located in South America in the year 2023.

Table 10. Ranking of the largest solar PV Farms in South America considering the installed capacity of solar energy. Year: 2023.

Ranking	Solar PV Farm Name	Country	Installed Capacity	Unit
1	Janaúba Solar Complex	Brazil	1200	MW
2	São Gonçalo PV Park	Brazil	864	MW
3	Futura 1 Solar Complex	Brazil	837	MW
4	Sol do Cerrado Solar Park	Brazil	766	MW
5	Helio Valgas Solar PV Park	Brazil	650	MW
6	CEME1 PV Park	Chile	480	MW
7	Sol do Sertão Solar PV Park	Brazil	475	MW

Table 10. *Cont.*

Ranking	Solar PV Farm Name	Country	Installed Capacity	Unit
8	Guanchoi PV Park	Chile	398	MW
9	Pirapora PV Park	Brazil	398	MW
10	SSM 1&2 Solar PV Park	Brazil	320	MW

The countries with the largest solar photovoltaic installations in the region by 2023 are Brazil and Chile. Brazil stands out with solar farms with an installed capacity of over 1000 MW. The following paragraphs describe the main technical characteristics of the largest solar photovoltaic installations in South America.

4.1.2. The Largest Solar PV Farms Under Operation in South America

(i) Janaúba Solar Complex, Minas Gerais Region, Brazil

The Janaúba solar PV facility is in the region of Minas Gerais, Brazil. Construction began on this solar facility in 2021, and it came into operation in 2022. The land area occupied by the solar facility is equivalent to 3069 Ha. The Janaúba solar PV facility consists of 20 PV farms with a total of 2.2 million solar PV panels with an installed capacity of 1.2 GW; more than 3.0 TWh of energy will be generated annually, which can avoid 4.3 million tonnes of CO_2 emissions. Figure 19 shows panoramic images of the solar facility, and Table 11 provides specifications of the infrastructure.

Figure 19. A landscape view of photovoltaic panels in the Janaúba Solar Complex, Brazil, in the year 2024.

Table 11. The main characteristics of the Janaúba Solar Complex, Brazil, in the year 2024.

Characteristics	Data	Units
Location	Minas Gerais Region	-
Energy Company	Elera Renovaveis	-
PV or CSP	Photovoltaic	-
Quantities of PV Modules	2,200,000	-
Module Type	Monocrystalline Silicon	-
Power of Modules	545	W
Modules' Technology	Bifacial Modules	-
Number of Inverters	1350	-

Table 11. *Cont.*

Characteristics	Data	Units
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	45	°
Installed Capacity	1200	MW
Capacity Factor	0.33	-

As shown in Table 11, this solar PV facility has a total of 2,200,000 PV modules of monocrystalline silicon. Furthermore, the power of the photovoltaic modules is 545 W, which, considering all the PV modules, means that the solar PV facility has an installed capacity equivalent to 1200 MW, and a tracking angle for the photovoltaic panels equivalent to 45° with an estimated capacity factor of 0.33.

(ii) São Gonçalo PV Park, Piauí Region, Brazil

Located in the state of Piauí, a semi-arid region of Brazil, the São Gonçalo solar park is a record-breaking project with an installed capacity of 864 MW, consisting of 2.2 million panels, operated by the company Enel Green Power. Considering the whole São Gonçalo complex, more than 2.2 TWh of energy will be generated annually, preventing the emission of about 1.3 million tons of CO_2 into the atmosphere every year. The construction of the first phase of the São Gonçalo solar PV facility, with an installed capacity of 475 MW, started in October 2018 and was connected to the grid in January 2020. In August 2019, Enel Green Power announced the start of works on an extension of the solar farm with an additional installed capacity of 133 MW, which was completed and came into operation in 2021. In addition, Enel Green Power started a third extension in 2022, with an additional installed capacity of 256 MW. This brings the current total installed capacity of the solar PV facility to 864 MW.

The solar PV complex in total covers an area of around 1200 Ha, where the 2.2 million solar panels use bifacial solar PV modules, which capture solar energy from both sides of the panel, with an expected increase in energy generation of up to 18%. Figure 20 shows panoramic images of the solar facility, and Table 12 provides specifications of the infrastructure.

Figure 20. A landscape view of photovoltaic panels in the São Gonçalo PV Park, Brazil, in the year 2024.

As shown in Table 12, this solar facility has a total of 2,200,000 PV modules of monocrystalline silicon. Furthermore, the power of the PV modules is 390 W, which, considering all the PV modules, means that the solar PV facility has an installed capacity equivalent to 864 MW, and a tracking angle for the photovoltaic panels equivalent to 42° with an estimated capacity factor of 0.32.

Table 12. São Gonçalo PV Park, Brazil—main characteristics.

Characteristics	Data	Units
Location	Piauí Region	-
Energy Company	Enel Green Power S.A.	-
PV or CSP	Photovoltaic	-
Quantities of PV Modules	2,200,000	-
Module Type	Monocrystalline Silicon	-
Power of Modules	390	W
Modules' Technology	Bifacial Modules	-
Number of Inverters	970	-
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	42	°
Installed Capacity	864	MW
Capacity Factor	0.32	-

(iii) Futura 1 Solar Complex, Bahia Region, Brazil

The Futura I Solar Complex operated by Eneva is in Juazeiro in the Bahia region in Brazil, which has an installed capacity equivalent to 837 MW and significantly contributes to a more renewable energy matrix. There are over 22 photovoltaic generators and more than 1.4 million solar PV panels over an area of 1649 Ha. Considering the whole Futura 1 Solar Complex, more than 2.0 TWh of energy will be generated annually, preventing the emission of about 1.0 million tons of CO_2 into the atmosphere every year. Figure 21 shows panoramic images of the solar facility, and Table 13 provides specifications of the infrastructure.

Figure 21. Landscape view of Futura 1 Solar Complex, Brazil—year 2024.

Table 13. Futura 1 Solar Complex, Brazil—main characteristics.

Characteristics	Data	Units
Location	Bahia Region	-
Energy Company	Eneva S.A.	-
PV or CSP	Photovoltaic	-
Quantities of PV Modules	1,400,000	-
Module Type	Monocrystalline Silicon	-
Power of Modules	600	W
Modules' Technology	Bifacial Modules	-
Number of Inverters	940	-
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	40	°
Installed Capacity	837	MW
Capacity Factor	0.30	-

As shown in Table 13, this solar PV facility has a total of 1,400,000 PV modules of monocrystalline silicon. Furthermore, the power of the PV modules is 600 W, which, considering all the PV modules, means that the solar facility has an installed capacity equivalent to 837 MW, and a tracking angle for the PV panels equivalent to 40° with an estimated capacity factor of 0.30.

4.2. New Trends Under Development in the Region

4.2.1. Implementation of the Hybridization of Solar PV Facilities with Onshore Wind Farm Infrastructures

Typically, onshore wind farm designs allow for a distance of 1 to 2 km between one row of wind turbines and another for energy efficiency reasons; once the wind passes through a wind turbine, it loses its energy and must travel a certain distance to recover it. This means that these facilities have a lot of available space that can be used to generate energy from other renewable sources. In this sense, the initiative consists of implementing a hybrid renewable energy installation where a solar PV plant is located inside an onshore wind farm [131,132].

For example, if we analyze the South American region, both the northeast of Brazil and the north of Chile have special conditions that favor this type of hybrid renewable energy infrastructure, since they not only have excellent wind conditions but are also located in places with excellent levels of solar radiation, a complement that allows the generation of energy both during the day and at night.

However, the synergies that arise from the hybridization of renewable energy plants go beyond the use of space and natural resources. Aspects such as the construction of roads and accesses, and the erection of transmission lines and substations can also be avoided or reduced, allowing the same elements to be used to generate a greater amount of energy [133].

There is also the possibility of building hybrid renewable energy parks from scratch, which allows synergies to be taken advantage of not only during the construction and operation phases but also during the development phase [134]. In this sense, environmental, social, territorial, basic engineering, and interconnection studies can be conducted at once for both renewable energy plants, distributing these fixed costs over a greater installed capacity [131].

Below are three successful case studies of hybrid renewable energy facilities in operation in the South American region:

(i) Neoenergia Hybrid Renewable Energy Complex—Luzia and Chafariz, Paraíba Region, Brazil

Iberdrola's subsidiary in Brazil, Neoenergia, operates the Luzia photovoltaic solar plant, the first to be installed in the South American country. It has 228,000 photovoltaic solar panels with a total installed capacity of 149 MW. The photovoltaic solar plant is joined to the Chafariz onshore wind farm in what is known as the Neoenergia hybrid renewable energy complex.

The onshore wind part of the project consists of 136 wind turbines and an installed capacity of 471 MW, which make up the Chafariz Complex, which is fully operational. This hybrid renewable energy complex has the Luzia photovoltaic solar installation and the wind farms that make up the Chafariz Complex, enabling it to reach a total installed capacity of more than 620 MW, and thus avoiding the emission of more than 100,000 tons of CO_2 per year. Figure 22 shows a panoramic view of the hybrid renewable energy complex currently in operation and Table 14 shows a summary of the main technical characteristics.

Table 14. Neoenergía hybrid renewable energy complex, Brazil—main characteristics.

Characteristics	Value	Units
Location	Paraíba Region	-
Concession Owner	Iberdrola S.A.	-

Table 14. *Cont.*

Characteristics	Value	Units
Wind Farm Name	Chafariz	-
Type of Wind Farm	Onshore	-
Number of Turbines	136	-
Turbines' Manufacturer/Model	SG132	-
Diameter of Turbines	130	m
Hub Height	150	m
Installed Capacity per Turbine	3.5	MW
Total Installed Capacity	471	MW
Wind Farm Capacity Factor	0.50	-
Solar Farm Name	Luzia	-
PV or CSP	Photovoltaic	-
Quantities of PV Modules	228,000	-
Module Type	Monocrystalline Silicon	-
Power of Modules	650	W
Modules' Technology	Bifacial Modules	-
Number of Inverters	165	-
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	45	°
Installed Capacity	149	MW
Solar PV Farm Capacity Factor	0.25	-
Total Installed Capacity Hybrid Facility	620	MW

Figure 22. Landscape view of Neoenergia hybrid renewable energy complex, Brazil—year 2024.

The wind and solar farms share an electrical substation and a 345 km distribution line, which connects the plants, located in a remote region of northeastern Brazil, to the national electricity grid. This is how the project combines two complementary energy sources, since wind production is stronger at night, when the solar plants are not operating, due to the wind regime in the region.

(ii) Azabache Hybrid Renewable Energy Complex—Azabache and Valle de Los Vientos, Antofagasta Region, Chile

The Valle de Los Vientos onshore wind farm is a renewable energy facility located 10 km from Calama, in the Antofagasta Region of Chile, in the heart of the Atacama Desert. It is made up of 45 wind turbines of 2 MW each, with a total installed capacity of 90 MW, and produces more than 200 GWh per year, avoiding the emission of more than 165,000 tons of CO_2 into the atmosphere. The installation began construction in 2012 and operations in 2013.

After conducting a series of technical–economic studies, it was decided to build an Azabache solar photovoltaic installation inside the Valle de Los Vientos onshore wind farm in 2020. In this sense, the solar photovoltaic installation has 154,170 photovoltaic solar panels and an installed capacity of 61 MW, beginning operations in 2022, producing more than 184 GWh per year, and avoiding the emission of more than 135,000 tons of CO_2 into the atmosphere.

Figure 23 shows a panoramic view of the hybrid renewable energy complex currently in operation, and Table 15 shows a summary of the main technical characteristics.

Figure 23. Landscape view of Azabache hybrid renewable energy facility, Chile—year 2024.

Table 15. Azabache hybrid renewable energy facility, Chile—main characteristics.

Characteristics	Value	Units
Location	Antofagasta Region	-
Concession Owner	Enel Green Power S.A.	-
Wind Farm Name	Valle de Los Vientos	
Type of Wind Farm	Onshore	-
Number of Turbines	45	-
Turbines' Manufacturer/Model	Vestas V100/2000	-
Diameter of Turbines	100	m
Hub Height	120	m
Installed Capacity per Turbine	2.0	MW
Total Installed Capacity	90	MW
Wind Farm Capacity Factor	0.52	-
Solar Farm Name	Azabache	-
PV or CSP	Photovoltaic	-
Quantities of PV Modules	154,170	-
Module Type	Monocrystalline Silicon	-
Power of Modules	395	W
Modules' Technology	Bifacial Modules	-
Number of Inverters	85	-
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	40	°

Table 15. *Cont.*

Characteristics	Value	Units
Installed Capacity	60.9	MW
Solar PV Farm Capacity Factor	0.30	-
Total Installed Capacity Hybrid Facility	150.9	MW

The Azabache photovoltaic solar installation (61 MW) is located within the Valle de Los Vientos wind farm (90 MW). The distance between the wind turbines allowed for sufficient space to install the photovoltaic solar panels, and the use of common roads and facilities between the two parks, such as the operation and maintenance building or the substation, brought about different synergies both in its construction and in its operation.

(iii) Las Salinas Hybrid Renewable Energy Complex—Las Salinas and Sierra Gorda, Antofagasta Region, Chile

Approximately 60 km from the city of Calama, Antofagasta Region, Chile, in the heart of the Atacama Desert, is the Las Salinas photovoltaic solar energy facility with an installed capacity of 205 MW, and which is also made up of a total of 458,044 panels with bifacial technology. This cutting-edge technology allows for greater efficiency in the generation of electric energy since it allows for the capture of solar radiation both from the top and from the bottom of each photovoltaic solar panel.

Due to the extraordinary wind conditions in the sector, the Sierra Gorda onshore wind farm is being built in the same place, which has an installed capacity of 112 MW and is made up of 56 wind turbines. This renewable energy facility generates more than 295 GWh per year and thus prevents the emission of more than 140,000 tons of CO_2 into the atmosphere per year. This is how the Las Salinas photovoltaic solar installation works together with the Terrestre Sierra Gorda wind farm, turning both units into the center of renewable generation in a hybrid format on an industrial scale with a joint installed capacity of 317 MW, thus being the largest hybrid renewable energy installation in Chile to date.

Figure 24 shows a panoramic view of the hybrid renewable energy complex currently in operation and Table 16 shows a summary of the main technical characteristics:

Figure 24. Landscape view of Las Salinas hybrid renewable energy facility, Chile—year 2024.

Table 16. Las Salinas hybrid renewable energy facility, Chile—main characteristics.

Characteristics	Value	Units
Location	Antofagasta Region	-
Concession Owner	Enel Green Power S.A.	-

Table 16. *Cont.*

Characteristics	Value	Units
Wind Farm Name	Sierra Gorda	
Type of Wind Farm	Onshore	-
Number of Turbines	56	-
Turbines' Manufacturer/Model	Siemens Gamesa G114/2000	-
Diameter of Turbines	114	m
Hub Height	130	m
Installed Capacity per Turbine	2.0	MW
Total Installed Capacity	112	MW
Wind Farm Capacity Factor	0.50	-
Solar Farm Name	Las Salinas	-
PV or CSP	Photovoltaic	-
Quantities of PV Modules	458,044	-
Module Type	Monocrystalline Silicon	-
Power of Modules	450	W
Modules' Technology	Bifacial Modules	-
Number of Inverters	285	-
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	40	°
Installed Capacity	205	MW
Solar PV Farm Capacity Factor	0.35	-
Total Installed Capacity Hybrid Facility	317	MW

Hybridization of energy projects, combining technologies such as solar and wind, has become an increasingly popular strategy for energy companies, since by sharing two or more renewable sources, companies can increase the efficiency of their projects with periods of complementary generation. Another important aspect to consider when designing this type of hybrid renewable energy installation is the impact of the shadow generated by the intermittent movement of wind turbine blades, which can be avoided by distancing solar photovoltaic installations in areas where there is greater availability of land use.

4.2.2. Use of the Battery Energy Storage Systems (BESSs) in Solar PV Farm Facilities

The massive and stable implementation of renewable energy generation on a large scale presents challenges to overcome, such as the intermittent dispatch of solar PV installations [135]. This is how the storage of electrical energy arises as an alternative to take advantage of resources and electrical production according to demand. BESSs are systems in which batteries, individually or more often together, are used to store the electricity produced by solar photovoltaic generating plants and make it available when needed [136]. In this sense, energy is released when there is high demand, and energy is stored when there is low demand. In this way, this process stabilizes the electrical network and guarantees a constant flow of energy [137].

In a BESS (see Figure 25), the fundamental components are the blocks formed by the batteries, but other elements are also present: (i) an inverter, which converts the direct electric current of the batteries into alternating electric current from the grid (and vice versa); (ii) a transformer, to adapt the voltage of the system to that of the grid; and finally, (iii) auxiliary systems (in particular, cooling and fire protection).

As in all storage systems, in BESSs, the electricity produced by a power plant or any other generating plant, even a single photovoltaic panel, is stored and then released at the desired times and hours [138].

The most widely used types of BESS in South America today are lithium-ion batteries: this is the most widespread, efficient, and increasingly cost-effective technology available today. Lithium BESS batteries can last up to 20 years, although over time their performance decreases. At the end of their useful life, they can be converted or recycled. However, research and the search for increasingly efficient and higher-quality technologies do not stop. Through feasibility studies and field tests, liquid air storage systems, flow batteries, or thermal storage continue to be explored as a response to future challenges. There are other types such as (i) a sodium-ion BESS, which is economical but has lower performance, (ii) an iron–air BESS, a promising but not yet mature solution, (iii) a flow BESS, which lasts longer thanks to the use of an innovative technique, and (iv) a solid-state lithium BESS, which is a promising technology for the future.

Figure 25. Example of battery energy storage system (BESS).

Below are experiences of BESS application projects in the South American region:

(i) BESS Coya Facility—Solar PV Farm and BESS Facility, Maria Elena, Antofagasta Region, Chile

The Coya solar PV solar facility is in Maria Elena, Antofagasta Region, and has an installed capacity of 181.25 MW. This facility avoids the emission of 311,293 tonnes of CO_2 per year. This solar energy facility has a battery energy storage system (BESS) technology which uses lithium batteries to store the renewable energy generated during the day. This BESS has a storage capacity of 638 MWh, with 139 MW installed capacity, avoiding the emission of 311,293 tons of CO_2 per year, and is the largest battery energy storage system in South America to date (see Figure 26). Through its 232 modules, Coya's BESS installed capacity will enable it to store the equivalent of 5 h of electricity and inject it into the grid during peak periods, representing the delivery of 200 GWh on average per year. It will also play an important environmental role by supplying enough green energy, thereby avoiding the emission of 65,000 tons of CO_2 annually.

Table 17 shows a summary of the main technical characteristics of this cutting-edge BESS currently in operation in Chile.

Table 17. BESS Coya Facility, Chile—main characteristics.

Characteristics	Value	Units
Location	Antofagasta Region	-
Concession Owner	Engie S.A.	-
BESS Technology	Lithium Batteries	.
Number of BESS Units	232	.
Storage Capacity	638	MWh
Installed Capacity	139	MW
Storage Time	5	h
Annual BESS Energy Supply	200	GWh

Table 17. *Cont.*

Characteristics	Value	Units
Solar Farm Name	Coya	-
PV or CSP	Photovoltaic	-
Quantities of PV Modules	369,432	-
Module Type	Monocrystalline Silicon	-
Power of Modules	490	W
Modules' Technology	Bifacial Modules	-
Number of Inverters	58	-
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	45	°
Installed Capacity	181.25	MW
Solar PV Farm Capacity Factor	0.35	-

Figure 26. BESS Coya Facility, Chile—year 2024. Adapted from [139].

Two more projects currently under construction in the Atacama Desert in Chile will be added to this initiative by 2024: BESS Tamaya (68 MW/418 MWh) and BESS Capricornio (48 MW/264 MWh). This will translate into approximately 255 MW of power for 5 h of energy dispatch, mainly at night.

Energy storage is one of the most important elements of the current energy transition and a priority for implementation in the South American region. In fact, its role is increasingly crucial in the face of the large-scale deployment of intermittent and unpredictable renewable sources. Thanks to storage systems, the electricity produced by intermittent renewable energy installations, both wind and solar, can be stored and released at the desired times: it can therefore be supplied to customers at any time, regardless of the time of day and weather conditions. Furthermore, due to their modular design, BESSs are characterized by great flexibility and scalability: additional battery packs can easily be added to an already operational system to increase its capacity.

In this way, the use of BESSs allows for a more constant and continuous use of energy from renewable sources such as the sun, thereby reducing dependence on fossil fuels and contributing to a reduction in greenhouse gas emissions in the fight against climate change. In this sense, it is expected that in the coming years, there will be significant technological advances that will make these systems more competitive, making them even more dynamic on a larger scale.

4.2.3. Implementation of Concentrated Solar Power (CSP) Facilities in the Region: A Pending Issue

In the South American region, there is an outstanding issue regarding the implementation of solar power concentration tower installations if we compare this with the operation of photovoltaic solar installations. For the implementation of this type of solar power concentration tower installations, a midday direct normal irradiance (DNI) ranging from 800 to 950 W/m^2 or equivalent to direct normal irradiance (DNI) levels in this area ranging from 5.0 to 8.0 kWh/m^2/day is required to be technically and economically feasible, where some geographical locations in Chile, Peru, Bolivia, Argentina, and Brazil have these conditions [140]. CSP needs not only high levels of DNI > 2000 kWh/m^2/year to be considered economically viable but also flat ground and sufficient water supply [141].

Although the investment and operation cost together with the construction time of solar power concentration tower installations is higher than in the case of photovoltaic solar installations, the capacity for energy storage and use during the night provides a comparative advantage that guarantees energy security and stability 24 h a day [130].

Despite the high costs and lack of experience in the construction and operation of solar power tower installations, there is a country in the South American region that has decided to bet on this alternative technology that has already been tested in other parts of the world such as the USA, Morocco, and Spain, among others. In this sense, Chile has been a pioneer country in the South American region, with the only solar power tower project in operation by 2024 [30,140]. On the other hand, countries with solar potential to develop this technology such as Brazil and Peru are still lacking. Technological alternatives are currently being evaluated that allow for the implementation of this technology in the South American region, making it more attractive and competitive from a cost-efficiency point of view. This is how the hybridization of solar concentration towers with photovoltaic solar installations allows for reducing investment and operation costs, providing greater flexibility and energy redundancy to the electrical system. Below is the only successful case of implementation of solar concentration tower technology in the South American region, as well as future projects linked to the original initiative:

(i) Cerro Dominador Hybrid Renewable Energy Facility—Concentrated Solar Power (CSP) and Solar PV Farm, Antofagasta Region, Chile

The Cerro Dominador solar thermal power plant is a 210 MW hybrid power plant that combines CSP energy with an installed capacity of 110 MW with PV solar energy consisting of 392,000 solar panels with an installed capacity of 100 MW. The hybrid solar thermal power plant together generates 950 GWh of energy per year. This renewable energy facility is in the commune of María Elena in the Antofagasta Region of Chile, approximately 24 km northwest of the town of Sierra Gorda in the heart of the Atacama Desert, one of the driest places in the world and with the highest solar radiation on the planet. Construction of the project began in 2014, and it was commissioned in 2021.

The 110 MW solar concentration tower installation has 10,600 heliostats, each with an area of approximately 140 m^2, on a plot of land of more than 1000 hectares, which concentrate the reflected solar radiation on a receiver located at the top of a 252 m high tower, through which molten salts circulate at about 550 °C, absorbing the heat.

This technology uses a series of mirrors (heliostats) that collect the sun's rays on two axes, concentrating the solar radiation on a receiver at the top of the tower, where the heat is transferred to the molten salts. The reflective element of the heliostat is a thin glass mirror with a low iron content. The structure on which the rest of the mirrors are placed is provided with a mechanism that allows for the tracking of two axes, the azimuth, and the elevation. The movement is carried out by a motor that receives the signal from the central control system, which provides a precise and constant aim at the reflective surface.

The molten salts that absorb heat at 550 °C are then used to transfer this heat to water, thus generating steam which is fed to a turbine connected to an electric generator and thus subsequently generating electricity. In addition, it has a thermal storage system for molten salts that allows for stable energy delivery 24 h a day. In this way, the emission of approximately 640,000 tons of CO_2 per year is avoided. This type of plant makes it possible to solve the intermittent generation of energy thanks to the storage of molten salts, thus having an operating autonomy of 17.5 h without the presence of the sun. The installation has the implementation of algorithms of a computer system that work automatically and measure the temperature of each heliostat remotely. Additionally, it is possible to know the exact point from which the maximum power can be extracted from a certain heliostat. That is, its optimal operating condition is defined and monitored in real-time and allows for the detection of possible failures of the heliostats.

Figure 27 below shows a panoramic view of the Cerro Dominador hybrid solar thermal plant in the Atacama Desert and Table 18 shows a summary of the main technical characteristics of renewable energy installation.

Figure 27. Landscape view of Cerro Dominador hybrid renewable energy facility, Chile—year 2024.

Table 18. Cerro Dominador hybrid renewable energy facility, Chile—main characteristics.

Characteristics	Value	Units
Location	Antofagasta Region	-
Concession Owner	Grupo Cerro S.A.	-
Concentrated Solar Plant Name	Cerro Dominador	
Type of Concentrated Solar Plant	Solar Power Tower	-
Tower Height	252	m
Number of Heliostats	10,600	-
Area of Heliostats	140	m^2
Type of fluids	Molten salts	-
Temperature of fluids	550	°C
Total Area of Concentrated Solar Plant	1000	Ha
Total Installed Capacity	110	MW
Time of Stored Energy in Form of Heat	17.5	h
Capacity Factor	0.95	-
Solar Farm Name	Cerro Dominador	-
Type of Solar Facility	Photovoltaic	-
Quantities of PV Modules	392,000	-
Module Type	Monocrystalline Silicon	-
Power of Modules	255	W
Module Technology	Bifacial Modules	-
Number of Inverters	150	-
Type of Structure	1-Axis Horizontal Tracker	-
Tracking Angle	40	°
Installed Capacity	100	MW
Solar PV Farm Capacity Factor	0.35	-
Total Installed Capacity Hybrid Facility	210	MW

The Atacama Desert in Chile offers ideal conditions for the implementation of CSP projects, as it has extraordinary solar irradiance conditions that are unique worldwide and does not have problems with sandstorms as is the case in other similar geographic locations in the world [30,140].

It is in this sense that an expansion of the current Cerro Dominador facility is being considered, an initiative called the Pampa Unión expansion project. Pampa Unión is a project under development that consists of a 210 MW photovoltaic solar plant with installed capacity in its first stage and will be in the Sierra Gorda commune in the Antofagasta Region, Chile. The project currently has the authorization of a social and environmental license to begin its construction. It is expected that in the second stage of this project, the installed capacity will be extended to 600 MW in the future.

In addition, there is another new project in the pipeline called Likana Solar. This project will be in a place called Llano de Quimal, located 41 km southeast of Calama. The Likana Solar project will consist of three towers, each of which will consist of a central tower solar thermal generator using concentrated solar technology like the Cerro Dominador project, with 12 h of energy storage and an installed capacity of 690 MW. Each of these units will be surrounded by a circular heliostat solar field consisting of 13,405 heliostats, which will be responsible for reflecting and focusing solar radiation toward the receiving tower located in the central area. The Likana Solar project is expected to generate an annual net electricity production of 3,150 GWh, which could position it as one of the largest CSP tower complexes in the world (see Figure 28).

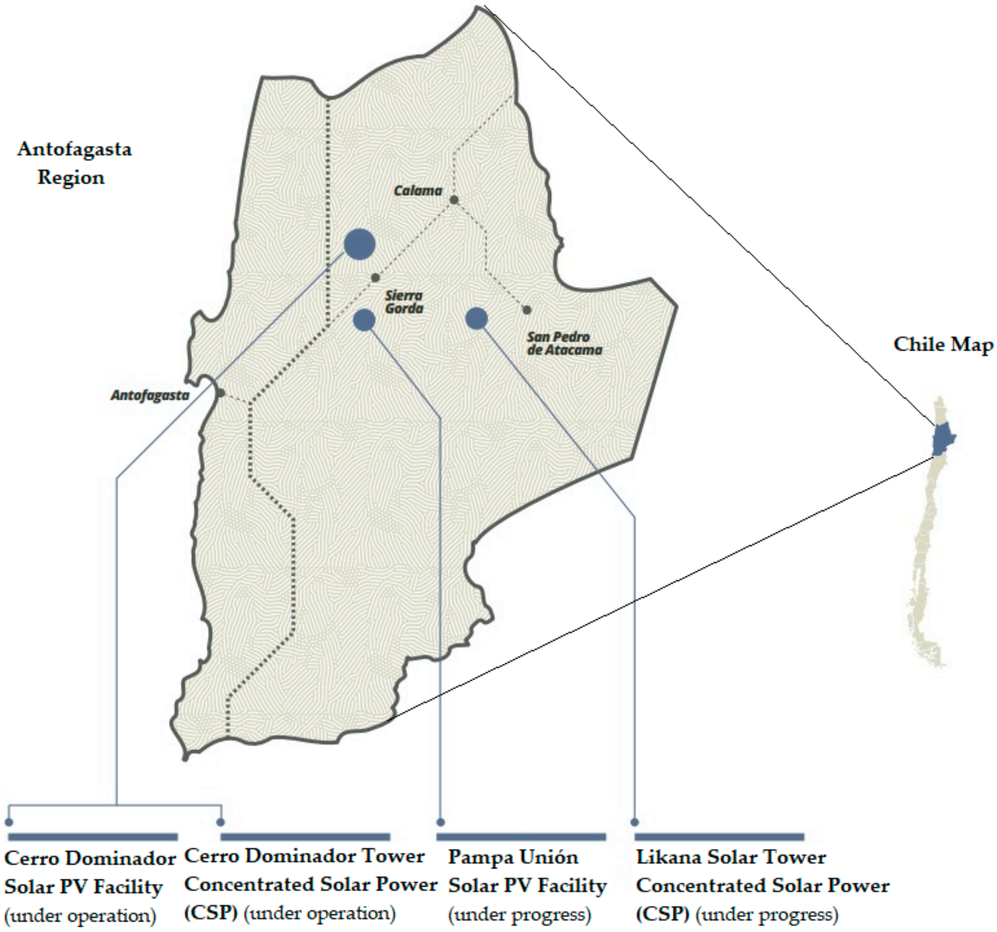


Figure 28. Mapping of Cerro Dominador, Pampa Unión, and Likana Solar energy projects in Antofagasta Region in Chile.

4.3. The Road to a Sustainable Paradigm with Disruptive Innovations

4.3.1. Prospective Utility-Scale Solar PV Farm Capacities in South America

The countries of South America offer high solar generation potential. In that sense, it is possible to implement large solar PV facilities in the region.

Figure 29 shows a mapping of the future installed capacity for each of the nations in the Latin American region.

Figure 29. Mapping of future facilities considering installed capacity in Latin America. Adapted from [14].

According to Figure 29, the countries with the biggest solar potential and opportunity to insert solar PV farm infrastructure are (i) Brazil, (ii) Chile, (iii) Argentina, (iv) Colombia, and (v) Peru. In the case of Brazil, a high potential is observed in the northern coastal zone equivalent to 3.0 GW, and in the central coastal zone, a potential equivalent to 6.0 GW is observed. On the other hand, Chile has the greatest solar potential in the Atacama Desert equivalent to 6.0 GW. Argentina is another country with high solar potential, where projects for solar PV farms are being planned with an installed power equivalent to 3.0 GW. Finally, Colombia has a high solar resource potential, where an installed capacity equivalent to 3.0 GW is projected.

4.3.2. Emerging Sustainable Initiatives Considering Floating Solar PV Facilities

New initiatives are being implemented in the South American region, including the installation of floating solar photovoltaic plants located in bodies of water. Floating solar photovoltaic plants allow for a reduction in evaporation and use new and available space to generate clean energy [142,143]. In this area, the countries of Brazil and Chile are the leaders in the region, and considering the size of the projects, the following cases stand out.

In 2019, the Sobradinho hydroelectric plant, located in the state of Bahia, Brazil, was modernized by implementing a floating solar system with an installed capacity equivalent to 1 MW (see Figure 30). The combination of solar and hydraulic energy is a response to meet the region's electricity consumption needs. In this sense, the Sobradinho hydroelectric plant is the first to reach the scale of 1 MW in the country. The floating solar photovoltaic plant has 3792 solar panels and produces 1.7 MWh of energy annually. However, the floating solar PV plant is expected to be expanded, and its capacity is planned to increase to 2.5 MW of installed capacity; in that sense, it is expected that the expanded installation should produce more than 4.2 MWh per year.

Figure 30. Panoramic view of floating solar PV facility in Sobradinho hydroelectric plant, Brazil.

The combination of hydroelectric and solar energy is quite promising in this case since (i) it avoids interruptions in energy production since hydroelectric energy is responsible for supplying the intermittency of solar energy, and (ii) in turn, it replaces hydroelectric energy when the Sobradinho plant is affected by climate change phenomena such as drought.

On the other hand, in 2023, on an irrigation reservoir within the Quilamuta Farm, in the Las Cabras commune, O'Higgins Region, Chile, the agricultural company Verfrut together with Solarity inaugurated the largest floating photovoltaic solar plant in the country. The facility is characterized by having 1.1 MW of installed capacity and 1998 solar panels located on floats that keep them above the water of the reservoir, covering a total area of 8260 square meters (see Figure 31). Meanwhile, eight current inverters are responsible for collecting the energy generated as direct current to convert it into alternating current that is injected directly for consumption at the Quilamuta Farm. The Quilamuta plant will provide clean energy for the self-consumption of Verfrut's operations, supporting the company's goal of promoting more sustainable processes in the production, packaging, export, and marketing of fresh fruit.

Figure 31. Panoramic view of floating solar PV facility in water reservoir of Fundo Quilamuta, Chile.

In this way, the Verfrut agricultural company promotes the development of the Sustainable Development Goals (SDGs) promoted by the United Nations Organization, UN, especially those related to the development of affordable and non-polluting energy, responsible production and consumption, and the implementation of climate action.

Finally, the last success story was inaugurated in 2024 in the state of São Paulo, Brazil, the first phase of the largest floating photovoltaic solar plant in Brazil. The project is located in the reservoir dam called Billings and is being developed by the Metropolitan Water and Energy Company (EMAE) and KWP Energia. The project has 7 MW of installed capacity, and 10,500 photovoltaic panels installed on high-density polyethylene floats, producing up to 10 GWh of energy per year (see Figure 32).

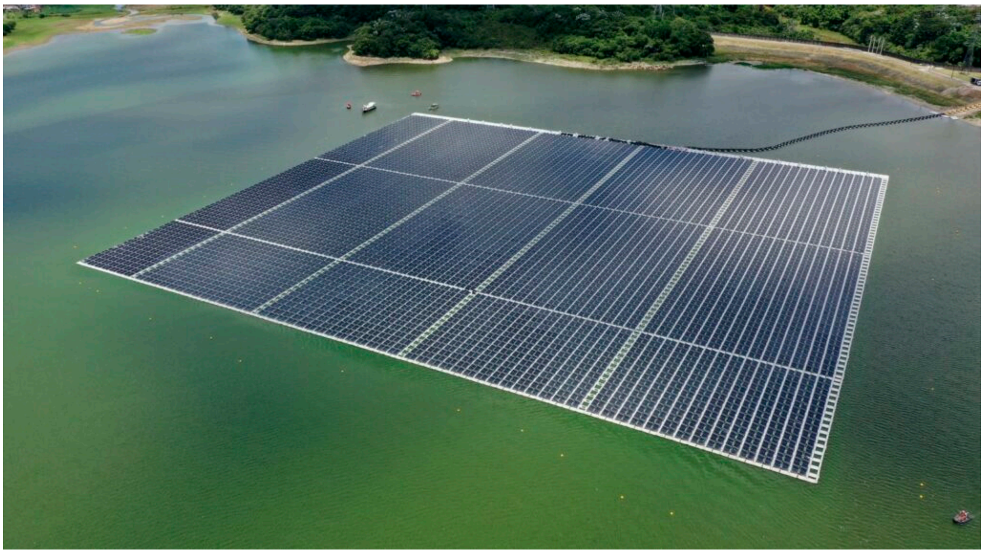


Figure 32. Panoramic view of floating solar PV facility in water reservoir of Billings Dam, Brazil.

This also ensures that the floating solar PV plant will be the largest in the country to operate commercially in the distributed generation mode, with generators located near the consumption centers.

4.3.3. Application of Artificial Intelligence, Remote Sensing, and Robotics in the Solar Energy Facilities Located in the South American Region

More and more energy companies are constantly looking for innovative and disruptive technological solutions to increase the efficiency, productivity, reliability, and predictability of operations. The emerging need to electrify the economy and society requires an upgrade of the electric transmission network and the implementation of digital equipment to optimize network control [144].

The industry has long since adopted SCADA systems (which allow for monitoring, control, and data acquisition), which have led to an increasing digitalization of processes and facilitated the automation of plant operations.

In this sense, digital technology has become a critical enabler for innovation and disruption in the industry. Some key aspects of digitalization are as follows: (i) data collection: using advanced analytics and insights driven by organizational methodologies to enable data-driven decision-making and agility; (ii) effectiveness: accelerated digital transformation regarding energy efficiency at every step of the value chain; and (iii) IoT: sensors and data communication networks across the value chain enabled by IoT and 5G technologies [145].

The use of LiDAR remote sensing solutions with the use of UAV drones for monitoring electrical generation, transmission, and distribution networks is also expanding (see Figure 33). Likewise, due to their scalability and cost efficiency, cloud solutions were an important step in advanced metering infrastructure, which introduced new decentralized energy consumption and exchange models to the sector [130].

Figure 33. An example showing the use of UAVs to detect anomalies in the panels of solar PV farms.

On the other hand, in the South American region, artificial intelligence is being used for more efficient management of electricity transmission and to solve bottlenecks that generate electricity spills, that is, electricity generated that cannot be used for economic reasons or due to the capacity of the electrical network [146].

There are solutions for the automation of high-voltage electrical networks. Artificial intelligence allows data to be captured and processed in real time with an algorithm, without human intervention, to return a set point or status to the network in real time. This makes it possible to deal with the intermittency caused by the integration of distributed renewable energy assets [147–150].

One of the challenges presented by the Atacama Desert region in Chile where solar PV plant projects are being located is the scarcity of water and the accumulation of dirt on solar panels due to dust. For this reason, innovative solutions are being incorporated for efficient, frequent, and autonomous dry cleaning of solar panels. Thanks to the integration of various technologies such as sensors, IoT, artificial intelligence, robotics, and automation, it is possible to have robots that allow for the cleaning of thousands of PV panels continuously (see Figure 34). In this way, it is also possible to have continuous monitoring of the status of the panels and manage their cleaning remotely. This represents an important advance in saving water use, time, and money, being a cutting-edge solution in issues related to sustainability and advances in digitalization technologies [151].

Figure 34. An example showing the use of smart robots to clean panels of solar PV farms.

The adoption of new technologies is not an easy process, especially in industries such as the electrical industry, which are complex systems in which failure can have serious consequences for industries and cities. In this sense, the regulation of the sector tends to be seen as one of the main obstacles to the adoption of new digital solutions. In addition, there is a certain degree of resistance to change in countries in the region that are undergoing a generational change, which still presents difficulties in opening to changes, mostly due to security issues, uncertainty about the performance of the operation, and fear of changes, but gradually, spaces are opening up to cutting-edge technological prototype solutions.

Considering the experience and development of solar energy in the South American region, there are a number of open research challenges that still have no answers. In this sense, for example, it is necessary to explore and design a digital tool that allows for optimizing the operation and maintenance of a hybrid solar thermal generation plant, for example, similar to that of the Cerro Dominador project. Some of these open research challenges include the following:

- How can the operation be optimized considering the different operating modes based on parameters and the analysis of real-time information?
- How can weather and energy sale conditions be integrated with the best scenarios and strategies according to the reality of the plant's layout and operation at any given time?
- How can the plant's 24/48 h load plans be made more efficient based on the analysis of real data from the facility?
- How can different variables and operating modes be integrated into a digital twin to simulate different operating scenarios?
- How can better forecasts and maintenance needs be obtained for systems, equipment, or parts of the facility based on information and analysis of parameters measured in real time and historical data?

4.4. Gaps and Limitations of This Review

The main shortcomings of this review lie in the lack of consideration of several critical factors for the comprehensive implementation of solar energy in South America. Although the paper provides a detailed overview of the potential and expansion of solar infrastructure, it fails to include an in-depth analysis of capital (CAPEX) and operational (OPEX) costs, which are essential for evaluating the economic feasibility and long-term sustainability of projects. This gap limits the understanding of the cost–benefit balance, especially when compared to other renewable energy sources and emerging technologies in the region. Additionally, this review does not adequately address the integration of advanced technologies such as Industry 4.0, which includes smart sensors, the Internet of Things (IoT), artificial intelligence, and digital twins. These tools are crucial for optimizing operational efficiency, predictive maintenance, and real-time decision-making, but their implementation and potential in solar projects across the region are not thoroughly discussed. Lastly, there is a lack of focus on circular economic principles, particularly in terms of recycling and reusing solar panels. Given the limited lifespan of these panels, the absence of a clear approach to managing future waste is a significant deficiency. Addressing these limitations could foster a discussion on how to tackle these challenges to ensure that the growth of solar energy in South America is both economically and environmentally sustainable.

The main challenge regarding the development of solar energy facilities in South America lies in reducing the capital (CAPEX) and operational (OPEX) costs of the projects. Currently, although the region has high solar irradiation potential, the widespread implementation of these infrastructures remains limited due to relatively high costs, especially compared to other energy sources. If these costs can be lowered through technological advancements, economies of scale, and supportive policies, solar solutions could expand on an urban, commercial, and industrial scale in a more widespread manner. This would enable solar energy to become a viable and competitive alternative, facilitating the transition to a more sustainable and low-carbon energy matrix.

5. Conclusions

All countries in the South American region considered in this study, Brazil, Chile, Argentina, Colombia, Peru, Uruguay, Bolivia, Ecuador, Venezuela, and Paraguay, have solar potential to develop this renewable energy, where the average theoretical potential (GHI) is 5.112 (kWh/m^2) and the average practical potential is 4.460 (kWh/kW). Chile leads with 5.365 (kWh/kW) of average practical potential, considering the extraordinary environmental characteristics of the Atacama Desert.

In this sense, all countries have implemented facilities linked to solar energy. Brazil, Chile, Argentina, Colombia, and Peru are at the forefront as of 2023 considering the implementation of large-scale solar PV farms in the South American region, with a collective installed capacity that exceeds 49 GW. Brazil leads with a total installed capacity equivalent to 37 GW followed by Chile with a total installed capacity of 8.7 GW considering solar PV farms.

As of 2023, considering the countries of the South American region under study, there are 663 large-scale solar PV farms in operation, leading Chile with 335 solar PV farms and followed by Brazil with 215. The reason why Chile leads in the quantity of facilities is because it has a greater number of small-scale solar PV farms in comparison with large-scale Brazilian solar PV farms. As of 2023, there is only one tower concentrated solar power (CSP) facility in operation in the South American region, located in the Atacama Desert region in Chile, with a total installed capacity of 110 MW and a time of stored energy in the form of heat equivalent to 17.5 h. Also, it is relevant to mention that Chile has started the implementation of hybrid renewable energy facilities in the region considering the operation of (i) solar PV farms with on-shore wind farms and (ii) solar PV farms with tower concentrated solar power (CSP). Additionally, incipient progress is shown to be linked with the implementation of floating solar PV farm facilities, which are popular in hydroelectric reservoirs, water reservoirs linked with agriculture, and water reservoirs used in mining, among others.

Some of the advantages that are important to highlight regarding the implementation of solar energy in the South American region are the following: (i) low social conflict, where the use of solar energy resources is accepted in nearby communities, which is why they are usually implemented in a short time; (ii) energy matrix diversity, where generation is concentrated in hydroelectric and thermal natural gas plants, and solar energy installations allow the matrix to be diversified in order to address problems of scheduled (maintenance) and unscheduled (gas pipeline breakage, droughts, effects of the El Niño phenomenon, among others) unavailability; (iii) environmental pollution level reductions, where solar photovoltaic installations allow for a reduction in greenhouse gas emissions; and (iv) quickly implemented installations, where compared to conventional fossil fuel plants, the execution and operation of solar photovoltaic generation projects take less time (on average, between two and three years, depending on the size).

Solar energy installations also pose challenges that must be considered in their implementation, such as (i) intermittency, presenting unavailability throughout the day, and (ii) large-scale integration. It is in this sense that a decisive role is being assumed in the South American region by hybrid solar–wind renewable energy installations and battery energy storage systems (BESSs) implemented in solar photovoltaic installations. On the one hand, the hybridization between onshore wind energy and solar photovoltaic energy allows for large-scale integration and at the same time addresses the intermittency of solar energy by operating wind turbines at night. On the other hand, historically, the most important energy storage technology has been pumped-storage hydroelectric plants, but currently, there are important technological advances and cost reductions in the use of batteries, especially lithium batteries, which can be placed anywhere. The diffusion of BESS storage facilities in the South American region is in the initial stage of implementation, but it is promising as it is increasing rapidly thanks to technological innovation that constantly improves the quality and performance of batteries. It is expected that, in the next decades, BESSs will be fully integrated into the electrical grids, with intermittent sources such as solar energy being able to provide energy to the electrical grid at any time, regardless of atmospheric conditions. At that time, it will be possible to have a combination of renewable energy sources for electricity generation in total without greenhouse gas emissions, in the not-too-distant future.

Finally, it is possible to mention that the South American region contributes to important efforts and advances in the mitigation of climate change, aligned with the sustainable development objectives promoted by the UN 2030 agenda, and advances steadily and progressively in its roadmap towards the decarbonization of its energy matrix by 2050, supported by the benefits of inexhaustible and renewable solar energy.

Author Contributions: Conceptualization, C.C.; formal analysis, C.C., V.G. and P.C.; investigation, C.C., V.G. and P.C.; resources, V.G. and P.C.; writing—original draft preparation, C.C.; writing—review and editing, C.C., V.G. and P.C.; visualization, C.C., V.G. and P.C.; supervision, C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Research Department of the Catholic University of Temuco, Chile.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

SDGs	Sustainable Development Goals
UN	United Nations
BAT	best available technology
PV	photovoltaic

CSP	concentrated solar power
GHGs	greenhouse gases
CO_2eq	carbon dioxide equivalent
NDCs	Nationally Determined Contributions
IRENA	International Renewable Energy Agency
ESMAP	Energy Sector Management Assistance Program
NGOs	Non-Government Organizations
DHI	diffuse horizontal irradiance
DNI	direct normal irradiance
GHI	global horizontal irradiance
PF	plant factor
BESS	battery energy storage system
R&D	research and development
AI	artificial intelligence
ML	machine learning
IoT	Internet of Things
CC	cloud computing
5G	first-generation cellular technology—mobile network that provides more connectivity and faster connection speeds
UAVs	unmanned aerial vehicles
LiDAR	Light Detection and Ranging
EIA	Environmental Impact Assessment
DEM	data extraction from metadata
DEC	data extraction from content
ECs	exclusion criteria
CAPEX	capital costs
OPEX	operational costs
EPC	Engineering, Procurement, and Construction
RER	renewable energy resource
ENSO	El Niño–Southern Oscillation
LCOE	Levelized Cost of Electricity
MW	megawatts
GW	gigawatts
MWh	megawatts-hour
GWh	gigawatts-hour
TWh	terawatts-hour
kWh/m^2	kilowatt-hour per square meter
kWh/kW	kilowatt-hour per kilowatt
Mt	millions of tons
Ha	hectare
h	Hours
masl	meters above sea level

References

1. Holechek, J.L.; Geli, H.M.E.; Sawalhah, M.N.; Valdez, R. A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050? *Sustainability* **2022**, *14*, 4792. [CrossRef]
2. Moriarty, P.; Honnery, D. Review: Renewable Energy in an Increasingly Uncertain Future. *Appl. Sci.* **2023**, *13*, 388. [CrossRef]
3. Hou, H.; Lu, W.; Liu, B.; Hassanein, Z.; Mahmood, H.; Khalid, S. Exploring the Role of Fossil Fuels and Renewable Energy in Determining Environmental Sustainability: Evidence from OECD Countries. *Sustainability* **2023**, *15*, 2048. [CrossRef]
4. Bhatt, U.S.; Carreras, B.A.; Barredo, J.M.R.; Newman, D.E.; Collet, P.; Gomila, D. The Potential Impact of Climate Change on the Efficiency and Reliability of Solar, Hydro, and Wind Energy Sources. *Land* **2022**, *11*, 1275. [CrossRef]
5. Solé, J. Climate and Energy Crises from the Perspective of the Intergovernmental Panel on Climate Change: Trade-Offs between Systemic Transition and Societal Collapse? *Sustainability* **2023**, *15*, 2231. [CrossRef]
6. Moriarty, P.; Honnery, D. Energy efficiency or conservation for mitigating climate change? *Energies* **2019**, *12*, 3543. [CrossRef]
7. Seminario-Córdova, R.; Rojas-Ortega, R. Renewable Energy Sources and Energy Production: A Bibliometric Analysis of the Last Five Years. *Sustainability* **2023**, *15*, 10499. [CrossRef]
8. Moreno, J.; Medina, J.P.; Palma-Behnke, R. Latin America's Renewable Energy Impact: Climate Change and Global Economic Consequences. *Energies* **2024**, *17*, 179. [CrossRef]

9. Seminario-Córdova, R. Latin America towards Sustainability through Renewable Energies: A Systematic Review. *Energies* **2023**, *16*, 7422. [CrossRef]
10. Peyerl, D.; Barbosa, M.O.; Ciotta, M.; Pelissari, M.R.; Moretto, E.M. Linkages between the Promotion of Renewable Energy Policies and Low-Carbon Transition Trends in South America's Electricity Sector. *Energies* **2022**, *15*, 4293. [CrossRef]
11. Oliveira, J.C.; Nogueira, M.C.; Madaleno, M. Do the Reduction of Traditional Energy Consumption and the Acceleration of the Energy Transition Bring Economic Benefits to South America? *Energies* **2023**, *16*, 7121. [CrossRef]
12. Chabla-Auqui, L.; Ochoa-Correa, D.; Villa-Ávila, E.; Astudillo-Salinas, P. Distributed Generation Applied to Residential Self-Supply in South America in the Decade 2013–2023: A Literature Review. *Energies* **2023**, *16*, 6207. [CrossRef]
13. International Energy Agency. *Latin America Energy Outlook*; International Energy Agency: Paris, France, 2023. Available online: https://www.iea.org/reports/latin-america-energy-outlook-2023 (accessed on 6 September 2024).
14. Global Energy Monitor. *A Race to the Top: Latin America 2023*; Global Energy Monitor: San Francisco, CA, USA, 2023.
15. Cacciuttolo, C.; Navarrete, M.; Atencio, E. Renewable Wind Energy Implementation in South America: A Comprehensive Review and Sustainable Prospects. *Sustainability* **2024**, *16*, 6082. [CrossRef]
16. International Energy Agency. *World Energy Outlook 2023*; International Energy Agency: Paris, France, 2023. Available online: https://www.iea.org/reports/world-energy-outlook-2023 (accessed on 6 September 2024).
17. Borowski, P.F. Mitigating Climate Change and the Development of Green Energy versus a Return to Fossil Fuels Due to the Energy Crisis in 2022. *Energies* **2022**, *15*, 9289. [CrossRef]
18. Barthelmie, R.J.; Pryor, S.C. Climate change mitigation potential of wind energy. *Climate* **2021**, *9*, 136. [CrossRef]
19. Pedruzzi, R.; Silva, A.R.; dos Santos, T.S.; Araujo, A.C.; Weyll, A.L.C.; Kitagawa, Y.K.L.; Ramos, D.N.d.S.; de Souza, F.M.; Narciso, M.V.A.; Araujo, M.L.S.; et al. Review of mapping analysis and complementarity between solar and wind energy sources. *Energy* **2023**, *283*, 129045. [CrossRef]
20. Miyake, S.; Teske, S.; Rispler, J.; Feenstra, M. Solar and wind energy potential under land-resource constrained conditions in the Group of Twenty (G20). *Renew. Sustain. Energy Rev.* **2024**, *202*, 114622. [CrossRef]
21. Cacciuttolo, C.; Cano, D.; Guardia, X.; Villicaña, E. Renewable Energy from Wind Farm Power Plants in Peru: Recent Advances, Challenges, and Future Perspectives. *Sustainability* **2024**, *16*, 1589. [CrossRef]
22. Li, P.; Lian, J.; Ma, C.; Zhang, J. Complementarity and development potential assessment of offshore wind and solar resources in China seas. *Energy Convers. Manag.* **2023**, *296*, 117705. [CrossRef]
23. IRENA. *Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects*; International Renewable Energy Agency: Masdar City, United Arab Emirates, 2019.
24. Arredondo, J.; Ramos, M. Auctions in Renewable Energy and the Grid Parity Using Solar Photovoltaic Technology in Peru. *J. Phys. Conf. Ser.* **2021**, *1841*, 7. [CrossRef]
25. Ray, M.; Chakraborty, B. Impact of demand response on escalating energy access with affordable solar photovoltaic generation in the Global South. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110884. [CrossRef]
26. Verástegui, F.; Villalobos, C.; Lobos, N.; Lorca Negrete, M.; Olivares, D. An optimization-based analysis of decarbonization pathways and flexibility requirements in the Chilean electric power system. In Proceedings of the ISES Solar World Congress and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry, International Solar Energy Society, Santiago, Chile, 4–7 November 2019; pp. 1624–1635.
27. Ukoba, K.; Yoro, K.O.; Eterigho-Ikelegbe, O.; Ibegbulam, C.; Jen, T.C. Adaptation of solar energy in the Global South: Prospects, challenges and opportunities. *Heliyon* **2024**, *10*, e28009. [CrossRef] [PubMed]
28. Asencios, Y. The Importance of Hydrogen for Brazil: A source of clean energy and a path to the production of nitrogen fertilizers. *SciELO Prepr.* 2022.
29. Kamal Chowdhury, A.F.M.; Wessel, J.; Wild, T.; Lamontagne, J.; Kanyako, F. Exploring sustainable electricity system development pathways in South America's MERCOSUR sub-region. *Energy Strategy Rev.* **2023**, *49*, 101150 . [CrossRef]
30. Nahui, J.; Aguinaga, A.; Dávila, F.; Méndez, O. Incidence of load profiles in the Levelized Cost of Electricity for a solar-PV generation system located in Lambayeque-Perú. In Proceedings of the LACCEI International Multi-Conference for Engineering, Education and Technology, Latin American and Caribbean Consortium of Engineering Institutions, Virtual, 9–10 December 2021.
31. Murray, C.; Platzer, W.; Petersen, J. Potential for solar thermal energy in the heap bioleaching of chalcopyrite in Chilean copper mining. *Miner. Eng.* **2017**, *100*, 75–82. [CrossRef]
32. Vakulchuk, R.; Overland, I.; Scholten, D. Renewable energy and geopolitics: A review. *Renew. Sustain. Energy Rev.* **2020**, *122*, 109547. [CrossRef]
33. Cárdenas, L.; Icaza, D.; Cárdenas, M.; Mejía, F.; Icaza, F.; Flores, M. System of generation of energy based on solar energy for the rural political movements centers. In Proceedings of the 8th International Conference on Renewable Energy Research and Applications, ICRERA 2019, Brasov, Romania, 3–6 November 2019; pp. 100–106.
34. Pourasl, H.H.; Barenji, R.V.; Khojastehnezhad, V.M. Solar energy status in the world: A comprehensive review. *Energy Rep.* **2023**, *10*, 3474–3493. [CrossRef]
35. Mahn, D.; Best, R.; Wang, C.; Abiona, O. What drives solar energy adoption in developing countries? Evidence from household surveys across countries. *Energy Econ.* **2024**, *138*, 107815. Available online: https://linkinghub.elsevier.com/retrieve/pii/S0140988324005231 (accessed on 12 October 2023). [CrossRef]

36. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
37. Kirby, A. Exploratory Bibliometrics: Using VOSviewer as a Preliminary Research Tool. *Publications* **2023**, *11*, 10. [CrossRef]
38. Boaye Belle, A.; Zhao, Y. Evidence-Based Software Engineering: A Checklist-Based Approach to Assess the Abstracts of Reviews Self-Identifying as Systematic Reviews. *Appl. Sci.* **2022**, *12*, 9017. [CrossRef]
39. Jia, C.; Mustafa, H. A Bibliometric Analysis and Review of Nudge Research Using VOSviewer. *Behav. Sci.* **2023**, *13*, 19. [CrossRef] [PubMed]
40. Galván, A.; Haas, J.; Moreno-Leiva, S.; Osorio-Aravena, J.C.; Nowak, W.; Palma-Benke, R.; Breyer, C. Exporting sunshine: Planning South America's electricity transition with green hydrogen. *Appl. Energy* **2022**, *325*, 119569. [CrossRef]
41. Dei, T.; Hirata, K.; Ushiyama, I. Wind, photovoltaic and mini-hydro hybrid generation in Bolivia: A case study at a mountainous village. *Wind. Eng.* **2005**, *29*, 271–286. [CrossRef]
42. Buch, L.F.; Filho, W.L. An assessment of the potential and barriers for the diffusion of renewable energy technologies in Bolivia. *Int. J. Energy Technol. Policy* **2012**, *8*, 109–127. [CrossRef]
43. Silva, D.D.; Cardoso, E.M.; Basquerotto, C.; Pereira, J.A.; Turra, A.E.; Feldhaus, J. Outlook on the Brazilian scenario of floating photovoltaic solar energy. *Energy Rep.* **2023**, *10*, 4429–4435. [CrossRef]
44. De Sousa, N.M.; Oliveira, C.B.; Cunha, D. Photovoltaic electronic waste in Brazil: Circular economy challenges, potential and obstacles. *Soc. Sci. Humanit. Open* **2023**, *7*, 100456. [CrossRef]
45. David, T.M.; de Souza, T.M.; Rizol, P.M.S.R. Photovoltaic systems: A review with analysis of the energy transition in Brazilian culture, 2018–2023. *Energy Inform.* **2024**, *7*, 14. [CrossRef]
46. Matos, D.; Lassio, J.G.; Castelo Branco, D.; Pereira Júnior, A.O. Perspectives for Expansion of Concentrating Solar Power (CSP) Generation Technologies in Brazil. *Energies* **2022**, *15*, 9286. [CrossRef]
47. Barbosa de Melo, K.; Kitayama da Silva, M.; Lucas de Souza Silva, J.; Costa, T.S.; Villalva, M.G. Study of energy improvement with the insertion of bifacial modules and solar trackers in photovoltaic installations in Brazil. *Renew. Energy Focus* **2022**, *41*, 179–187. [CrossRef]
48. Carpio, L.G.T. Efficient spatial allocation of solar photovoltaic electric energy generation in different regions of Brazil: A portfolio approach. *Energy Sources Part B Econ. Plan. Policy* **2021**, *16*, 542–557. [CrossRef]
49. Nadaleti, W.C.; de Souza, E.G.; de Souza, S.N.M. The potential of hydrogen production from high and low-temperature electrolysis methods using solar and nuclear energy sources: The transition to a hydrogen economy in Brazil. *Int. J. Hydrog. Energy* **2022**, *47*, 34727–34738. [CrossRef]
50. de Souza, T.L.S.; Lima, R.L.F.A.; de Lima, C., Jr. Dirt on photovoltaic modules and efficient energy generation in the Brazilian semiarid. *Rev. Bras. Eng. Agric. E Ambient.* **2022**, *26*, 321–326. [CrossRef]
51. de Sousa Torres, G.; de Oliveira, T.A.P.; de Leles Ferreira Filho, A.; Melo, F.C.; Domingues, E.G. Techno-economic assessment of concentrated solar and photovoltaic power plants in Brazil. *Renew. Energy Power Qual. J.* **2021**, *19*, 583–588. [CrossRef]
52. Martelli, V.; Chimenti, P.; Nogueira, R. Future scenarios for the Brazilian electricity sector: PV as a new driving force? *Futures* **2020**, *120*, 102555. [CrossRef]
53. Viviescas, C.; Lima, L.; Diuana, F.A.; Vasquez, E.; Ludovique, C.; Silva, G.N.; Huback, V.; Magalar, L.; Szklo, A.; Lucena, A.F.; et al. Contribution of Variable Renewable Energy to increase energy security in Latin America: Complementarity and climate change impacts on wind and solar resources. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109232. [CrossRef]
54. Sulaeman, S.; Brown, E.; Quispe-Abad, R.; Müller, N. Floating PV system as an alternative pathway to the amazon dam underproduction. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110082. [CrossRef]
55. da Rocha Santos, F.; D'Angela Mariano, J.; Sestrem Junior, J.A.; Junior, J.U. Analysis of solar photovoltaic energy potential in Brazilian hydroelectric reservoirs through floating panels. *Braz. Arch. Biol. Technol.* **2019**, *62*, e19190012.
56. Vilaça Gomes, P.; Knak Neto, N.; Carvalho, L.; Sumaili, J.; Saraiva, J.T.; Dias, B.H.; Miranda, V.; Souza, S.M. Technical-economic analysis for the integration of PV systems in Brazil considering policy and regulatory issues. *Energy Policy* **2018**, *115*, 199–206. [CrossRef]
57. Urbanetz, I.V.; de Moura Netto, A.; Scolari, B.; Leite, V.; Urbanetz, J. Current panorama and 2025 scenario of photovoltaic solar energy in Brazil. *Braz. Arch. Biol. Technol.* **2019**, *62*, e19190011. [CrossRef]
58. Soria, R.; Lucena, A.F.P.; Tomaschek, J.; Fichter, T.; Haasz, T.; Szklo, A.; Schaeffer, R.; Rochedo, P.; Fahl, U.; Kern, J. Modelling concentrated solar power (CSP) in the Brazilian energy system: A soft-linked model coupling approach. *Energy* **2016**, *116*, 265–280. [CrossRef]
59. Fichter, T.; Soria, R.; Szklo, A.; Schaeffer, R.; Lucena, A.F.P. Assessing the potential role of concentrated solar power (CSP) for the northeast power system of Brazil using a detailed power system model. *Energy* **2017**, *121*, 695–715. [CrossRef]
60. Ferreira, A.; Kunh, S.S.; Fagnani, K.C.; De Souza, T.A.; Tonezer, C.; Dos Santos, G.R.; Coimbra-Araújo, C.H. Economic overview of the use and production of photovoltaic solar energy in brazil. *Renew. Sustain. Energy Rev.* **2018**, *81*, 181–191. [CrossRef]
61. Malagueta, D.; Szklo, A.; Soria, R.; Dutra, R.; Schaeffer, R.; Moreira Cesar Borba, B.S. Potential and impacts of Concentrated Solar Power (CSP) integration in the Brazilian electric power system. *Renew. Energy* **2014**, *68*, 223–235. [CrossRef]
62. Nogueira, C.E.C.; Vidotto, M.L.; Niedzialkoski, R.K.; De Souza, S.N.M.; Chaves, L.I.; Edwiges, T.; dos Santos, D.B.; Werncke, I. Sizing and simulation of a photovoltaic-wind energy system using batteries, applied for a small rural property located in the south of Brazil. *Renew. Sustain. Energy Rev.* **2014**, *29*, 151–157. [CrossRef]

63. de Martino Jannuzzi, G.; de Melo, C.A. Grid-connected photovoltaic in Brazil: Policies and potential impacts for 2030. *Energy Sustain. Dev.* **2013**, *17*, 40–46. [CrossRef]
64. Viana, T.S.; Rüther, R.; Martins, F.R.; Pereira, E.B. Assessing the potential of concentrating solar photovoltaic generation in Brazil with satellite-derived direct normal irradiation. *Sol. Energy* **2011**, *85*, 486–495. [CrossRef]
65. do Sacramento, E.M.; Sales, A.D.; de Lima, L.C.; Veziroglu, T.N. A solar-wind hydrogen energy system for the Ceará state-Brazil. *Int. J. Hydrog. Energy* **2008**, *33*, 5304–5311. [CrossRef]
66. Martins, F.R.; Pereira, E.B.; Silva, S.A.B.; Abreu, S.L.; Colle, S. Solar energy scenarios in Brazil, Part one: Resource assessment. *Energy Policy* **2008**, *36*, 2853–2864. [CrossRef]
67. Martins, F.R.; Rüther, R.; Pereira, E.B.; Abreu, S.L. Solar energy scenarios in Brazil. Part two: Photovoltaics applications. *Energy Policy* **2008**, *36*, 2865–2877. [CrossRef]
68. Neelkanth Dhere, B.G. THE DEVELOPMENT OF SOLAR PHOTOVOLTAIC ENERGY IN BRAZIL. *Sol. Cells* **1989**, *26*, 13–23. [CrossRef]
69. Da Silva, E.P.; Marin Neto, A.J.; Ferreira, P.F.P.; Camargo, J.C.; Apolinário, F.R.; Pinto, C.S. Analysis of hydrogen production from combined photovoltaics, wind energy and secondary hydroelectricity supply in Brazil. *Sol. Energy* **2005**, *78*, 670–677. [CrossRef]
70. Quiñones, G.; Felbol, C.; Valenzuela, C.; Cardemil, J.M.; Escobar, R.A. Analyzing the potential for solar thermal energy utilization in the Chilean copper mining industry. *Sol. Energy* **2020**, *197*, 292–310. [CrossRef]
71. Maximov, S.A.; Mehmood, S.; Friedrich, D. Multi-objective optimisation of a solar district heating network with seasonal storage for conditions in cities of southern Chile. *Sustain. Cities Soc.* **2021**, *73*, 103087. [CrossRef]
72. Viole, I.; Valenzuela-Venegas, G.; Zeyringer, M.; Sartori, S. A renewable power system for an off-grid sustainable telescope fueled by solar power, batteries and green hydrogen. *Energy* **2023**, *282*, 128570. [CrossRef]
73. Vargas Gil, G.M.; Bittencourt Aguiar Cunha, R.; Giuseppe Di Santo, S.; Machado Monaro, R.; Fragoso Costa, F.; Sguarezi Filho, A.J. Photovoltaic energy in South America: Current state and grid regulation for large-scale and distributed photovoltaic systems. *Renew. Energy* **2020**, *162*, 1307–1320. [CrossRef]
74. León, M.; Silva, J.; Ortíz-Soto, R.; Carrasco, S. A Techno-Economic Study for Off-Grid Green Hydrogen Production Plants: The Case of Chile. *Energies* **2023**, *16*, 5327. [CrossRef]
75. Cornejo-Ponce, L.; Vilca-Salinas, P.; Arenas-Herrera, M.J.; Moraga-Contreras, C.; Tapia-Caroca, H.; Kukulis-Martínez, S. Small-Scale Solar-Powered Desalination Plants: A Sustainable Alternative Water-Energy Nexus to Obtain Water for Chile's Coastal Areas. *Energies* **2022**, *15*, 9245. [CrossRef]
76. Behar, O.; Peña, R.; Kouro, S.; Kracht, W.; Fuentealba, E.; Moran, L.; Sbarbaro, D. The use of solar energy in the copper mining processes: A comprehensive review. *Clean. Eng. Technol.* **2021**, *4*, 100259. [CrossRef]
77. Haas, J.; Khalighi, J.; de la Fuente, A.; Gerbersdorf, S.U.; Nowak, W.; Chen, P.J. Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. *Energy Convers. Manag.* **2020**, *206*, 112414. [CrossRef]
78. Bayo-Besteiro, S.; de la Torre, L.; Costoya, X.; Gómez-Gesteira, M.; Pérez-Alarcón, A.; deCastro, M.; Añel, J. Photovoltaic power resource at the Atacama Desert under climate change. *Renew. Energy* **2023**, *216*, 118999. [CrossRef]
79. Hernández, C.; Barraza, R.; Saez, A.; Ibarra, M.; Estay, D. Potential map for the installation of concentrated solar power towers in Chile. *Energies* **2020**, *13*, 2131. [CrossRef]
80. Cardemil, J.M.; Cortés, F.; Díaz, A.; Escobar, R. Thermodynamic evaluation of solar-geothermal hybrid power plants in northern Chile. *Energy Convers. Manag.* **2016**, *123*, 348–361. [CrossRef]
81. Suuronen, A.; Lensu, A.; Kuitunen, M.; Andrade-Alvear, R.; Celis, N.G.; Miranda, M.; Perez, M.; Kukkonen, J.V.K. Optimization of photovoltaic solar power plant locations in northern Chile. *Environ. Earth Sci.* **2017**, *76*, 824. [CrossRef]
82. Starke, A.R.; Cardemil, J.M.; Escobar, R.A.; Colle, S. Assessing the performance of hybrid CSP + PV plants in northern Chile. *Sol. Energy* **2016**, *138*, 88–97. [CrossRef]
83. Mena, R.; Escobar, R.; Lorca Negrete-Pincetic, M.; Olivares, D. The impact of concentrated solar power in electric power systems: A Chilean case study. *Appl. Energy* **2019**, *235*, 258–283. [CrossRef]
84. Grágeda, M.; Escudero, M.; Alavia, W.; Ushak, S.; Fthenakis, V. Review and multi-criteria assessment of solar energy projects in Chile. *Renew. Sustain. Energy Rev.* **2016**, *59*, 583–596. [CrossRef]
85. Girard, A.; Roberts, C.; Simon, F.; Ordoñez, J. Solar electricity production and taxi electrical vehicle conversion in Chile. *J. Clean. Prod.* **2019**, *210*, 1261–1269. [CrossRef]
86. Agostini, C.A.; Nasirov, S.; Silva, C. Solar PV Planning Toward Sustainable Development in Chile: Challenges and Recommendations. *J. Environ. Dev.* **2016**, *25*, 25–46. [CrossRef]
87. Moreno-Leiva, S.; Díaz-Ferrán, G.; Haas, J.; Telsnig, T.; Díaz-Alvarado, F.A.; Palma-Behnke, R.; Kracht, W.; Román, R.; Chudinzow, D.; Eltrop, L. Towards solar power supply for copper production in Chile: Assessment of global warming potential using a life-cycle approach. *J. Clean. Prod.* **2017**, *164*, 242–249. [CrossRef]
88. Vega, M.I.; Zaror, C.A. The effect of solar energy on the environmental profile of electricity generation in Chile: A midterm scenario. *Int. J. Energy Prod. Manag.* **2018**, *3*, 110–121. [CrossRef]
89. Valenzuela, C.; Mata-Torres, C.; Cardemil, J.M.; Escobar, R.A. CSP + PV hybrid solar plants for power and water cogeneration in northern Chile. *Sol. Energy* **2017**, *157*, 713–726. [CrossRef]
90. Ferrada, P.; Araya, F.; Marzo, A.; Fuentealba, E. Performance analysis of photovoltaic systems of two different technologies in a coastal desert climate zone of Chile. *Sol. Energy* **2015**, *114*, 356–363. [CrossRef]

91. Jiménez-Estévez, G.; Palma-Behnke, R.; Román Latorre, R.; Morán, L. Heat and Dust: The Solar Energy Challenge in Chile. *IEEE Power Energy Mag.* **2015**, *13*, 71–77. [CrossRef]
92. Escobar, R.A.; Cortés, C.; Pino, A.; Salgado, M.; Pereira, E.B.; Martins, F.R.; Boland, J.; Cardemil, J.M. Estimating the potential for solar energy utilization in Chile by satellite-derived data and ground station measurements. *Sol. Energy* **2015**, *121*, 139–151. [CrossRef]
93. Cáceres, G.; Anrique, N.; Girard, A.; Degrève, J.; Baeyens, J.; Zhang, H.L. Performance of molten salt solar power towers in Chile. *J. Renew. Sustain. Energy* **2013**, *5*, 053142. [CrossRef]
94. Fuentealba, E.; Ferrada, P.; Araya, F.; Marzo, A.; Parrado, C.; Portillo, C. Photovoltaic performance and LCoE comparison at the coastal zone of the Atacama Desert, Chile. *Energy Convers. Manag.* **2015**, *95*, 181–186. [CrossRef]
95. Marcher, T.; Bauer, S.; Allende, M.; Mathiesen, C. Valhalla-Innovative pumped hydro storage facilities in Chile: Challenges from a rock mechanical point of view. *Geomech. Und Tunnelbau.* **2015**, *8*, 387–393. [CrossRef]
96. Larraín, T.; Escobar, R. Net energy analysis for concentrated solar power plants in northern Chile. *Renew. Energy* **2012**, *41*, 123–133. [CrossRef]
97. Parrado, C.; Girard, A.; Simon, F.; Fuentealba, E. 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. *Energy* **2016**, *94*, 422–430. [CrossRef]
98. Betancur, S.; Ortega-Avila, N.; López-Vidaña, E.C. Strengths, Weaknesses, Opportunities, and Threats Analysis for the Strengthening of Solar Thermal Energy in Colombia. *Resources* **2024**, *13*, 3. [CrossRef]
99. Villamizar, D.N.G.; Suárez, O.M.D.; Camperos, J.A.G. Technical and economic analysis of a photovoltaic solar system in Norte de Santander, Colombia. *J. Appl. Eng. Sci.* **2023**, *21*, 275–284.
100. López, A.R.; Krumm, A.; Schattenhofer, L.; Burandt, T.; Montoya, F.C.; Oberländer, N.; Oei, P.-Y. Solar PV generation in Colombia-A qualitative and quantitative approach to analyze the potential of solar energy market. *Renew. Energy* **2020**, *148*, 1266–1279. [CrossRef]
101. Abril, S.O.; Pabón León, J.A.; García Mendoza, J.O. Study of the benefit of solar energy through the management of photovoltaic systems in Colombia. *Int. J. Energy Econ. Policy* **2021**, *11*, 96–103. [CrossRef]
102. Carvajal-Romo, G.; Valderrama-Mendoza, M.; Rodríguez-Urrego, D.; Rodríguez-Urrego, L. Assessment of solar and wind energy potential in La Guajira, Colombia: Current status, and future prospects. *Sustain. Energy Technol. Assess.* **2019**, *36*, 100531. [CrossRef]
103. Mulcué-Nieto, L.F.; Echeverry-Cardona, L.F.; Restrepo-Franco, A.M.; García-Gutiérrez, G.A.; Jiménez-García, F.N.; Mora-López, L. Energy performance assessment of monocrystalline and polycrystalline photovoltaic modules in the tropical mountain climate: The case for Manizales-Colombia. *Energy Rep.* **2020**, *6*, 2828–2835. [CrossRef]
104. Aristizabal, A.J.; Ospina, D.; Castaneda, M.; Zapata, S.; Banguero, E. Optimal power flow model for building integrated photovoltaic systems operating in the andean range. *Indones. J. Electr. Eng. Comput. Sci.* **2019**, *16*, 52–58. [CrossRef]
105. Sandoval-Rodriguez, C.L.; Rincon-Quintero, A.D.; Angulo-Julio, C.A.; Lengerke, O.; Rodriguez-Nieves, A.J.; Castillo-Leon, N.Y. A parabolic solar collector for harnessing solar energy in Bucaramanga, Colombia. *Sustain. Eng. Innov.* **2023**, *5*, 151–160.
106. Orjuela-Abril, S.; Torregroza-Espinosa, A.; Duarte-Forero, J. Innovative Technology Strategies for the Sustainable Development of Self-Produced Energy in the Colombian Industry. *Sustainability* **2023**, *15*, 5720. [CrossRef]
107. Moreno, C.; Milanes, C.B.; Arguello, W.; Fontalvo, A.; Alvarez, R.N. Challenges and perspectives of the use of photovoltaic solar energy in Colombia. *Int. J. Electr. Comput. Eng.* **2022**, *12*, 4521–4528. [CrossRef]
108. Becerra-Fernandez, M.; Sarmiento, A.T.; Cardenas, L.M. Sustainability assessment of the solar energy supply chain in Colombia. *Energy* **2023**, *282*, 128735. [CrossRef]
109. Pedraza-Yepes, C.A.; Berdugo-Rolong, K.E.; Ruiz-Muñoz, D.E.; Higuera-Cobos, O.F.; Hernández-Vásquez, J.D. Feasibility Study for the Implementation of Photovoltaic Panels in Public Transportation in Barranquilla. *Energies* **2023**, *16*, 7161. [CrossRef]
110. Murillo, W.; Agudelo, H.D.; Mena, M.F.; Banguero, E.; Palomino, R.; Córdoba, S.; Aristizábal, A.J. Experimental techno-economic analysis of an autonomous photovoltaic system operating in Chocó, Colombia. *Energy Rep.* **2023**, *9*, 258–273. [CrossRef]
111. Rodríguez-Urrego, D.; Rodríguez-Urrego, L. Photovoltaic energy in Colombia: Current status, inventory, policies and future prospects. *Renew. Sustain. Energy Rev.* **2018**, *92*, 160–170. [CrossRef]
112. Ariza Taba, M.F.; Mwanza, M.; Çetin, N.S.; Ülgen, K. Assessment of the energy generation potential of photovoltaic systems in Caribbean region of Colombia. *Period. Eng. Nat. Sci.* **2017**, *5*, 55–60. [CrossRef]
113. Domenech, B.; Ferrer-Martí, L.; García, F.; Hidalgo, G.; Pastor, R.; Ponsich, A. Optimizing PV Microgrid Isolated Electrification Projects—A Case Study in Ecuador. *Mathematics* **2022**, *10*, 1226. [CrossRef]
114. Boero, A.; Agyenim, F. Modeling and simulation of a small-scale solar-powered absorption cooling system in three cities with a tropical climate. *Int. J. Low-Carbon Technol.* **2019**, *15*, 1–16. [CrossRef]
115. Lata-Garcia, J.; Jurado-Melguizo, F.; Sanchez-Sainz, H.; Reyes-Lopez, C.; Fernandez-Ramirez, L. Optimal sizing hydrokinetic-photovoltaic system for electricity generation in a protected wildlife area of Ecuador. *Turk. J. Electr. Eng. Comput. Sci.* **2018**, *26*, 1103–1114. [CrossRef]
116. Tian, A.; Zünd, D.; Bettencourt, L.M.A. Estimating Rooftop Solar Potential in Urban Environments: A Generalized Approach and Assessment of the Galápagos Islands. *Front. Sustain. Cities* **2021**, *3*, 632109. [CrossRef]
117. Zalamea-Leon, E.; Barragán-Escandón, A.; Ordoñez-Castro, A. Photovoltaic assessment to achieve energy neutral buildings and cities in equatorial Andean climate. *Renew. Energy Power Qual. J.* **2023**, *21*, 51–56. [CrossRef]

118. Cevallos Escandón, A.M.A.; Barraganescandón, B.E.A.; Zalamea-León, E.; Serrano-Guerrero, X. Hydrogen capacity for use in public transportation using the excess electricity generated by photovoltaics from rooftops in the urban area of Cuenca, Ecuador. *Renew. Energy Power Qual. J.* **2022**, *20*, 49–54. [CrossRef]
119. Cevallos-Escandón, A.; Barragan-Escandón, E.A.; Zalamea-León, E.; Serrano-Guerrero, X.; Terrados-Cepeda, J. Assessing the Feasibility of Hydrogen and Electric Buses for Urban Public Transportation using Rooftop Integrated Photovoltaic Energy in Cuenca Ecuador. *Energies* **2023**, *16*, 5569. [CrossRef]
120. Bermeo, I.; Matute, L.; Barragán-Escandón, E.; Serrano-Guerrero, X.; Zalamea-León, E. Technical and economic feasibility study of a solar plant on a commercial surface in azogues, Ecuador. *Renew. Energy Power Qual. J.* **2021**, *19*, 177–183. [CrossRef]
121. Gustavo, C.; Pessolani, B. An Application of the Multiple Streams Framework to the Analysis of the Inclusion of Solar Energy in the Energy Mix in Paraguay. *Lat. Am. Policy* **2016**, *7*, 163–186.
122. Love, T.; Garwood, A. Wind, sun and water: Complexities of alternative energy development in rural northern Peru. *Rural. Soc.* **2011**, *20*, 294–307. [CrossRef]
123. Canziani, F.; Vargas, R.; Castilla, M.; Miret, J. Reliability and energy costs analysis of a rural hybrid microgrid using measured data and battery dynamics: A case study in the coast of perú. *Energies* **2021**, *14*, 6396. [CrossRef]
124. Delgadillo, J.E.M.; Monterrey, G.M.P.; Aguilar, J.C.T.; Casaño, R.D.L.C. Photovoltaic technology employment in Peru. A literature review. *Eng. Solid Mech.* **2022**, *10*, 387–398. [CrossRef]
125. Canziani, F.; Vargas, R.; Gastelo-Roque, J.A. Hybrid Photovoltaic-Wind Microgrid With Battery Storage for Rural Electrification: A Case Study in Perú. *Front. Energy Res.* **2021**, *8*, 528571. [CrossRef]
126. Caravantes, D.; Carbajal, J.; Celis, C.; Marcelo-Aldana, D. Estimation of hydrogen production potential from renewable resources in northern Peru. *Int. J. Hydrog. Energy* **2024**, *50*, 186–198. [CrossRef]
127. Narvaez, G.; Bressan, M.; Pantoja, A.; Giraldo, L.F. Climate change impact on photovoltaic power potential in South America. *Environ. Res. Commun.* **2023**, *5*, 081004. [CrossRef]
128. De Barbosa, L.S.N.S.; Bogdanov, D.; Vainikka, P.; Breyer, C. Hydro, wind and solar power as a base for a 100% renewable energy supply for South and Central America. *PLoS ONE* **2017**, *12*, e0173820. [CrossRef] [PubMed]
129. Posso, F.; Zambrano, J. Estimation of electrolytic hydrogen production potential in Venezuela from renewable energies. *Int. J. Hydrog. Energy* **2014**, *39*, 11846–11853. [CrossRef]
130. Cacciuttolo, C.; Guardia, X.; Villicaña, E. Implementation of Renewable Energy from Solar Photovoltaic (PV) Facilities in Peru: A Promising Sustainable Future. *Sustainability* **2024**, *16*, 4388. [CrossRef]
131. Martinez, A.; Iglesias, G. Hybrid wind-solar energy resources mapping in the European Atlantic. *Sci. Total Environ.* **2024**, *928*, 172501. [CrossRef]
132. Costoya, X.; deCastro, M.; Carvalho, D.; Gómez-Gesteira, M. Assessing the complementarity of future hybrid wind and solar photovoltaic energy resources for North America. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113101. [CrossRef]
133. Gao, Y.; Meng, Y.; Dong, G.; Ma, S.; Miao, C.; Xiao, J.; Mao, S.; Shao, L. The wind-solar hybrid energy could serve as a stable power source at multiple time scale in China mainland. *Energy* **2024**, *305*, 132294. [CrossRef]
134. Barva, A.V.; Joshi, S. Empowering hybrid renewable energy systems with BESS for self-consumption and self-sufficiency. *J Energy Storage* **2024**, *82*, 110561. [CrossRef]
135. Zhang, R.; Lee, M.; Huang, L.; Ni, M. Optimization of battery energy storage system (BESS) sizing in different electricity market types considering BESS utilization mechanisms and ownerships. *J. Clean. Prod.* **2024**, *470*, 143317. [CrossRef]
136. Kurdi, Y.; Alkhatatbeh, B.J.; Asadi, S. The influence of electricity transaction models on the optimal design of PV and PV-BESS systems. *Sol. Energy* **2023**, *259*, 437–451. [CrossRef]
137. Liao, J.T.; Chuang, Y.S.; Yang, H.T.; Tsai, M.S. BESS-Sizing Optimization for Solar PV System Integration in Distribution Grid. *IFAC-Pap.* **2018**, *51*, 85–90. [CrossRef]
138. Pinto, G.X.A.; Naspolini, H.F.; Rüther, R. Assessing the economic viability of BESS in distributed PV generation on public buildings in Brazil: A 2030 outlook. *Renew. Energy* **2024**, *225*, 120252. [CrossRef]
139. Engie. *Investor Presentation Engie Energía Chile*; Engie: Paris, France, 2023.
140. Nasirov, S.; Agostini, C.; Silva, C.; Caceres, G. Renewable energy transition: A market-driven solution for the energy and environmental concerns in Chile. *Clean Technol. Environ. Policy* **2018**, *2018*, 434. [CrossRef]
141. Zhang, H.L.; Baeyens, J.; Degrève, J.; Cacères, G. Concentrated solar power plants: Review and design methodology. *Renew. Sustain. Energy Rev.* **2013**, *22*, 466–481. [CrossRef]
142. Koondhar, M.A.; Albasha, L.; Mahariq, I.; Graba, B.B.; Touti, E. Reviewing floating photovoltaic (FPV) technology for solar energy generation. *Energy Strategy Rev.* **2024**, *54*, 101449. [CrossRef]
143. Djalab, A.; Djalab, Z.; El Hammoumi, A.; TINA, G.M.; Motahhir, S.; Laouid, A.A. A comprehensive Review of Floating Photovoltaic Systems: Tech Advances, Marine Environmental Influences on Offshore PV Systems, and Economic Feasibility Analysis. *Sol. Energy* **2024**, *277*, 112711. [CrossRef]
144. Bennagi, A.; AlHousrya, O.; Cotfas, D.T.; Cotfas, P.A. Comprehensive study of the artificial intelligence applied in renewable energy. *Energy Strategy Rev.* **2024**, *54*, 101446. [CrossRef]
145. Shoaei, M.; Noorollahi, Y.; Hajinezhad, A.; Moosavian, S.F. A review of the applications of artificial intelligence in renewable energy systems: An approach-based study. *Energy Convers. Manag.* **2024**, *306*, 118207. [CrossRef]

146. Balachandran, G.B.; Devisridhivyadharshini, M.; Ramachandran, M.E.; Santhiya, R. Comparative investigation of imaging techniques, pre-processing and visual fault diagnosis using artificial intelligence models for solar photovoltaic system—A comprehensive review. *Meas. J. Int. Meas. Confed.* **2024**, *232*, 114683. [CrossRef]
147. Ghenai, C.; Ahmad, F.F.; Rejeb, O.; Bettayeb, M. Artificial neural networks for power output forecasting from bifacial solar PV system with enhanced building roof surface Albedo. *J. Build. Eng.* **2022**, *56*, 104799. [CrossRef]
148. Sharma, M.; Pareek, S.; Singh, K. An efficient power extraction using artificial intelligence based machine learning model for SPV array reconfiguration in solar industries. *Eng. Appl. Artif. Intell.* **2024**, *129*, 107516. [CrossRef]
149. Olabi, A.G.; Abdelkareem, M.A.; Semeraro, C.; Al Radi, M.; Rezk, H.; Muhaisen, O.; Al-Isawi, O.A.; Sayed, E.T. Artificial neural networks applications in partially shaded PV systems. *Therm. Sci. Eng. Prog.* **2023**, *37*, 101612. [CrossRef]
150. Al Smadia, T.; Handam, A.; Gaeid, K.S.; Al-Smadi, A.; Al-Husban, Y.; Khalid, A.s. Artificial intelligent control of energy management PV system. *Results Control Optim.* **2024**, *14*, 100343. [CrossRef]
151. Hassan, G.; Sami Yilbas, B.; Al-Sharafi, A.; Al-Sulaiman, F.; Abdulhamid Abubakar, A. Dust mitigation strategies concerning solar energy applications: A comprehensive review. *Sol. Energy* **2024**, *277*, 112728. [CrossRef]