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Review

Distributed Generation Applied to Residential Self-Supply in South America in the Decade 2013–2023: A Literature Review

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Abstract: The implementation of residential distributed generation (DG) in South America has shown significant growth in the last decade, driven by increased research on photovoltaics and renewable energy sources. Regulatory policies and business models have been crucial in fostering the adoption of DG in the region, with residential self-supply being the most receptive sector for implementing the concept. This article presents a literature review on DG as applied to residential self-supply in South America by comprehensively analyzing documents published between 2013 and 2023, applying the PRISMA methodology. In total, 37 literature resources have been systematically selected and reviewed to contribute to the identification of trends and developments in the field of DG in the residential sector, as well as to highlight areas that require further research and attention from stakeholders, including policymakers, investors, technology providers, and consumers in the South American context.

Keywords: distributed generation; net metering; regulatory policies; residential self-supply; renewable energy

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1. Introduction

Electricity plays a vital role in modern life, and its demand has experienced steady growth worldwide due to population growth, economic development, and urbanization [1]. Current electricity systems, based mainly on centralized generation and intensive use of fossil fuels, face significant challenges related to energy security, sustainability, and climate change [2,3]. These challenges have driven the search for more sustainable and decentralized solutions for energy generation and distribution, such as distributed generation (DG) [4]. DG refers to producing energy on a small scale and close to the point of consumption, using renewable and non-renewable energy sources. DG has become increasingly popular worldwide due to its multiple benefits, which include reducing losses in power transmission and distribution, decreasing reliance on interconnected power systems with large-scale centralized generation, and promoting the adoption of clean and renewable energy [4–6].

Electricity can be generated in two main ways: through renewable sources, which are those that can be naturally regenerated, such as solar and wind energy; and through non-renewable sources, which are those that are depleted as they are used, such as fossil fuels [2,4]. Transitioning to cleaner and renewable energy sources is an important goal in working to decrease greenhouse gas emissions, decarbonize the world's energy generation matrices, and achieve long-term sustainability. DG can be realized through various technologies, such as solar panels [7,8], wind turbines [2], thermal cogeneration systems [9], hydro microturbines, and biomass combustion systems [4]. These smaller-scale, renewable energy sources are more sustainable and less polluting than traditional fossil fuel power plants.

The residential sector is one of the primary energy consumers in South America and represents an area of great interest for DG application. Energy self-supply in the residential sector can reduce demand on electricity grids, promote energy efficiency, foster local development, and improve the population's quality of life. In addition, residential DG can favor social and energy inclusion in rural and remote areas where access to the power grid is limited [10]. Despite the potential of DG in the residential sector, its implementation in South America faces several challenges. These include the lack of adequate policies and regulatory frameworks [5,11], limited availability of financing [11,12], technical barriers [13,14], and the need to increase the awareness and education of the population regarding the benefits and opportunities of DG. Moreover, the geographic, economic, and cultural diversity in the region poses specific challenges for the adoption of DG in each country. The study of DG applied to the residential sector in South America is of utmost importance to understand and address the challenges and opportunities in the region.

This paper presents a literature review to provide a comprehensive view of the current state of DG applied to residential self-supply in South America. To ensure the review process's replicability, integrity, and transparency, a comprehensive analysis of the scientific literature published in 2013–2023 was conducted using the PRISMA methodology [15]. The findings of this study will contribute to identifying trends and developments in the field of DG in the residential sector, and to highlighting areas that require further research and attention from stakeholders, including policymakers, investors, technology providers, and consumers.

2. Literature Review Methodology

2.1. Study Selection Criteria

The data collection process began by searching for relevant scientific articles in the Scopus, Science Direct, and IEEE Xplore databases, using the search terms "distributed AND generation AND residential", and filtering for the time range from 1 January 2013 to 1 July 2023. In the Scopus database, it was possible to filter additionally by country. The filter "Country/territory" was added for the countries of Argentina, Brazil, Chile, Colombia, Ecuador, and Peru to refine the search for publications relevant to the South American region. The South American countries Bolivia, Guyana, Paraguay, Suriname, Uruguay, and Venezuela did not have articles indexed in Scopus for this search.

All types of publications other than scientific articles were excluded (thus excluding review articles, letters to the editor, opinion articles, conference abstracts, discussions, encyclopedias, and books). This was achieved by applying the filter "Document type: Article" in Scopus, "Article type: Research Article" in Science Direct, and the filter "Journals" in IEEE Xplore. This filter was unnecessary in SciELO since it only contains scientific articles.

To include articles written in Spanish (the official language in the region), the SciELO database was used, applying the filters for the same period and for all the countries that were available in the database (excluding Guyana and Suriname, which appeared in the database). Finally, in SciELO the search term "generación AND distribuida AND residencial" was applied.

2.2. Search Process and Selection of Studies

The review of articles was performed following the PRISMA methodology [15]. This methodology provides an approach to ensure the replicability, integrity, and transparency of searches for scientific articles to be used in systematic reviews or meta-analyses. Each step in the systematic review process is illustrated in Figure 1.

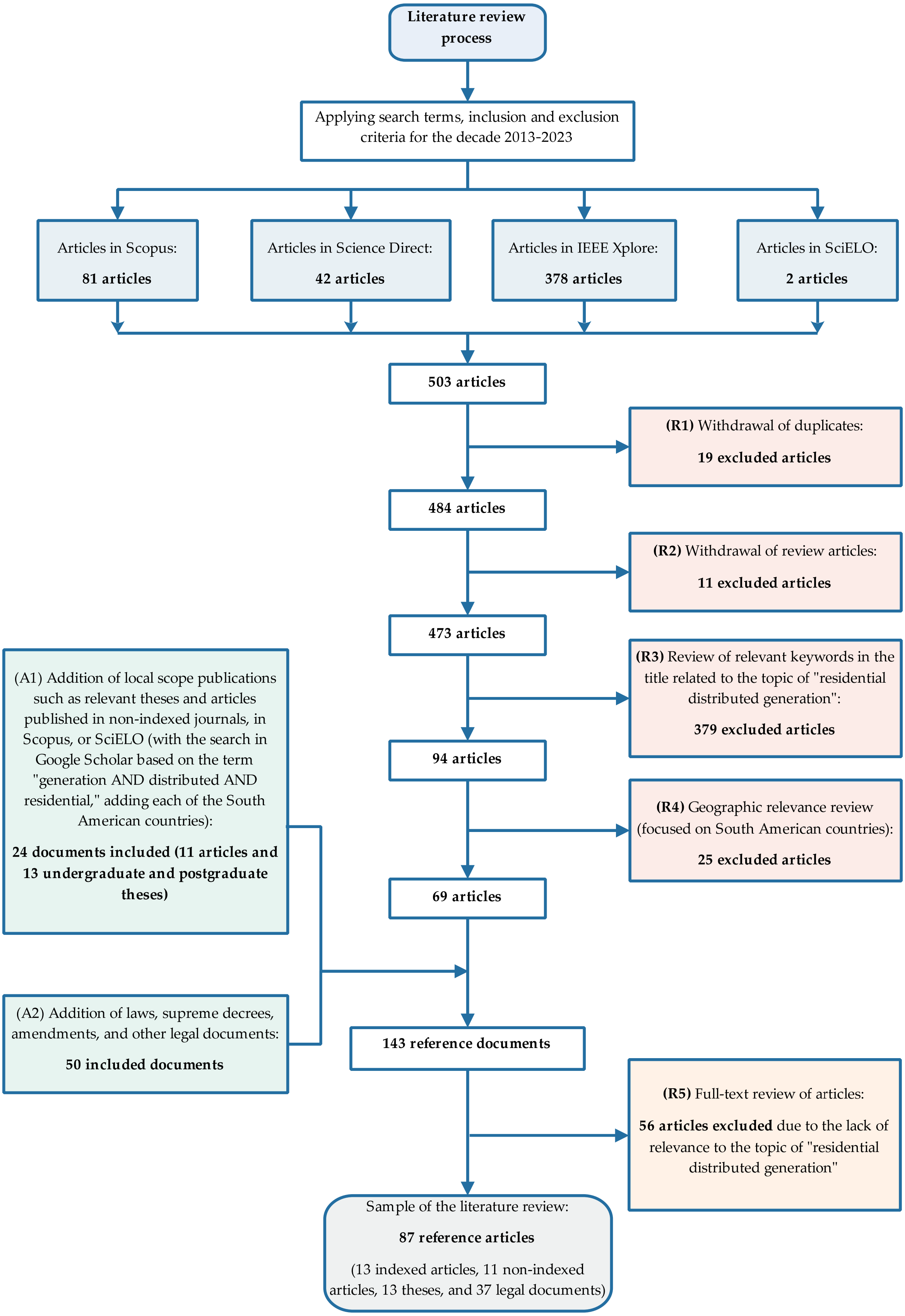

Figure 1. Flowchart of the literature review process.

Potentially relevant articles were extracted from each database, considering the inclusion and exclusion criteria defined in the previous section, which obtained 503 research papers. The metadata of each article was stored in an Excel database containing the URL link, title, authors, author keywords, indexing keywords (if available), abstract, journal name, volume and number, year of publication, DOI code, and search source (Scopus, Science Direct, IEEE Xplore, or SciELO).

According to the flowchart in Figure 1, a first review, R1, was performed to eliminate 19 duplicate articles in the database, leaving 484 articles. Then, a second review, R2, was carried out to discard review articles that were not correctly filtered by the database filters, eliminating 11 articles. At this point, the database consisted of 473 articles.

In order to identify the essential general topics covered in these articles, a third review, R3, was applied. With these results, two-word cloud plots were constructed to show those words that appeared in at least ten articles (threshold arbitrarily chosen to achieve clarity in the generated bibliometric layout), constructing (i) a word cloud plot with the keywords of the articles (Figure 2a); and (ii) a relevant word cloud plot of the article titles (Figure 2b). To generate these graphs, the stop words: prepositions, connectors, pronouns, and articles, among others, were eliminated using the base provided in [16]. From this analysis, the most prominent relevant words in the clouds that were thematically linked to residential distributed generation (DG) were considered: residential, distributed, generation, photovoltaic, microgrid, wind, solar, energy policy, demand response, energy efficiency, renewable energy, smart grids, and residential microgrid. The word energy was not considered because it was present in almost all articles evaluated and did not allow for information filtering.

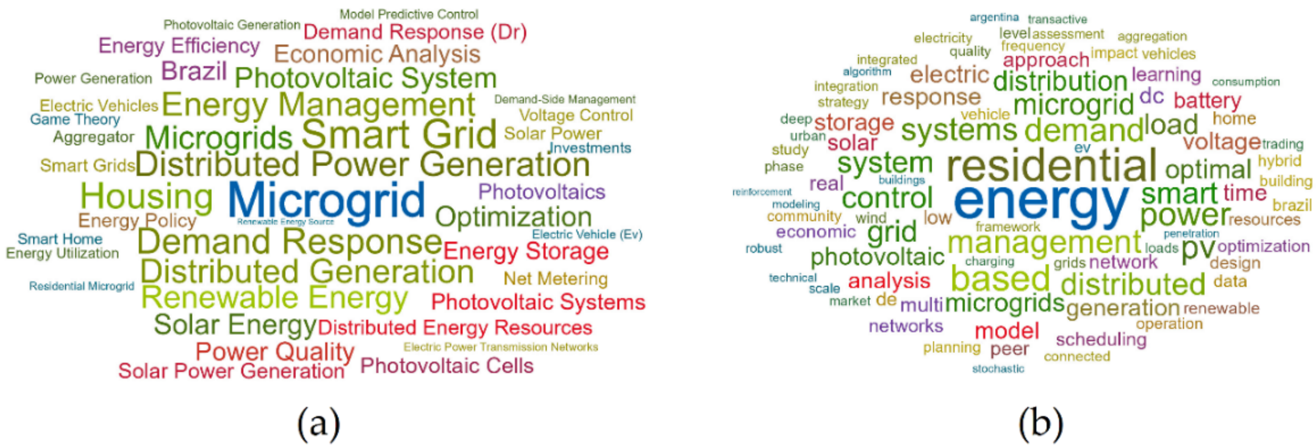

Figure 2. Word cloud plots for data visualization of: (**a**) article keywords and (**b**) relevant words of the article titles.

Subsequently, the R4 review was carried out (see Figure 1), wherein the geographical relevance of the articles was evaluated (given that not all databases allowed filtering by country; only Scopus allowed this). Those articles not involving direct information on the South American countries detailed in the previous section were discarded. Twenty-five articles were eliminated, leaving sixty-nine in the database. Table 1 summarizes all the inclusion and exclusion criteria used in the review.

2.3. Addition of Relevant Information Outside Indexed Articles

A second search for non-indexed articles and graduate and postgraduate theses was performed to include relevant information from outside of the indexed bases (Addendum, A1, in Figure 1). In the Google Scholar search engine, the temporal filter was applied for 2013–2023, and the search term "generation AND distributed AND residential" was entered, adding the name of each South American country. All PDF files available on the first two pages of each search for each country were extracted. We found 11 scientific articles from journals not indexed in Scopus, SciELO, IEEE Xplore, or Science Direct and 13 graduate theses of relevance to the main topic of this review. It should be noted that the articles considered here as non-indexed can be either non-indexed or indexed in databases such as Latindex, Redalyc, or ROAD.

Table 1. Criteria for the selection of research articles for the systematic literature review.

Concept	Type of Criterion	Criterion
Article Indexing	Inclusion	Article indexed in Scopus, Science Direct, IEEE Xplore, or SciELO.
Language of Publication	Inclusion	Spanish or English.
Date of Publication	Inclusion	Between 1 January 2013 and 1 July 2023.
Geographical Scope of the Publication	Inclusion	It deals with information applicable to South American countries: Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, and Venezuela.
Main Topic of the Publication	Inclusion	In the first instance, all articles contained in their title, abstract, or keywords the terms: distributed, generation, and residential; or its translation into Spanish: generación, distribuida, and residencial.
Type of Publication	Exclusion	All publications other than "original article" were excluded. Review articles, letters to the editor, opinion articles, conference abstracts, discussions, encyclopedias, and books, among others, were not included.
Keywords in Titles	Exclusion	All articles that did not include in their title the keywords: residential, distributed, generation, photovoltaic, microgrid, wind, solar, energy policy, demand response, energy efficiency, renewable energy, smart grids, and residential microgrid were excluded.

In addition, a Google search was performed for the technical standards, laws, supreme decrees, amendments, and other legal documents associated with DG in the South American countries (Addendum, A2, in Figure 1). Thirty-five legal documents were included, including laws, decrees, and amendments.

An exhaustive review of all collected documents was applied as a last step to verify their relevance, R5 (See Figure 1). Fifty-six scientific articles were withdrawn after verifying that they addressed methodological and theoretical topics associated with artificial intelligence, algorithms, control systems, and other conceptual issues that did not provide relevant information for the present review. Consequently, 87 reference documents were found to be used in the critical analysis presented in this review article. Of these, 13 were indexed articles, 11 were non-indexed articles, 13 were graduate theses, and 50 were legal documents.

2.4. Data Extraction and Synthesis Process

The extracted information was organized to address the topics on DG in the residential sector according to its type; policies and regulatory frameworks; implementation and adoption cases; economic, social, and environmental impact; challenges and barriers; opportunities. This process was carried out after a thorough review of each document considered for this review.

The graphics provided in following sections were made in RStudio [17], using the libraries countrycode [18], ggplot2 [19], ggpubr [20], ggwordcloud [21], stopwords [22], tidytext [23], and wordcloud [24].

3. Descriptive Analysis of the Literature on Residential DG in South America

The literature obtained in the search for information was critically analyzed under three key points: (i) the trend in the number of publications; (ii) to identify the topics of most significant interest in research on residential DG in South America; and (iii) to identify the journals with the highest volume of publications on residential DG in South America.

3.1. Trends in the Number of Publications

Distributed generation applied to residential self-supply in South America has experienced a significant evolution over the last decade. An upward trend was identified for each year when observing the number of publications associated with residential DG. At the beginning of the evaluated period, the number of publications was considerably low. From 2018 onwards, the scientific interest in DG increased dramatically. It should be considered that the low count observed in 2023 is because the review considered articles published up to July of the same year. The trend seems to be stable despite the reduction in articles obtained at each step of the filtering designed in this review (Figure 3). It is expected that, in the coming years, the amount of research in this field will continue to grow in line with countries' interest in its applications.

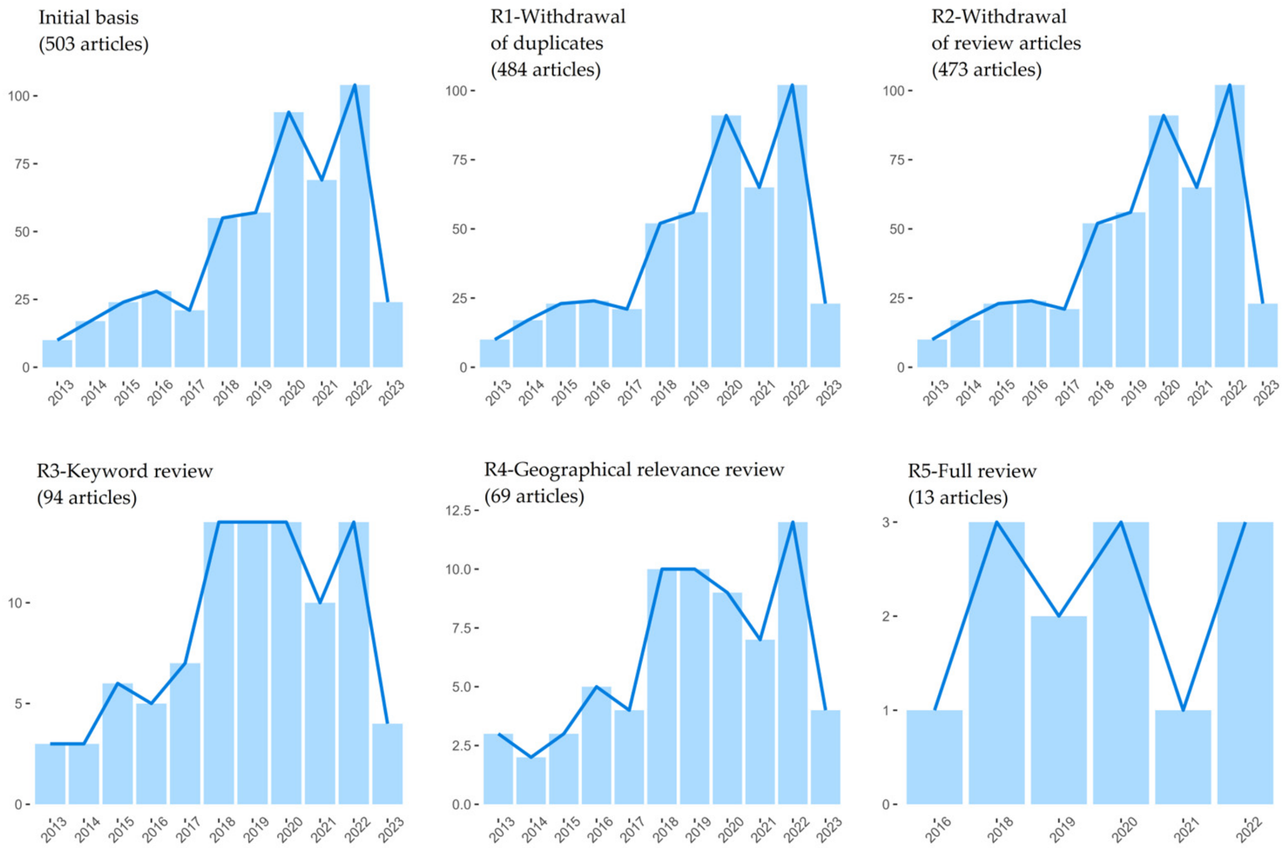

Figure 3. Trend in the number of publications on residential distributed generation for the articles obtained from the databases consulted for the review. The title of each graph indicates the corresponding stage in the flowchart of the literature review (Figure 1) and the number of scientific articles used in each case.

3.2. Topics of Research Interest

The key areas of interest and focus that researchers and practitioners in the region have explored have been identified through a review of the literature. The percentage of occurrence of keywords in selected papers (n = 37) was reviewed, excluding the 50 legal papers (Table 2, Figure 4). A central theme in the analyzed documents is the growing importance of using photovoltaic energy (78.38%) as the leading source technology for DG (54.05%). In general terms, there is an increasing focus on developing research on renewable energy sources (32.43%).

Table 2. Frequency of occurrence of keywords in the 37 scientific documents (13 indexed articles, 13 graduate theses, 11 non-indexed articles) obtained in the review. The keywords were grouped into general topics according to their thematic orientation.

General Topic	Keyword	Frequency of Appearance	Percentage
Photovoltaic Energy	solar energy, solar, solar power generation, solar generation power systems, photovoltaic solar energy, distributed photovoltaics, photovoltaic panel, photovoltaic distributed generation, photovoltaic generation, photovoltaic penetration, photovoltaic systems, residential PV systems, rooftop photovoltaic, grid connected photovoltaic systems	29	78.38%
Distributed Generation	distributed generation, distributed power generation, distributed energy resources (DER), distribution, energy sources, DG	20	54.05%
Energies From Non-Conventional, Renewable Sources	renewable energy, RE, non-conventional renewable energy sources, renewable energy sources (RES), RES integration	12	32.43%
Economy	business model, electricity market, markets, electric tariffs, financial analysis, feed-in tariffs, feed-in tariff, tariff design, value proposition, profitability	11	29.73%
Smart Grids	smart grid, on-grid systems, smart grid transformation, network, distribution network, grid connected, electrical distribution network, adapted network	9	24.32%
Regulatory Policies	regulatory framework, public policies, regulatory standard, economic regulation, mype, grid code	6	16.22%
Microgrids	residential photovoltaic distributed micro generation, microgrid (MR), microgeneration, microgrid optimization	6	16.22%
Energy Management	energy management, demand management, demand management strategies, energy management system (EMS)	6	16.22%
Levelized Cost of Electricity	levelized cost of electricity, average energy consumption levelized cost of electricity (LCOE)	5	13.51%
Energy Injection Systems	net metering, measurement, net billing	5	13.51%
Network Parity	grid parity	4	10.81%
Pollution	environmental pollution, carbon bonds, CO_2, GHG, SO_2	4	10.81%
Power Systems	power system analysis computing, power system		8.11%
Energy Utility	electric utility, impacts on a utility, low voltage utility networks	3	8.11%
Energy Saving	energy saving, energy efficiency	3	8.11%
Self-Consumption	self-sufficiency, self-consumption	2	5.41%
Storage	energy storage	2	5.41%
Incentives	incentive mechanisms	2	5.41%
Wind Energy	wind power	1	2.70%
Innovation	technological innovation	1	2.70%
Others	harmonics, electric vehicle, emulator, end-user decision, energy homeostasis, electric power, energy transition, FED, GDA, learning rates, load reallocation, Monte Carlo simulations, load profile modeling, NOX, vehicle to grid (V2G), California, Chile	1	2.70%

Figure 4. Word cloud plot of the keywords of the 37 scientific documents (13 indexed articles, 13 theses, 11 non-indexed articles) obtained in the review.

Thanks to recent research, improvements in the efficiency of photovoltaic systems in the last decade have allowed DG to reach grid parity (10.81%), which means energy savings. That implies that the costs of generating power through these systems are now comparable to, or even lower than, those of conventional power. Research into smart grids (24.32%), development of microgrids (16.22%), promotion of self-consumption (5.41%), and energy storage (5.41%) have marked a milestone in the adoption of DG systems in residential environments. All this development has resulted in incentives for homeowners to seriously consider investing in clean and sustainable energy solutions [10,25].

Regulatory policies (16.22%) and business models (29.73%) have also been crucial in adopting DG systems. Energy injection system schemes (net billing and net metering, 13.51%) and renewable energy regulations (32.43%) have provided an ideal scenario for increasing economic incentives. In addition, the legal framework implemented during the last decade has facilitated the implementation and growth of DG in South America [5,11,26,27].

However, there are still challenges facing DG systems in the region, including cost-effectiveness and economics (29.73%) and the need for a stronger regulatory framework [28]. As the levelized cost of electricity (13.51%) continues to decrease and technology advances, DG is likely to further establish itself as a viable and attractive solution for residential energy self-supply in South America [26]. The following sections will detail the findings of the review.

3.3. Scientific Journals with Production

Regarding the scientific journals that housed the 24 articles (13 indexed and 11 non-indexed) obtained in the review, none was found to show a predominant character (Table 3). The most significant scientific contribution came from the journal Ingeniare Revista Chilena de Ingeniería, indexed in SciELO, and IEEE Latin America Transactions, indexed in Scopus. Of the indexing sources, it was possible to identify that 50% (10 articles) are hosted in journals indexed in Scopus, 20% (4 articles) in Latindex, REDALYC, or ROAD, and 10% (2 articles) in SciELO. In addition, the remaining 20% (4 articles) belong to journals currently not indexed or in the process of being indexed.

Table 3. Frequency of publication in scientific journals of the 24 articles (13 indexed and 11 non-indexed) obtained in the review.

Journals	Indexing	Number of Articles
Ingeniare Revista Chilena de Ingeniería	SciELO	3
IEEE Latin America Transactions	Scopus	2
Renewable Energy	Scopus	2
Anuario de Relaciones Internacionales	Non-Indexed	1
Applied Energy	Scopus	1
Brazilian Archives of Biology and Technology	Scopus	1
Brazilian Journals of Business	Latindex, Redalyc, ROAD	1
CIDEL	Non-Indexed	1
Energies	Scopus	1
Energy Policy	Scopus	1
Energías Renovables y Medio Ambiente	Latindex, Redalyc, ROAD	1
IEEE Access	Scopus	1
Información Tecnológica	Non-Indexed	1
Ingeniería y Desarrollo	SciELO	1
Ingenius	Scopus	1
Lecturas de Economía	Scopus	1
Observatorio Latinoamericano y Caribeño	Latindex, Redalyc, ROAD	1
Revista Politécnica	Scopus	1
TecnoL	Non-Indexed	1
UIS Ingenierías	Latindex, Redalyc, ROAD	1

4. Distributed Generation Technologies in South America

4.1. Distributed Generation

Although there is no single definition, the concept of distributed generation (DG) has been proposed by several international organizations, such as the International Energy Agency (IEA), the International Council on Large Electric Systems (CIGRE), the Electric Power Research Institute (EPRI), and the Institute of Electrical and Electronics Engineers (IEEE) [3,29]. DG refers to the production of electrical energy through small generation plants located close to consumption points [3] as opposed to centralized generation in large power plants, often far from consumption points. DG uses non-conventional renewable energy sources (NCRE) such as solar, wind, biomass or hydroelectric, cogeneration, and energy storage technologies [29]. This form of power generation can improve energy efficiency, reduce transmission and distribution losses, increase grid resilience, and decrease greenhouse gas emissions [11,30].

In this regard, DG in South America is oriented towards micro-scale application. According to its power, DG is classified as micro DG (1 W to 5 KW power), small DG (5 KW to 5 MW), medium DG (5 MW to 50 MW), and large DG (50 MW to 300 MW) [3]. It is only in micro DG that consumers can create generation microgrids for self-consumption; larger distribution networks will always exist in the rest of the classes [2]. Microgrids are especially relevant because they seek to integrate renewable energy sources to meet energy demand, thus reducing local dependence on fossil fuels and other conventional energy sources [30]. Microgrids allow local communities, commercial entities, and campuses to quickly and efficiently increase the total electricity supply through local generators, photovoltaic cells, wind turbines, and other means [31,32].

4.2. DG Energy Sources Used in South America

Several NCRE technologies are found in the literature reviewed. Among them are solar photovoltaic energy [11,27,29,33–35], wind energy [27,28,36], geothermal energy, hydrothermal energy [34], biomass (incineration) [27,33], biogas (anaerobic digestion) [3,29], tidal (or ocean) energy [2,34], low-capacity hydroelectric energy [37], and cogeneration [11]. All of them have been and are being implemented or regulated as a response to the social, economic, and environmental problems linked to the use of fossil fuels in electricity generation, as well as to the vulnerability to climate change of countries that depend mainly on water sources for energy production [26,30].

South America's trend towards using DG as part of the countries' regular electricity generation system has been growing. Evidence of this is the increasing development of regulatory policies and incentives for investment in this type of technology based on NCRE [5,11,27]. The following is a description of the various renewable energy sources harnessed in DG in South America, based on the literature review from 2013 to 2023.

4.2.1. Photovoltaic Solar Energy

Photovoltaic solar energy is an attractive option for DG, being a sustainable solution to the depletion of fossil fuels. It is the most widely used alternative source for DG in South America [8,38,39], including promotion and legal regulations specifically aimed at it (Regulation No. ARCERNNR-001/21, Ecuador; Law 25.019, Argentina; Law No. 18,585 and Decree No. 451/011, Uruguay). This technology can be used directly for electricity supply, stored in batteries, or integrated into the electrical grid [33,37]. This clean and environmentally friendly technology can be installed on various scales, from residential systems to large solar plants [3,12]. Its implementation provides a decentralized approach for consumers to produce their own electrical power, which helps to reduce demand on distribution grids and improves the efficiency and sustainability of the overall energy system [3,34,37].

4.2.2. Small Wind Turbines

Wind energy is another renewable energy source that has experienced rapid growth in recent years [2]. It can be exploited either onshore or offshore, the second option being more expensive but with a higher generation potential due to the higher wind speed and stability [32,33]. This is a viable option for DG, especially in rural and isolated areas with limited access to the electric grid [4].

4.2.3. Small-Scale Hydroelectric Power

Hydropower is one of the oldest and most widely used renewable energy sources worldwide [1,2]. It is a relatively reliable and constant energy source as it does not depend on external factors such as the sun or wind that tend to vary on shorter time scales [35].

Hydropower can be an option for DG, especially in regions with abundant water resources and limited public grid access. However, it is essential to consider the potential environmental and social impacts associated with the construction of dams and reservoirs, such as the alteration of aquatic and terrestrial ecosystems and the displacement of local communities [1,2].

4.2.4. Batteries and Energy Storage Systems

Energy storage systems, such as batteries, play a crucial role in integrating and managing intermittent renewable energy sources such as solar and wind [28]. These systems allow for storing the energy produced during periods of high generation and releasing it when needed, improving the stability and reliability of the power grid [4,12]. Among the types of batteries most commonly used in DG are lithium-ion, nickel-cadmium, and lead-acid [30]. Energy storage systems can be implemented at residential, industrial, and commercial levels, facilitating self-consumption and participation in energy markets [4,28].

4.2.5. Other Emerging Technologies

Other emerging technologies could significantly impact DG in the near future. Some of these technologies include:

- *Fuel cells:* devices that directly convert chemical energy from a fuel, such as hydrogen or methanol, into electricity and heat through an electrochemical process without combustion [2,6,9].
- *Biogas:* a type of renewable energy obtained from the anaerobic decomposition of organic matter, such as agricultural, animal, or food industry waste [1]. It can be used to generate electricity and heat through cogeneration engines or gas turbines, or it can even be purified and converted into biomethane to be used as a substitute for natural gas [9]. Only one initiative in Brazil is relevant for implementing this technology. Other than that, it is a renewable energy source scarcely mentioned in the review literature.
- *Cogeneration systems:* technologies that allow the simultaneous generation of two forms of energy from a single fuel source, such as natural gas, biomass, or biogas. Cogeneration produces electricity and useful heat [9]. These systems are highly efficient and can significantly reduce fossil fuel consumption and greenhouse gas emissions compared to conventional generation. Their application is on a very small scale, in industries and buildings, as distributed micro-generation. Only one record of its application was obtained in Chile [9].
- *Wave and tidal energy:* technologies that take advantage of the movement of waves and tidal currents to generate electricity, with great potential in coastal and marine areas [2,4]. Despite this, it is contemplated in the legislation of Colombia (Law 1715 of 2014) and Peru (Legislative Resolution No. 30044) for possible regulation in the event of projects of this type in such countries.
- *Low enthalpy geothermal energy:* use of heat stored in the subsoil at accessible depths to generate electricity and heat through heat exchangers and geothermal heat pumps. In South American countries that have access to the Andes Mountains, the volcanic activity of these mountains provides large amounts of geothermal energy, being estimated, for example, at 950 MW in the specific case of Ecuador [1]. Other Andean countries would also have similar potential to be exploited in future projects.

5. Policies and Regulatory Frameworks in South American Countries

5.1. Analysis of Policies and Regulatory Frameworks at the Country Level

Although this review does not focus on the legal aspect of DG in South America, an intensive search was carried out on the policies implemented in each country in the energy aspect of DG. We found 50 legal documents, including laws, decrees, regulations, and resolutions, associated with energy regulation, of which Chile had seven, Argentina, Colombia, and Peru had six, Brazil, Ecuador, Uruguay, and Venezuela had five, Paraguay had three, and Bolivia had two. It is worth noting that Paraguay was the country with the oldest energy regulation legislation among the countries evaluated (1964). Before 2000, all countries already had at least one energy policy enacted. A significant international event for this milestone was probably the signing of the Kyoto Protocol in 1997. Likewise, Paraguay and Argentina were among the first countries to enact laws on renewable resources, followed closely by Peru and Uruguay.

Regarding enacting regulations that regulate and promote distributed generation, 14 legal documents were found that regulate and promote DG in South American countries (Table 4). Some countries have at least two documents (Brazil, Colombia, Ecuador, Peru, and Uruguay), and one, Bolivia, has no specific regulation for distributed generation. Paraguay was the pioneer country in establishing DG policies (Law No. 3009, 2006). The rest of the countries generated legislation after the Alianza de Energía y Clima de las Américas—EPCA of 2009 (Figure 5).

Table 4. Government policies that encourage and regulate distributed generation in South American countries.

Country	Policy	Description
Argentina	Ley N° 27.424	Regime for the Promotion of Distributed Generation of Renewable Energy Integrated to the Public Electricity Grid. This law establishes the legal and regulatory framework to promote the distributed generation of renewable energy in Argentina, allowing residential, commercial, and industrial users to generate energy from renewable sources and connect to the public electricity grid.
Bolivia	Ninguno	There is no specific law that directly promotes distributed generation in Bolivia. However, Law No. 6977, the General Electricity Law, and Law No. 3058, the Hydrocarbons Law, establish a regulatory framework for the electricity sector and encourage the development of renewable and alternative energies, which may include distributed generation projects.
Brazil	Resolução Normativa ANEEL N° 687/2015	This resolution, issued by the National Electric Energy Agency (ANEEL), establishes the regulatory framework for distributed generation in Brazil. The resolution introduces the Electric Energy Compensation System, which allows users to inject surplus energy into the grid and receive credits for subsequent consumption. This resolution modified and improved the previous grid-code (Resolução Normativa No. 482/2012), expanding energy compensation options and simplifying connection procedures for distributed generation systems.
Brazil	Lei N° 14.300/2022	This law, in force today, offers greater regulatory security to investors and consolidates the distributed generation market as one of the most attractive investments in the country. It also establishes a legal framework for distributed generation in the electricity sector.
Chile	Ley N° 20.571	This law establishes the legal framework for small-scale distributed generation, allowing users to inject surplus energy into the grid and receive compensation through the net billing mechanism.
Colombia	Ley 1715 de 2014	This law promotes the integration of non-conventional energy sources, including distributed generation, into the National Energy System. It establishes fiscal and economic incentives to promote investment in distributed generation projects.
Colombia	Resolución CREG 030 de 2018	This resolution defines the conditions for connecting distributed generation projects to the electric power distribution system and establishes the applicable tariffs for purchasing energy surpluses.
Ecuador	Regulación N° ARCERNNR-001/21	Issued by the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR), this regulation establishes the regulatory framework for distributed generation for the self-supply of regulated electricity consumers. It also defines the compensation scheme for surplus energy injected into the grid.
Ecuador	Resolución N° ARCERNNR-002/21	This resolution complements Regulation No. ARCERNNR-001/21 and establishes the technical and commercial conditions to be met concerning the development and operation of distributed generation plants owned by companies that the Governing Ministry authorizes to carry out the generation activity.
Paraguay	Ley N° 3009	As in Bolivia, no specific law directly promotes distributed generation in Paraguay. However, in addition to Law No. 966/64, which creates the National Electricity Administration (ANDE), this special regulation exists. This law establishes the regulations for the independent production and transportation of energy and regulates cogeneration and self-generation.
Peru	Decreto Supremo N° 028-2021-EM	This decree establishes the technical and economic conditions for connecting distributed generation facilities to the electricity system and applying the energy compensation mechanism (net billing).
Peru	Decreto Legislativo N° 1221	This law establishes incentives for generating electricity from renewable sources, including distributed generation projects.

Table 4. *Cont.*

Country	Policy	Description
Uruguay	Ley N° 18585	This law encourages the generation of electricity from renewable sources and establishes promotion mechanisms, including distributed generation.
Uruguay	Decreto N° 354/009	This decree regulates small-scale distributed generation in Uruguay and establishes the framework for connecting these systems to the electricity grid and compensation for energy surpluses.
Venezuela	Gaceta Oficial N° 39.823	Law of the Electric System and Electric Service of Venezuela (Official Gazette No. 39.823). This law seeks to promote distributed generation through the diversification of the energy matrix and the incorporation of renewable energy sources, as well as to promote the participation of the private sector and communities in generating electric energy.

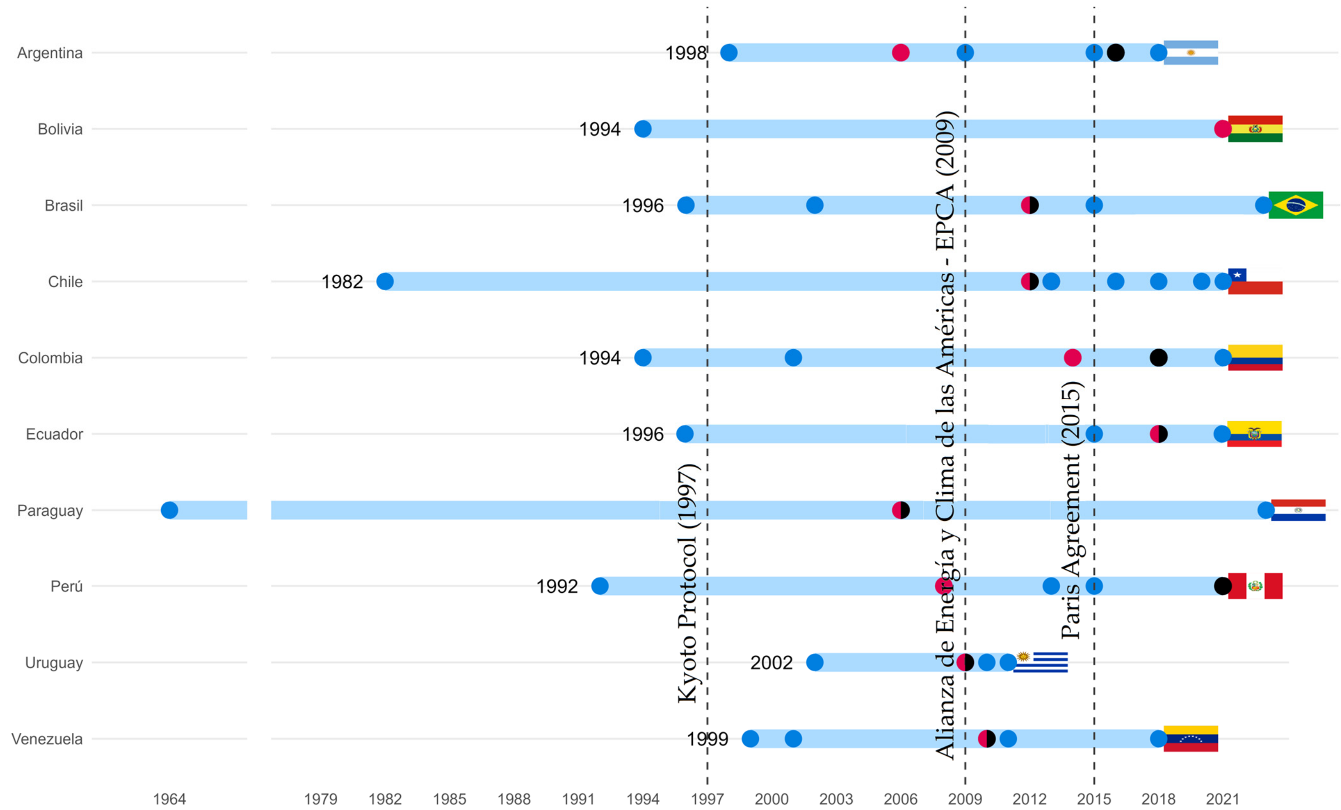

Figure 5. Timeline of energy and electricity legislation in South American countries. The year of the first national regulation per country, the first document on renewable energies (red circle), and the first specific document on distributed generation (black circle) are shown. The blue circles indicate the years in which new regulations appeared or existing regulations were updated. The semicircles indicate that both documents were dated in the same year. The dotted lines indicate key events: Kyoto Protocol (1997), Alianza de Energía y Clima de las Américas-EPCA (2009), and Paris Agreement (2015).

5.1.1. Argentina

The Renewable Energy in Rural Markets Project (PERMER), created in 1999, is Argentina's first DG experience, providing renewable energy to homes, schools, agricultural producers, and rural communities isolated from the Argentine Interconnection System (SADI). However, grid-connected DG began with the enactment of Law No. 27,424 in 2017, implemented through Decree 986/2018 and Resolution 314/2018. Technical Provision 28/2019 allows prosumers to install energy storage systems. The law seeks to promote energy efficiency, reduce losses in the interconnected system, reduce electricity system costs, protect the environment, and guarantee users' rights regarding equity, non-discrimination, and free access to services and facilities for electricity transmission and distribution [5,28,36].

Since 2010, due to national policies such as Law 26,190 and the GENREN Program, Argentina has experienced significant growth in installed PV capacity, focused on renewable sources [28]. Although there were two previous laws to promote renewable energy generation (Law 25,019 in 2006 and Law 27,191 in 2015), these focused on centralized generation through solar parks. Law 27,424 of 2017, on the other hand, represents a paradigm shift by allowing each household to be a point of distribution and generation of on-site energy, taking advantage of local resources [36].

5.1.2. Bolivia

In Bolivia, Law No. 3588/2007, "On Promotion and Development of the Use of Renewable and Non-Conventional Energies", establishes a legal framework for promoting and developing renewable and non-conventional energies, including DG. However, the lack of specific regulations and implementation of policies and support programs to promote DG and self-consumption have limited its development. In 2019, the Ministry of Hydrocarbons and Energy announced plans to boost DG in the country by creating an action plan that contemplates the implementation of compensation mechanisms and promotion of investment in the sector.

5.1.3. Brazil

In Brazil, the adoption of PV systems began in the electrification of remote and off-grid homes, later expanding to interconnected systems [12]. Initially, off-grid systems were implemented in research projects or through government initiatives during the 1990s. Subsequently, in the 2000s, power distribution companies began to employ PV systems to bring electricity to homes with difficulties in accessing the grid due to the high costs of extending cables or environmental constraints. These actions were carried out under regulation RN83 of 2004, established by the National Electric Energy Agency (ANEEL), in the context of the National Program for Universal Access to Electric Energy (Programa Luz para Todos). It was estimated that, by 2012, Brazil had between 30 and 40 MW of isolated PV systems [38].

In 2012, Brazil enacted ANEEL Resolução Normativa No. 482/2012, which regulates the access of DG systems to the electricity grid and establishes an energy compensation system, allowing consumers to offset the energy generated and consumed, thus reducing their electricity bills [36]. This resolution was amended in 2015 by ANEEL Resolução Normativa ANEEL N° 687/2015, which expanded the possibilities of DG and improved the conditions for connecting PV systems to the grid.

In addition, the country has implemented policies to incentivize the adoption of renewable energy, such as tax reductions and the promotion of financing for solar energy projects [11,12]. An example of this is the Distributed Power Generation Development Program (ProGD), launched in 2015, which aimed to increase the participation in DG in Brazil, primarily through PV systems. Until 2021, Brazil experienced significant growth in the adoption of PV systems and DG [38].

In 2022, the Lei N° 14.300/2022 [40] was enacted, establishing a legal framework for DG in Brazil's electricity sector. This law enhances regulatory security for investors and firmly consolidates the DG market as a highly attractive investment opportunity in the country. Whether for individual remote self-consumption or organized consumer groups through shared generation, DG installations receive compensation via energy credits from energy consumers. This mechanism empowers consumers to generate renewable energy and share excess energy with the grid.

However, recent trends have shown a reduction in the import of photovoltaic modules in Brazil. In the first half of 2023, photovoltaic module imports decreased by around 21% compared to the same period in 2022, as per Greener's survey [41,42]. This decline, mainly attributed to Centralized Generation (CG) projects slated for implementation in 2023–2024, aligns with changes in the DG market influenced by macroeconomic and political factors and the introduction of transitional rules under Lei N° 14.300/2022. This shift in the market landscape has led to decreased sales volumes of photovoltaic systems in the first quarter of 2023, accompanied by a rise in distributor equipment inventory. The price dynamics of photovoltaic systems have also experienced a drop, particularly in residential and small commercial setups, attributed to decreasing module costs and high wholesale inventory [43]. This evolving market scenario offers a comprehensive insight into Brazil's distributed generation dynamics during the evaluated period.

5.1.4. Chile

Although there is no official definition of DG in Chile, Law No. 20,571, enacted in 2012, establishes the legal framework for small-scale power generation and its connection to the grid (net billing). This law is complemented by Decree 88, amended in 2020, which regulates the sale of energy and surplus power at the instantaneous marginal cost and the node price of the power [32,36]. Law No. 20,257, enacted in 2008, establishes the promotion of non-conventional renewable energy sources and the diversification of the energy matrix. In addition, DFL 4/2018 establishes the regulatory framework for electric power transmission and open access to transmission and distribution facilities. Law No. 20,928 and Law No. 27,345 reinforce the promotion of renewable energies and the modernization of the electricity sector.

5.1.5. Colombia

Colombia has experienced significant advances in legislation for integrating non-conventional renewable energy sources into its regulatory framework. Law 1715 of 2014 is the starting point, establishing fiscal incentives such as income tax reduction, VAT and tariff exemptions, and accelerated asset depreciation. In addition, Law 143 (Electricity Law), Law 697 (Rational and Efficient Use of Energy), and Law 2099 also influence the country's energy sector.

Resolution CREG 030 of 2018 addresses the regulation of DG and self-generation activities on a small and large scale in the National Interconnected System. On the other hand, Resolution CREG 015 of 2018 and Resolution CREG 030 of 2018 established the rules for self-generation activity in Non-Interconnected Zones. These regulations represent a solid framework for developing and expanding DG and self-generation in Colombia, allowing non-conventional renewable energy sources to be included in the energy sector [11].

5.1.6. Ecuador

In Ecuador, the Organic Law of the Public Electric Energy Service (LOSPEE) enacted in 2015, establishes the legal and regulatory framework for the electricity sector. The Organic Law on Energy Efficiency, published in March 2019, seeks to promote energy's efficient, rational, and sustainable use in all its forms. The former Electricity Sector Regime Law was repealed, and Executive Decree 856 established the bases for generating, transmitting, and distributing electric power. Regulations No. ARCERNNR-001/21 and No. ARCERNNR-002/21 promote DG, self-consumption, and grid connection for small and medium-scale facilities. These regulations seek to strengthen the country's drive and coupling towards a sustainable change in its productive matrix and the incorporation of new technologies into its electricity master plan [27,28].

5.1.7. Paraguay

Distributed generation in Paraguay is mainly governed by Law No. 6977 and Law No. 3009, which establish a legal framework to promote the production and use of renewable energies. However, there is still a need to develop specific regulations and implement concrete measures to encourage DG and self-consumption. In 2019, Paraguay's Development Finance Agency (AFD) launched a credit line to finance DG and renewable energy projects, representing a step forward in promoting DG in the country. In addition, Law No. 966/64 establishes mechanisms to promote energy infrastructure development and cooperation between public and private entities in the electricity sector. Although promising, these initiatives still require additional actions and greater coordination among the different actors involved to achieve a significant impact in promoting DG and self-consumption in Paraguay.

5.1.8. Peru

In Peru, Legislative Decree No. 1221, promoted in 2015, encourages electricity generation from renewable sources and diversifies the energy matrix. Although this regulation boosts DG, a specific regulatory framework is still required for its application in self-consumption [3]. Legislative Resolution No. 30,044 and Decree-Law No. 25,844 establish the basis for the operation of the electricity sector, including the promotion of renewable energies.

In March 2021, the Peruvian Ministry of Energy and Mines (MINEM) presented the draft Supreme Decree No. 028-2021-EM, which seeks to promote DG and self-consumption of electricity from renewable sources, including compensation for surplus energy generated and access to incentives and tax benefits for those who implement DG systems. In addition, Bill No. 719/2021-CR, submitted to Congress, proposes changes in the electricity sector regulation that could boost the adoption of DG and self-consumption in the country. Although these initiatives represent significant advances in promoting DG in Peru, their approval and effective implementation must be reflected in the national energy sector [35,44].

5.1.9. Uruguay

Distributed generation in Uruguay began to be developed as of Decree No. 277/002 of 2002, focusing on auto producers and generators connected to medium voltage lines with a maximum capacity of 5 MW. Likewise, Decree No. 173/010, implemented in 2010, establishes net metering to encourage DG based on renewable sources, allowing users to exchange electricity with the distribution grid at equal rates. Uruguayan regulations define DG as generation from self-producers and generators connected to medium voltage lines, with a maximum capacity of 5 MW. Since 2009, Decree No. 354/009 limits the amount of energy that can be injected into the grid by facilities under the net metering regime to their annual consumption, aiming to promote self-supply and avoid the sale of energy. In addition, Decree No. 451/011 establishes tax benefits to promote investment in renewable energy and DG projects. Implementing these regulations has positioned Uruguay as a leader in the region in terms of adopting renewable energies and DG [36].

5.1.10. Venezuela

In Venezuela, energy policy has historically been focused on hydrocarbon exploitation, being a country with one of the largest oil reserves in the world. However, in recent years, efforts have been made to diversify the energy matrix and take advantage of renewable sources. In 2015, the Law of the Plan of the Homeland 2013–2019 (Official Gazette No. 6118) was enacted, establishing the diversification of the energy matrix and promoting DG being among its objectives.

The Organic Law of the Electric System and Service of 2010 (Official Gazette No. 39610) regulates the generation, transmission, distribution, and commercialization of electric energy in the country and establishes general principles on using renewable sources but does not explicitly address DG. In 2011, the National Center for DG Technology (CNTGD) was created as a body attached to the Ministry of People's Power for Electric Energy to promote DG projects based on renewable energy sources. Despite these efforts, no specific regulations have been implemented to facilitate the adoption of DG at the residential and commercial levels.

6. Implementation and Adoption of Distributed Generation in the Residential Sector in South America

This section investigates the burgeoning landscape of distributed generation (DG) in South America's residential sector. It explores adoption trends and successful projects, offering insights into the region's progress toward sustainable and decentralized energy solutions. Figure 6 offers a concise overview of the key findings in this context.

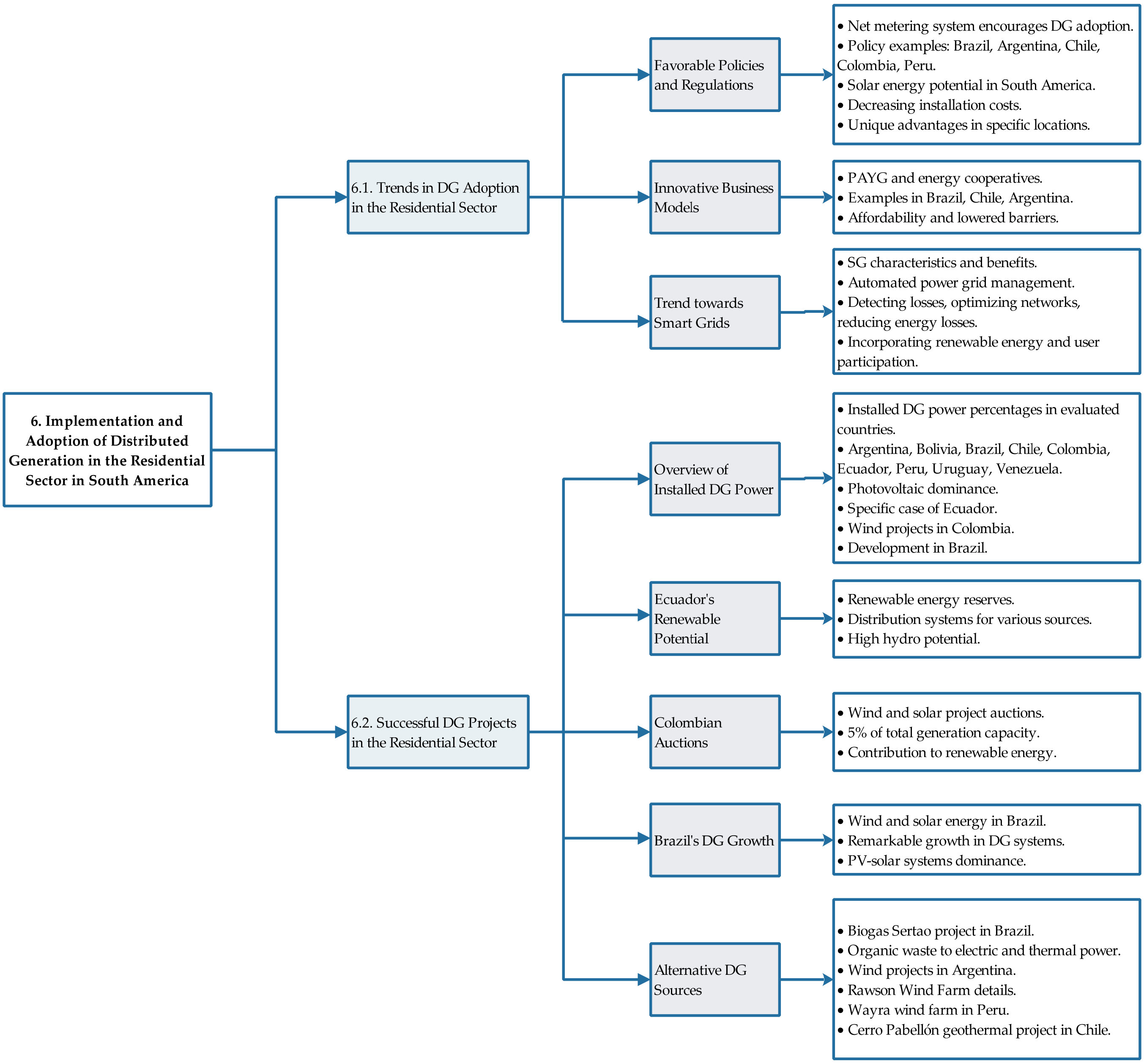

Figure 6. Overview of the key findings in the implementation and adoption of distributed generation in the residential sector in South America.

6.1. Trends in the Adoption of DG in the Residential Sector

The adoption of DG in the residential sector in South America has experienced remarkable growth in recent years, driven by several trends and factors. Among these, favorable policies and regulations, the growth of PV, the incorporation of innovative business models, and the trend towards smart grids (SG) stand out.

Regarding policies and regulations, the net metering system has been instrumental in encouraging the adoption of DG in the residential sector [35,39]. This measure allows consumers to sell surplus energy produced by their PV installations to the grid, thus encouraging investment in renewable generation systems. Countries such as Brazil, Argentina, Chile, Colombia, and Peru have implemented, or are in the process of implementing, this type of policy, contributing to the growth of photovoltaic energy in the region.

It is well known that South America has abundant solar resources, mainly in its areas with suitable slopes and deserts in the dry southern Andes and the Pacific desert coast between Peru and Chile [44]. These characteristics have favored the adoption of photovoltaic systems in the residential sector. It should be noted that each location has specific climatic characteristics that increase the advantages of using this technology. Investment in solar technologies is on the rise, which has generated a trend of lower installation costs and has made solar energy more accessible to consumers [6,11,39].

In the specific case of Ecuador, it is observed that the participation in renewable sources prevails in the highlands (56.0%) and the Amazon region (37.7%), with practically negligible participation in the coastal (5.4%) and insular (0.9%) regions. In these last two areas, the most significant problems of energy quality and efficiency accumulate and, counterintuitively, it is where the best radiation levels exist to promote photovoltaic energy.

Likewise, there are local initiatives to implement DG technologies other than solar or photovoltaic. Wind projects are scarcely developed in South America. A particular case wherein this renewable energy source outperformed solar was in the 2019 call of the Colombian Ministry of Mines and Energy, where six wind and two solar projects were obtained to be developed until 2022, generating a total award of 1398 MW [11].

Implementing business models like net metering is promising in South America. In this model, the energy sold is paid at the same price (or similar) to the purchase tariff for users with energy surplus in a DG system [10]. Incorporating new business models, such as the pay-as-you-go (PAYG) model and energy cooperatives, could facilitate DG adoption in the residential sector in South American countries [45]. The attempted implementation of this is only known to be occurring in the private sector in Brazil, Chile, and Argentina. These models allow consumers to access renewable energy systems more affordably and with lower barriers to entry for new users [10,26].

With the widespread adoption of DG and the development of appropriate regulatory policies, it is unsurprising that trends such as smart grids (SGs) are beginning to be considered in the South American landscape. SGs are characterized by the flow of electrical and control data information to create an automated and comprehensive distributed power grid. They allow for detecting non-technical losses, optimizing networks and reducing energy losses, remotely connecting and disconnecting customers, limiting supply power, incorporating DG (such as large-scale renewable energies), enabling user participation in the energy price market, creating load profiles, and automated restoration of the power grid before failures [12,28].

6.2. Successful DG Projects in the Residential Sector

In order to encourage the development of DG projects based on renewable energy sources in South America, several initiatives have been carried out. However, most of them are mainly linked to photovoltaic energy. For 2018, the percentage of installed DG power concerning the overall power of the evaluated countries fluctuated between 0.0% (Paraguay and Venezuela) and 3.5% (Peru), with the rest of the countries maintaining levels below 0.30% (Argentina with 0.03%; Uruguay and Bolivia with 0.05%; Chile with 0.07%; Ecuador with 0.08%; Brazil with 0.22%; Colombia with 0.26%) [46]. Some successful projects in the region are involved in these relatively low percentages.

In Ecuador, significant reserves of renewable energy sources are not adequately exploited [27]. In 2020, distribution systems were developed for various renewable sources, including biogas, wind, thermal, hydro, and solar energy. The effective installed capacity in Ecuador is 8080.39 MW, of which 64.9% corresponds to renewable energy sources [28].

Hydraulic sources represent 96.9% of the renewable sources, while only 3.1% corresponds to wind, solar and biomass combined. However, despite this high potential, the development of solar PV is still incipient, especially in micro DG [27]. The solar potential of some countries, such as Ecuador, may considerably exceed the exploitable hydroelectric potential [28].

In an effort to encourage the incorporation of alternative renewable energy sources, Colombia has held auctions. The Ministry of Mines and Energy (MME) auction in October 2019 awarded 1298 MW of installed capacity to five wind and three solar projects, equivalent to approximately 5% of the country's total generation capacity. In addition, with the 1398 MW awarded to six wind and two solar projects in the reliability-charge firm energy auction held in March 2019, these projects constitute about 11% of the total generation capacity in Colombia for non-conventional renewable energy [11].

In Brazil, wind energy accounted for 11.41% of the electricity matrix in 2021, while solar energy reached 2.53%. Large-scale hydroelectric and thermal power predominate the Brazilian electricity matrix, with 56.20% and 25.29%, respectively. The growth in Brazil has been remarkable, going from only two DG systems in 2012 to more than 185,867 pieces of equipment in 2021, of which 99.8% are solar [36].

Other examples of success applying GD with sources other than photovoltaic energy include the Biogas Sertao project in Pernambuco, Brazil. This initiative takes the organic waste of agro-industrial industries to produce electric and thermal power [47]. It is currently in the fundraising stage for its maintenance and development.

In the field of wind generation, Argentina has a large number of parks distributed over its territory. An outstanding example is the Rawson Wind Farm, located in the province of Chubut, one of the largest wind farms in South America, with a capacity of 377,900 MWh, 109 MW of installed capacity, and 55 wind turbines [48]. In Peru, the Wayra wind farm is one of the first wind power initiatives in the country. It is located in Marcona, department of Ica, and has two projects. Wayra I has 30 wind turbines, which provide a capacity of 132.3 MW and an annual average of 600 GWh, avoiding the emission of 258,000 tons of CO_2 equivalent each year. The Wayra extension is under development and will generate 177 MW of extra capacity [49].

Chile has been exploring and developing geothermal energy projects in recent years. The Cerro Pabellón project is the first geothermal plant in South America. It is located in the Atacama Desert, Antofagasta Region, and has two units with a gross installed capacity of 24 MW each for a total capacity of 48 MW. It produces 340 GWh per year, avoiding the emission of more than 166,000 tons of CO_2 equivalent into the atmosphere each year [50].

7. Economic, Social, and Environmental Impact of Residential DG in South America

Turning attention to the multifaceted impact of residential DG in South America, this section delves into its economic, social, and environmental dimensions. Examining factors influencing profitability and net metering adoption, as well as the pivotal role in curbing emissions, the following lines offer insights into DG's contribution to sustainability and societal welfare. An overview of critical insights is encapsulated in Figure 7.

7.1. Economic and Social Aspect of Residential DG

The profitability of distributed generation projects depends on several factors, including size, productive capacity, incentives, and the possibility of net metering. Net metering is the most widespread business model among DG projects in South America and is applied for PV generation [32]. Different scenarios of PV-powered microgrid projects were analyzed and it was found that, in the absence of net metering, projects with a production capacity greater than 10 kW generated economic losses, while smaller-scale projects were profitable. However, when net metering was included in the analysis, projects became more profitable.

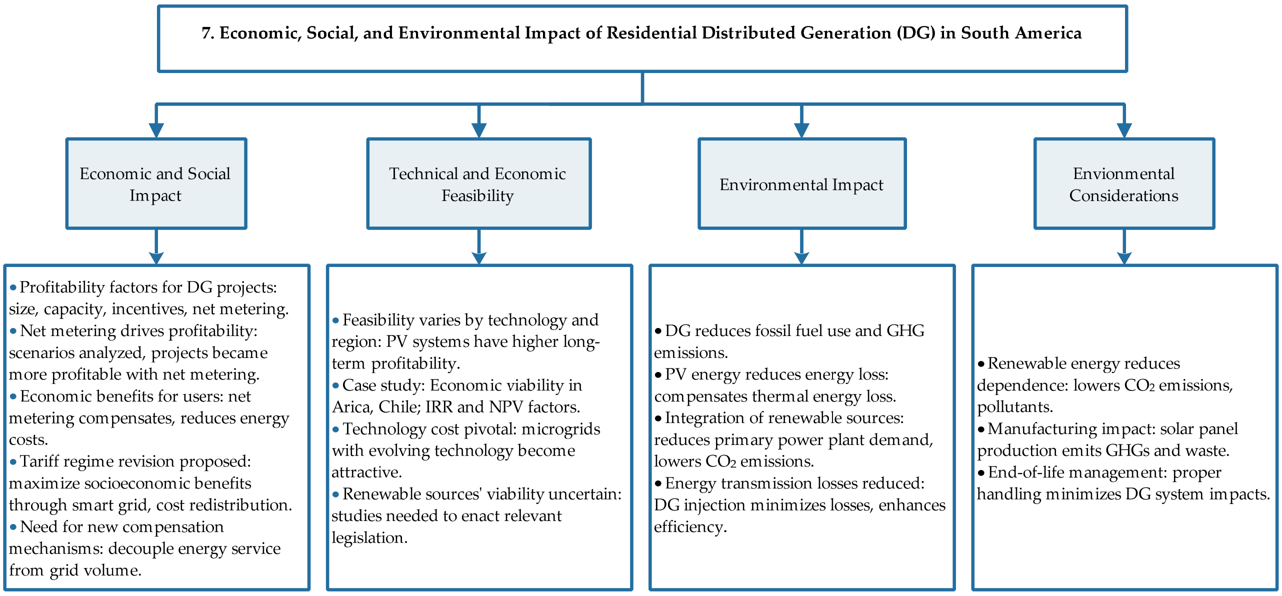

Figure 7. Insights into economic, social, and environmental impact of distributed generation in the residential sector in South America.

From the user's point of view, the scheme or business model under which the service of injecting surplus energy into the system is applied is relevant. Net metering generates the most significant economic benefit for the user since it is a compensation mechanism. The user's surplus balance can be used during the following month and reduce energy use costs [5,39]. In this sense [5,25], in the context of Argentina, we propose that a particular revision of the tariff regime imposed on users owning DG with photovoltaic sources is necessary. Power metering strategies, the use of smart grid, and redistribution of costs, among others, could be considered to maximize the socioeconomic benefit.

From the point of view of cost regulation, [44] argued that it is necessary to establish and promote new compensation mechanisms in the planning of DG processes. It is essential to decouple energy service compensation from the volume of energy distributed through the grid to ensure an environment that benefits both private investment and users. In addition, compensation schemes should evaluate the performance of distribution network operators and tariff periods should be increased gradually to drive investments in innovation with long payback periods. Since DG sources can be diverse, regulating costs can take years of political and legal decisions in each country.

In addition, the technical and economic feasibility of DG integration in various regions of South America depends on the technology and renewable energy source used. The results of [34] also revealed that, from a private perspective, small-scale DG projects were not profitable in any of the sectors studied, mainly due to high initial investment costs. However, these authors also highlighted that PV systems have lower unit energy production costs than other energy sources, resulting in higher medium- and long-term profitability.

In a particular application case in Arica, northern Chile, Ref. [8] found that DG projects were economically viable, provided that the Internal Rate of Return (IRR) was higher than the cost of capital and that the Net Present Value (NPV) was positive. In addition, these authors suggested that concentrating energy demand during sunshine hours might be more convenient than selling the generated electricity to the grid. However, for the country of Chile, it has been identified that medium- and small-size projects under Law 20.571, without the active participation of the state, are not profitable for a private company [51].

Another critical aspect, in addition to regulations and state support for private investment, is that implementing residential DG would be attractive for private actors once technologies in the area become more economical and reach grid parity levels [26]. Under current conditions, low-tech microgrid projects focused on generation could be economically viable. However, they do not outweigh the benefits of individual residential self-consumption in terms of costs and management. Several recent studies in Ecuador and Argentina identified that the use of DG for self-consumption is not viable because the initial cost of installation and maintenance of DG equipment is much higher than the value of the conventional energy tariff [26,52]. As innovative technologies become more widespread, such as electric vehicles that can function as batteries for the system, implementing microgrids with high technology content becomes more relevant [32].

The economic analysis for other renewable energy sources that can be implemented in DG remains uncertain in South America. Studies and simulations are needed to help identify the weak points of these technologies and, with this, to enact the pertinent legislation to encourage their massification.

7.2. Environmental Aspect of Residential DG

One of the advantages of implementing residential DG is its contribution to reducing greenhouse gas (GHG) emissions and other pollutants, and to decrease the use of fossil fuels generally used in industry, such as oil, coal, or natural gas, as well as in conventional thermal energy production. The penetration level, or injection percentage, of photovoltaic energy in a conventional thermal energy system has been proposed to reduce the use of conventional fuels and greenhouse gas emissions [6]. In any distribution system, there are energy losses in transformers and lines. Authors in [51] disaggregated the origin of the lost energy and found that a higher percentage of photovoltaic energy injection reduces, or compensates for, the energy loss fed by thermal energy by 28.1%.

Small- and medium-sized projects, including other DG sources such as photovoltaic, can reduce the energy production demand in the primary power plants by up to 33.51% [6]. If the power plant in question works with a conventional system of burning fossil fuels, greenhouse gas emissions are reduced by up to 1493.19 tons of CO_2 equivalent [6].

Likewise, any energy transmission and distribution process through lines and transistors generates an energy loss that is consumed from the original production source [4,5]. The surplus energy produced by residential DG that is injected into the primary system would help reduce the need for energy use to make up for energy losses. In conventional systems using thermal energy (burning fossil fuels), this reduces greenhouse gas emissions (tons of CO_2 equivalent) and generates greater energy efficiency.

Promoting the use of renewable energies reduces dependence on fossil fuels, which contributes to reducing CO_2 emissions and other pollutants. However, it is also essential to consider the environmental impacts associated with the manufacture, installation, and disposal of residential DG systems. For example, producing solar panels can generate GHG emissions and hazardous waste, although these impacts are minor compared to the emissions avoided during their lifetime. In addition, the end-of-life management of equipment and materials used in DG systems needs to be adequately managed to minimize impacts.

8. Challenges and Barriers to the Implementation of DG in the Residential Sector in South America

This section probes the intricate challenges hindering the integration of DG in South America's residential sector. Addressing technical obstacles, factors influencing implementation, innovation potential, and the role of private sector involvement, the discussion sheds light on impediments and opportunities in the DG landscape. An encapsulation of pivotal insights is presented in Figure 8, offering a broad perspective on the subject matter.

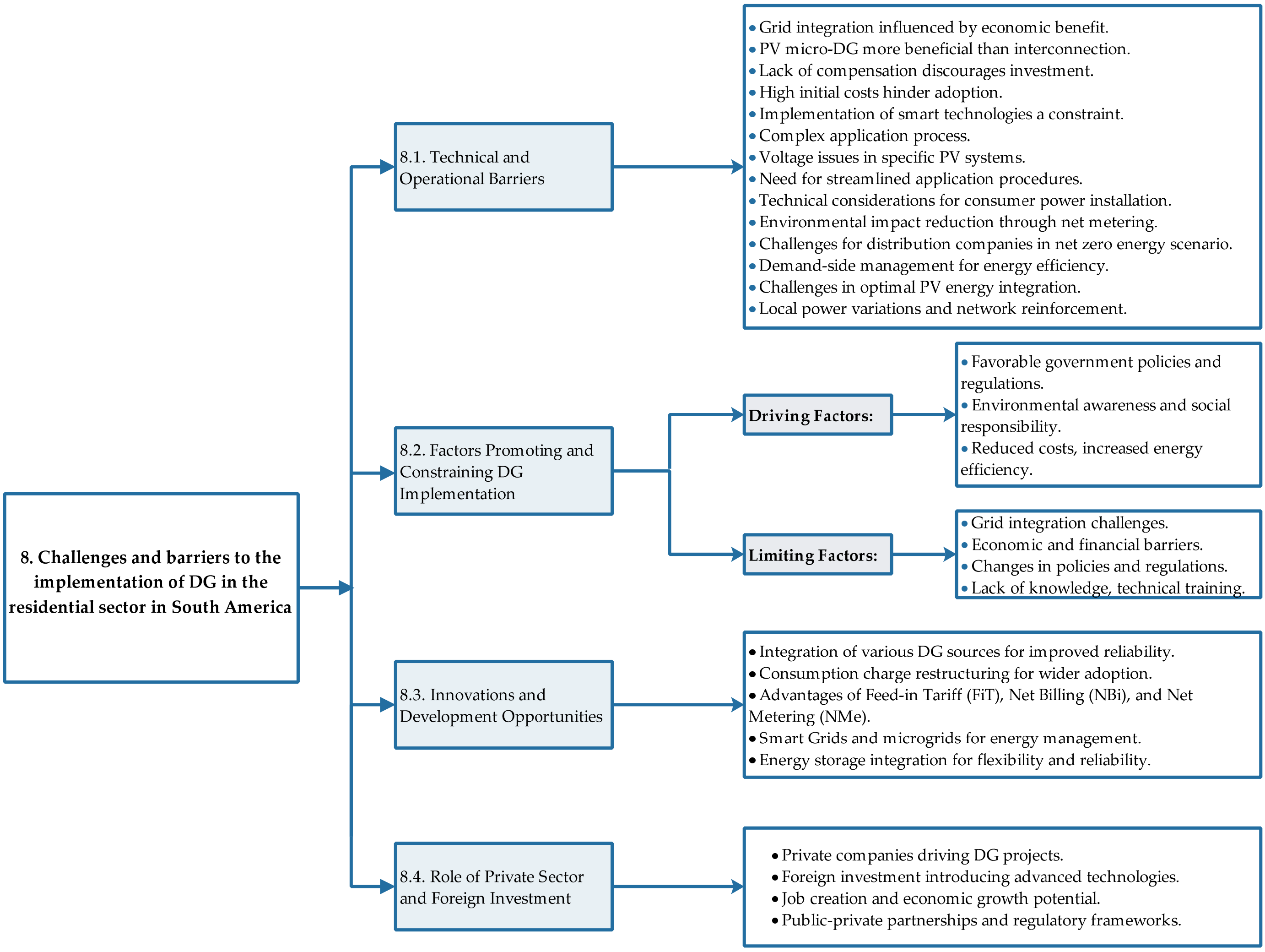

Figure 8. Overview of the critical insights derived from the exploration of challenges, factors, innovations, and the role of the private sector in implementing DG in South America.

8.1. Technical and Operational Barriers and Challenges

In South American countries, such as Peru, the grid integration of users using energy sources such as photovoltaic energy depends on the economic benefit it generates or fails to generate. It is currently known that distributed residential PV micro DG for self-consumption generates more significant benefits than being integrated into the interconnected power system [35].

In some cases, users inject photovoltaic energy and energy from other sources into the distribution system and are not economically rewarded nor compensated for reducing their monthly payment rate [35]. This barrier discourages new users from investing in residential DG systems.

At the economic level, an important constraint continues to be the initial cost of installing a residential DG system. Users should be able to access low-interest loans, state subsidies, or differentiated tax benefits to incentivize the adoption of these energy alternatives [35]. Another feature that can act as a barrier, at least in the short or medium term, is the implementation of smart technologies associated with smart grids, such as smart meters and control systems. While these can help to improve energy efficiency and reduce operating costs, installing and acquiring such equipment can be a significant constraint for developing regions.

The application process to connect a micro DG system is also a major barrier [35]. In this respect, it is important at the country level to reduce the bureaucracy behind these applications and to offer online application systems so that users feel comfortable with the administrative procedure required. This can be solved by private initiative or active collaboration between private entities and the state.

On a technical level, in specific PV systems, the maximum voltage at low voltage busbars has been observed as the percentage of PV power injected increases. Although there is no evidence that this increased voltage exceeds what is allowed by the standard, it must be considered that this regulation varies from country to country and that the voltage level will be mainly due to the system's characteristics. This barrier should be simulated and evaluated before implementing a medium or large DG project [6].

Technical constraints can always be addressed at the local level. National policies should consider the mediated reality of their systems, protocols, and technologies to adopt the DG systems they wish to implement progressively. For example, at the level of a consumer in residential systems, the maximum power that can be installed is associated with the product of the local voltage, the current supported by the circuit breaker at the entrance of the house or property, the number of phases, and the power factor [36]. These are all important considerations that projects must consider for their implementations. Furthermore, this generates fluctuations in the initial cost of installation, the final cost of service, and even the cost of injection in systems that use net metering.

In terms of reducing environmental impacts, implementing strategies such as net metering is attractive. There is even talk of net zero energy building, a scenario where users produce the same amount of energy as is consumed, their annual balance, input, and output, being zero. Reaching this point, although necessary for protecting nature, results in a destructive effect on distribution companies. They could have substantial economic losses, to the point of not being able to sustain and maintain the lines, transformers, and other systems that make possible both centralized generation and DG [44].

In the context of DG, demand-side management focuses on managing energy flows locally to reduce energy demand at times of high load and increase energy efficiency [1,53]. To this end, technologies such as smart meters are used, which can be programmed to automatically reduce energy consumption at times of high demand, which can help reduce the load on the power grid and avoid overloads on distribution transformers [33]. The current cost of equipment that allows the development of smart grids, and with it demand management, is high. The economic constraint could be a competitive disadvantage to conventional energy distribution. Although demand-side management can also help promote renewable energy use and reduce dependence on fossil fuels in the region, initiatives with significant private and state investment funds are required to reduce the installation prices that the end user regularly pays.

However, Ref. [7] evaluated different scenarios where different amounts of PV energy were injected into a system. Their results show that grids with lower transformer modulus allow a higher penetration of distributed photovoltaic generation (DPVG), increasing the cost per km^2. There is an optimal level of penetration that minimizes costs, but it is often not reached due to the capacity factor. For distribution companies, it is desirable to develop networks with lower costs per km^2, limiting the penetration of DPVG. Increasing penetration beyond that which is technically supported would imply networks with smaller transformer modules, resulting in higher costs per km^2, or modifications to the existing network architecture, such as increasing the number of transformers or changing the impedance, which would generate additional costs and would often be technically unfeasible. Furthermore, even for low levels of PV penetration, some systems will require reinforcement due to voltage issues to enable DPVG integration [13].

This reality varies with the conditions of each country. This same scenario evaluated in the Brazilian context has resulted in incipient viability [12], so it is expected that the entry of more users for DPVG in the country will shortly increase.

Overcoming the barriers above does not mean that DG technologies are free of limitations. It is to be expected that constraints associated with other types of energy distribution, such as those generated by various demand-side management scenarios, will continue to appear. The methods of selecting a user's load composition and identifying the user's demand profile are fundamental to energy system planning [54].

8.2. Factors Promoting and Constraining the Implementation of DG in the Residential Sector

The implementation of DG in the residential sector in South America is influenced by a combination of political, economic, social, and technical factors. In order to promote the adoption of DG in the region, these challenges need to be addressed by implementing appropriate policies and regulations, promoting public awareness and technical training, and strengthening grid infrastructure. The following are the factors driving DG implementation in the residential sector in South America:

- *Favorable government policies and regulations:* implementing policies and regulations that promote the adoption of DG technologies, such as tax incentives, subsidies, feed-in tariffs, and net metering systems, can significantly boost the adoption of these technologies in the residential sector. In each country, one regulation has led the way in promoting DG.
- *Environmental awareness and social responsibility:* growing concerns about climate change and environmental sustainability can motivate homeowners to adopt DG solutions to reduce their carbon footprint and contribute to the diversification of the energy matrix.
- *Reduced costs and increased energy efficiency:* the adoption of DG technologies can lead to savings in energy costs and improve the energy efficiency of homes. Lower equipment and component prices can also facilitate their adoption.

Along these lines, the main factors limiting the implementation of DG in the residential sector in South America have been identified:

- *Economic and financial barriers:* initial investment in DG systems can be high, making adoption difficult for households with limited resources. In addition, a lack of financing and accessible credit options can hinder the adoption of these technologies.
- *Changes in policies and regulations:* changing policies and regulations, such as lowering feed-in tariffs or removing incentives, can disincentivize the adoption of DG systems. A stable and predictable regulatory framework is essential to drive investment in this sector.
- *Lack of knowledge and technical training:* lack of information and awareness of the advantages and characteristics of DG technologies and lack of technical training for installation and maintenance can limit their adoption in the residential sector.
- *Challenges in grid integration:* the injection of energy generated by DG systems into the electricity grid may present technical and infrastructural challenges, such as upgrading and reinforcing distribution networks to support the increasing amount of distributed energy generated.

8.3. Innovations and Development Opportunities

Despite the benefits of DG, completely replacing other conventional power generation sources with sources such as photovoltaics is not plausible in our reality. Even if the number of solar panels was infinite, an external grid would still have to deliver power during non-sunlight hours [6]. However, innovation will come from the integration of various DG sources. Creating mixed systems, i.e., where there are storage structures integrated into the system, would reduce the hourly gaps in energy production by sources dependent on environmental conditions, such as wind, sun, or tides [33], and consumers could use this energy at times of low or no wind, photovoltaic, or ocean generation, as appropriate.

One of the innovations at the management level needed for DG to become widespread worldwide is the structure of consumption charges. To accelerate the penetration of this type of system, based on the experience of European countries, it is necessary to implement incentive mechanisms such as Feed-in Tariff (FiT), Net Billing (NBi) and Net Metering (NMe) [5]. The pioneering countries in this area are Germany, Spain, Italy, and Japan. The level of integration of DG in their national energy systems is remarkable. The economic management mechanism that these countries have adopted is the payment of a differential tariff, FiT, paying a different tariff depending on the size or typology of the systems, and with dynamic cost reduction using both probabilistic methods [55] and based on the annual reduction in the cost of the technologies [54].

In South American countries, the NMe and NBi business models are used [39]. Net metering allows users connected to the system to receive credits on their electricity bill for the energy they produce and supply to the grid. On the other hand, net billing allows users connected to the system to sell the surplus energy they produce to the utility company and receive payment for it. Both policies have advantages and disadvantages, depending on the specific legislation of each country or region. Implementing the correct legal regulations to promote NMe and NBi in South American countries is necessary.

The concept of smart grids to efficiently manage energy generation, distribution, and consumption in local communities is another relevant innovation in DG in South America [1,33,53]. Microgrids can increase the resilience of communities to potential disruptions in the centralized power grid and optimize the management of energy demand and supply [53].

Another key innovation in DG that goes hand in hand with smart grids [53] is integrating energy storage systems, such as batteries, which enable greater flexibility and reliability in power supply to households [14,56]. Energy storage can also facilitate the integration of intermittent renewable energy sources, such as solar and wind, into the power grid [53]. Since batteries account for 15–50% of the total cost of a photovoltaic project, it is critical to maximize their lifetime, using methods such as automatic switching systems between the power generated by the PV system and the municipal power grid [53]. In this way, if the capacity of the solar panels and batteries is insufficient to meet the demand, it is automatically switched to the municipal power grid supply. In addition to conventional batteries for storing solar energy, other storage alternatives conserve energy in the form of heat, expanding the options available for thermal applications [56].

8.4. The Role of the Private Sector and Foreign Investment in DG Promotion

The private sector and foreign investment are key in promoting DG in South America. Both local and international private companies can develop, finance, and manage DG projects, thus expanding the energy infrastructure and increasing the efficiency of energy supply in the residential sector. For example, Enel, a multinational energy company, has actively promoted DG projects in Argentina, Brazil, Colombia, and Peru, generating 16,116 MW and a supply reaching 23.3 million users [57]. In addition, foreign investment in renewable energy and DG projects can introduce more advanced technologies and innovative business models, increasing the sector's competitiveness and quality of services.

On the other hand, private sector involvement and foreign investment in promoting DG can also boost job creation and economic growth. For example, Germany's SMA Solar Technology AG, a world leader in solar inverter technology, has invested in production and training facilities in Chile. Its facilities provide a capacity of 137.6 MW, generating employment and knowledge transfer in the region [58]. In addition, public–private partnerships and collaboration between governments and companies can create more favorable regulatory frameworks and promote fiscal incentives, which in turn encourage more significant investment in DG projects in the region [45].

9. Discussion

The literature review on distributed generation (DG) applied to residential self-supply in South America lays a strong foundation for understanding the current landscape. Its robust methodology, emphasis on critical trends like photovoltaic (PV) prevalence, and implications for policy, research, and technology adoption render it a helpful resource for advancing DG within the residential sector of South America. Nonetheless, it could elevate its impact by addressing limitations and refining its focus on emerging technologies and socio-economic dimensions.

The review's strength lies in its inclusive approach, encapsulating a spectrum of renewable energy technologies and their application in residential DG. It notably underscores the dominance of PV solar energy, constituting a substantial portion of the examined papers. Highlighting the surge in DG adoption in the last five years, driven by PV systems and renewable sources, the review captures the field's dynamic evolution.

However, some limitations deserve consideration. While the review briefly introduces emerging technologies like fuel cells, biogas, and wave energy, a more thorough exploration of their potential, challenges, and feasibility could enhance comprehensiveness. Moreover, a more nuanced exploration of potential socio-economic implications and the role of community engagement in DG adoption could provide a holistic perspective.

The review accentuates the significance of regulatory policies and business models in propelling DG adoption, emphasizing the pivotal role of net metering. Nonetheless, while addressing challenges such as cost-effectiveness and regulatory robustness, further elaboration on policy effectiveness and potential implementation barriers could enrich the analysis.

Regarding implications and significance, the review underscores the need for additional research, particularly in domains such as cost-effectiveness, economics, and regulatory frameworks. Nevertheless, it could benefit from delving deeper into specific research questions that could guide future investigations. For example, a more comprehensive exploration of the socio-economic impacts of DG adoption, the dynamics of community engagement, and strategies to overcome technical barriers could provide valuable insights.

10. Recommendations

It is recommended to encourage and strengthen regulatory policies and business models that support adopting distributed generation systems in residential environments, focusing on promoting renewable energy sources such as photovoltaic energy. It is also essential to continue researching and developing emerging technologies in the field of DG, such as natural gas fuel cells, biogas, cogeneration systems, wave and tidal energy, and low-enthalpy geothermal energy, which could have a significant impact on sustainability and energy efficiency in the region. In addition, it is crucial to address economic and regulatory challenges to facilitate the cost-effectiveness and adoption of DG systems in the region.

On the other hand, it is suggested that South American governments and regulators work closely with industry and academia to establish and promote new compensation and regulatory mechanisms for DG processes. This will benefit both private investment and users while helping to reduce dependence on fossil fuels and increase energy efficiency. It is also essential to reduce bureaucracy in the application process to connect a DG system and facilitate access to low-interest loans, state subsidies, and differentiated tax benefits. Finally, the authors urge stakeholders to consider the environmental impacts associated with the manufacture, installation, and disposal of residential DG systems and to properly manage the end-of-life of the equipment and materials used to minimize impacts.

11. Conclusions

The literature review reported in this article offers a comprehensive analysis of the current status of distributed generation (DG) within the South American residential context. Its methodological robustness, adhering to the PRISMA methodology for systematic and transparent analysis, ensures the reliability and replicability of its findings. The study aims to identify trends, developments, and research gaps benefiting key stakeholders, including policymakers, investors, technology providers, and consumers.

A critical analysis of the literature found reveals that in the last decade, residential DG in South America has experienced significant growth, especially from 2018 onwards, driven mainly by using photovoltaic (PV) systems and adopting renewable energy sources. The use of PV is the leading topic in research on residential DG in South America, with 78.38% occurrence in the analyzed papers. Efficiency in PV systems has made it possible to achieve grid parity, which makes these systems more accessible and competitive compared to conventional energy. In addition, research in smart grids, microgrid development, self-consumption, and energy storage has marked a milestone in adopting DG systems in residential environments.

Regulatory policies and business models, such as net metering, have been fundamental in adopting DG systems, providing economic incentives and an adequate legal framework. Despite progress there are challenges in the region, such as cost-effectiveness, economics, and the need for a more robust regulatory framework. There is no marked dominance of one journal regarding scientific production on residential DG in South America. Nevertheless, two regional indexed journals emerged as the main contributors to the present survey.

DG in South America focuses on micro-scale applications, allowing consumers to create microgrids for self-consumption and promoting the integration of renewable energy sources. Solar photovoltaic energy is the most widely used option due to its sustainability and ease of implementation at different scales. Other renewable energy sources, such as wind, small-scale hydro, and biomass, are also used in regional DG projects, although to a lesser extent.

Energy storage technologies, such as batteries, are crucial to improving grid stability and reliability in DG systems using intermittent renewable energy sources such as solar and wind. In addition, emerging technologies such as natural gas fuel cells, biogas, cogeneration systems, wave and tidal energy, and low-enthalpy geothermal energy could significantly impact DG.

Implementing DG in South America can improve energy efficiency, reduce transmission and distribution losses, increase grid resilience, and reduce greenhouse gas emissions. DG adoption in the residential sector has grown in recent years due to favorable policies and regulations, the growth of PV, innovative business models, and the trend toward smart grids. Despite the challenges, South America has abundant solar resources and several success stories in Ecuador, Colombia, Brazil, Argentina, Peru, and Chile regarding using renewable energy sources such as solar, wind, biogas, and geothermal.

Finally, while the review encapsulates a diverse array of technologies, an avenue exists for more comprehensive discussions on select facets. For instance, the fleeting mentions of emerging technologies like fuel cells, biogas, and wave energy could substantially benefit from a deeper exploration, delving into their latent potential, challenges, and feasibility within the South American context. Moreover, the review's coverage could be augmented with a thoughtful consideration of potential socio-economic ramifications and the intricate role of community engagement in catalyzing the adoption of residential DG.

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