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A Comprehensive Evaluation of Off-Grid Photovoltaic Experiences in Non-Interconnected Zones of Colombia: Integrating a Sustainable Perspective

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Abstract: This research presents the findings of an evaluation of off-grid photovoltaic (PV) systems and their sustainability models in Colombia within the "Evaluation of Isolated Photovoltaic Systems and Their Sustainability Models" project supported by the Global Environment Fund (GEF). It involves the analysis of primary and secondary information on the photovoltaic energy projects for rural electrification in this country. Part of the information was obtained through interviews with different stakeholders who work in solar electrification in non-interconnected zones (NIZ), covering rural and island contexts. It was complemented by a comparative analysis of international projects implemented in Latin America. The results are shown as lessons learned, with a SWOT (strengths, weaknesses, opportunities, and threats) study representing the current situation of rural electrification with PV technology as perceived and describing the opportunities for the improvement of rural electrification strategies based on the successful experiences in the region. This research offers a comprehensive overview of how Colombian electrification could be led to address the last mile gap, integrating a solid sustainable perspective for the long-term view and ensuring community involvement towards a just energy transition. Therefore, this study proposes a series of guidelines to support those public policies that foster access to energy in the rural non-interconnected zones of Colombia.

Keywords: off-grid; photovoltaics; sustainability; rural electrification; mini-grids; solar home systems; NIZ; non-interconnected zones; Colombia

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1. Introduction

The investments made in the Latin American energy sector in recent decades have been remarkable. Thus, the quality of service has improved; the electricity loss has been reduced and the generation capacity, with a large percentage of renewable sources, has increased. Broadly, most countries have chosen to liberalize the market. They are electrifying rural areas with sustainable technologies, and their biggest challenge has been bringing an electrical power supply to isolated communities, mainly due to population dispersion and the difficulty in reaching these areas [1,2]. Although electricity coverage has reached more than 97%, in some countries, such as Bolivia, Peru, and Honduras, electrification efforts have concentrated on urban areas, where per capita income is higher and the costs of expanding the electrical grid are low, while the electrification rates of rural areas remain low, especially in Central America, the Andean region and the Amazon. The low access rates of these areas are explained by the poverty of the population and by the complex geographic characteristics of some regions, but also by the delays in the implementation of electrification policies or by the use of inappropriate designs both for the implementation and business model [3] and the technological solution. Many of the energy access projects, mainly based on top-down measures, suffered major deficiencies and failed, among the reasons can be cited: resources were not allocated to maintain and operate the equipment delivered to the communities, the beneficiaries were not trained to use or repair the systems, or there was a lack of regulations and institutions available to ensure the long-term sustainability of the projects [3–6].

In rural and remote areas, the service is not profitable enough to attract investors. Therefore, since the nineteen-nineties, national authorities have implemented specific electrification programs to ensure energy access to these areas. Furthermore, in most countries, social tariffs are set to increase the affordability of the service [3]. According to several studies [3,4,7–9], the adoption of renewable energies (RE) has become a cost-effective solution for rural areas, in which off-grid and small-scale electricity generation systems are often used. However, technology is not the only key to success. For these programs to succeed, the design of equipment and the choice of specific technological options must go beyond the technocratic logic which cares only about cost efficiency.

Rural electrification programs rely greatly on fiscal resources to meet their overall goals and to foster the social and economic progress of the most disadvantaged populations as well as drive every country's ability to attract private investors and international cooperation funds. One of the main financial supports of Latin American governments is the IDB (Inter-American Development Bank), which allocates about 15% of its resources to the funding of off-grids and mini-grids which are connected to the grid and use renewable technology. However, in 2014, the IDB's budget was reduced by nearly 45%, and, to date, its portfolio of projects aimed at financing off-grid systems is far below the requirements of the region to achieve universal access to energy [7,10]. Most of the investment remains dedicated to high-impact countries [11]. However, and at the global level, there is a continuous deficit between required and current investments to address the energy access gap and the Latin America region is not the exception, where large-scale projects accumulate most of the capital [11,12], jeopardizing a fair sustainable development and in turn a fair energy transition.

In this regard, the article's objective is to carry out an evaluation study of isolated photovoltaic solar systems (solar home systems—SHS, and hybrid PV diesel mini-grids) and their sustainability schemes, in order to outline policy recommendations to reinforce energy access strategies in NIZ of Colombia, as part of the fulfillment of the SD7 (Sustainable Development Goal 7). This research is developed under the framework of the "Evaluation of Isolated Photovoltaic Systems and Their Sustainability Models" project, which focuses on the Colombian electrification experience, within the program "Mechanisms and Networks for Technology Transfer Related to Climate Change in Latin America and the Caribbean" supported by the GEF.

It includes the analysis of primary and secondary information on the photovoltaic energy projects for the electrification of rural areas in Colombia, which was obtained through an extensive literature review and interviews with different stakeholders working in NIZs. The evaluation is complemented by a comparative study on international experiences in Latin American countries to identify best practices that could be adopted by the Colombian electrification model. The results are shown as lessons learned, with a SWOT study representing the current situation of rural electrification with PV technology as perceived and describing the opportunities for improvement based on the successful experiences in the region. Lastly, a series of guidelines are proposed to support those public policies that foster access to energy in the rural non-interconnected areas of Colombia.

2. Rural Electrification in NIZ of Colombia

The electric power service in Colombia is determined as an essential public service in article 56 of the Political Constitution and is the result of the energy chain of electricity generation, transmission, distribution, and commercialization activities, defined in Law 143 of 1994. These activities form the National Interconnected System (SIN—*Sistema Interconectado Nacional*). According to Law 855 of 2003, the regions that do not have access to the SIN are called NIZ and reach 53% of the Colombian territory [13]. The NIZs are characterized by having a low population density, low levels of electricity consumption compared to the urban environment, and a low level of income, which decreases their ability to pay for electricity services.

The challenges arising from supporting universal access to energy in Colombia are reflected in the National Plan for Rural Electrification (PNER—*Plan Nacional de Electrificación Rural*), which seeks to make the necessities of rural communities compatible with the technological solutions to be implemented, to develop capacity building, and to increase social awareness about the efficient use of energy. According to the Ministry of Mines and Energy (MME), the plans that deal with rural electrification in Colombia are: The Energy Coverage Expansion Plan (PIEC), the National Energy Plan (PEN) 2020-50, the PNER 2018-31, the Sustainable Rural Energization Plan (PERS) and the *Plan Todos Somos PAZcífico* (PTSP) (the translation is not easy because it includes a wordgame: Plan We Are All Pacific (ocean), but it adds the word Paz (Peace) something like "Peacecific"). Their main goal is to provide the basic guidelines for the broadening of electric coverage, the efficient allocation of public resources for electrification projects, and the promotion of electric generation solutions according to the characteristics of the different communities, especially with Non-Conventional Renewable Energy Sources (FNCER—*Fuentes No Convencionales de Energía Renovable*), and teaching the communities how to use energy adequately.

The Energy and Gas Regulation Commission (CREG—*Comisión de Regulación de Energía y Gas*) determines the general criteria and methodologies to remunerate the generation, distribution, and commercialization of electricity, and the general tariff formulas to calculate the unit cost of the public electricity service in non-interconnected areas. In the case of solar systems, the tariff includes the requirements stipulated in Law 142 of 1994 and for example, since 2007 with Resolution CREG 91 these costs were expressed in -COP/Wp, and from 2020 with the Resolution CREG 166 were expressed in -COP/month. Now, the CREG Resolution 101 26 of 2022 express the costs in COP/day and COP/kWh for systems with prepaid billing. These regulations must be applied to every photovoltaic system that is installed in the NIZ, regardless of the institution that has financed the project.

In general, the NIZ tariff framework has shown significant weaknesses. In fact, neither the projects financed by the Financial Support Fund for the Electrification of Non-interconnected Areas (FAZNI—*Fondo de Apoyo financiero para la Energización de las Zonas No Interconectadas*) nor those funded by the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE—*Instituto de Planificación y Promoción de Soluciones Energéticas*) itself—which are the subject of this study—have implemented it for stand-alone systems, i.e., users are not paying for the power generated with isolated photovoltaic systems designed for domestic use. However, the CREG 166 of 2020 sets a tariff for the electric service of stand-alone photovoltaic systems whose power is over 500 Wp. Furthermore, the CREG is seeking to update the regulation of the electric power service in the NIZ, through the project of resolution CREG 701007 of 2022 that establishes the new regulations applicable.

Regulatory Framework

The legal framework of the rural electrification of Colombia is shown in Table 1 [14], with the milestones that have marked differences and advances for renewable energy, such as in their implementation in the NIZ, for their operation, administration, and maintenance (OAM). Since 2014, rural electrification projects are a major promotion in NIZ.

Table 1. Electricity sector laws: summary.

Law	**Law 143, 1994** **Electricity Law**	**Law 1715, 2014** **Renewable Energies**	**Law 2099, 2021** **Energy Transition**
Goal	Regulate the activities of generation, interconnection, transmission, distribution, and commercialization of electricity.	Promote the use of renewable energy through their integration into the electricity market, NIZ, and other essential uses for the sustainable development of the country.	Strengthen the energy transition towards FNCER and boost the national energy market.
Milestones	Promote free competition in the activities of the electric sector such as generation, transmission, distribution, and commercialization.	Regulates tax incentives (VAT exclusion, accelerated depreciation, duty exemption and income deduction).	Extends the declaration of Public Utility and Social Interest to storage, and OAM of these sources.
	MME defines the criteria for the use of renewable and conventional energy sources under an efficiency approach.	Declare projects with FNCER as a public utility or social interest.	The incentives applicable to renewable energy and energy efficiency projects will be in force for a period of 30 years.
	Guarantees subsidies to users in strata I, II, and III [1] and those with lower incomes in rural areas.	Promotes self-generation and distributed generation.	Ratifies the tax incentives of Law 1715 and extends them to efficient energy management projects.

[1] The social strata correspond to the way in which households are classified taking into account different criteria that do not depend on the income of a person or family but are based on the conditions of the home in which the family group lives and the environment or area in which said dwelling is located. Strata 1, 2, and 3 correspond to people with fewer resources, who are beneficiaries of subsidies in home public services.

The main normativity of NIZ is summarized in Figure 1 which presents the tariff model, the subsidies, the planning, the tax benefits, and the goals in the sector chronologically. From 2020, there are changes in the tariff model, although since 2022 there are considerable changes with respect to the subsidies (for example, the resolution 40239 establishes the criteria for the subsidies, expanding the subsidy from 33 to 50 kWh/month in communities with less of 50 users) and with the tariff for SHS established within the Resolution CREG 101 26.

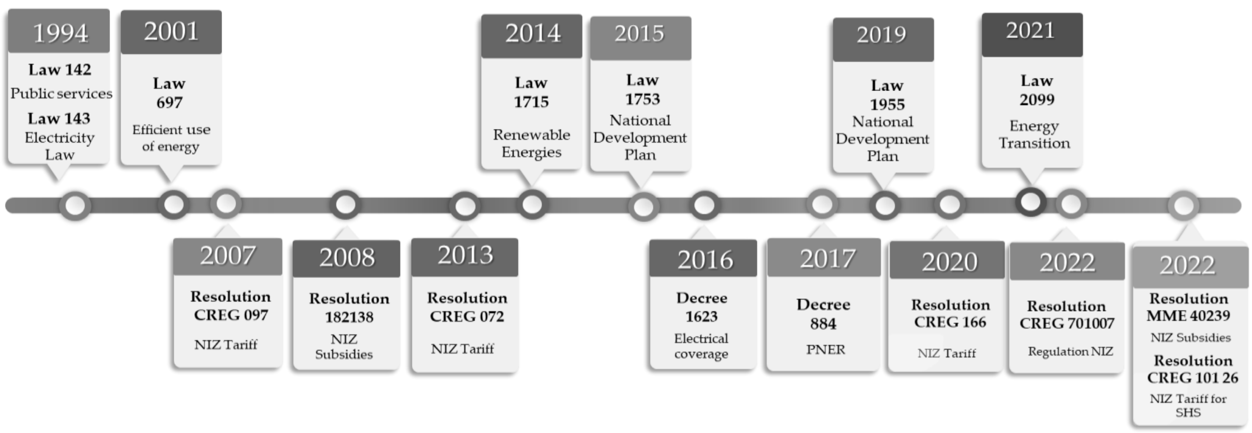

Figure 1. NIZ regulation. Own elaboration.

3. Material and Methods

The research methodology employs a mixed-methods approach to collect primary and secondary information, both of which are required to identify gaps and strengths in sustainability schemes, lessons learned, opportunities, and the required actions to strengthen the national regulation toward sustainable electrification projects with PV technology in NIZ. It is summarized in Figure 2.

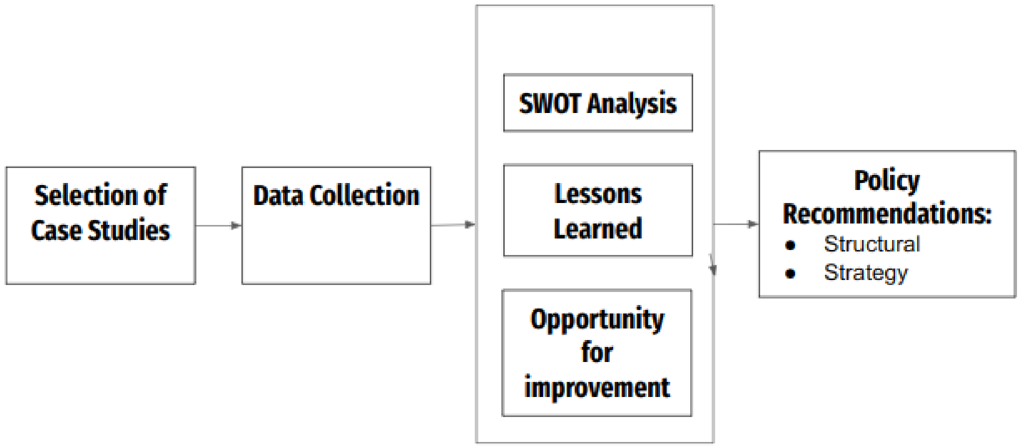

Figure 2. Methodological steps and methods.

From seventy-eight projects proposed by the Ministry of Mines and Energy of Colombia, six Colombian case studies were selected using multi-criteria analysis [15] and four filters. The case studies selected are projects that are data-driven and operational, located in places where the research team and participants are not exposed to risks derived from the presence of different illegal armed groups. The selection ensures the diversity of projects in geography, culture, governance, the generation system, and business models, and includes projects that are part of local and regional development plans/programs (Development Plans with a Territorial Focus—PDET, Administrative and Planning Region—RAP) due to their potential contribution to public energy policies. The data collection took place between March and November 2020. Interviews with local leaders, groups, installation businesses, governmental actors, decision-makers, and other stakeholders provided the primary data. Regulatory frameworks, official and international publications, government records, local organizations, scientific articles, and bibliographic databases provided secondary data. The identification of gaps and strengths in sustainability schemes uses a SWOT analysis framework (strengths, weaknesses, opportunities, and threats), investigating the sustainability of the projects from aspects with a direct influence on the stability of the local projects, including management, technological, socio-economic, gender equality, environmental, and social impact [16]. Furthermore, a specific SWOT analysis was carried out for rural areas and islands. The identification of lessons learned is through reflection and a critical examination of success and failure factors affecting the sustainability of solar projects in Colombia's NIZ. The method used to search for relevant information is content analysis, which entails breaking down the text, labeling small sections of it with codes, and establishing categories. The coding system contains deductive and inductive (theory-based and exploratory coding) categories [17,18]. The software used for the content analysis was Atlas TI. The documentation of lessons learned follows the IDB Knowledge Management System [19]. The identification of opportunities for improvement in the Colombian mode considers the SWOT analysis findings, the lessons learned from the national case studies, and the most positive aspects of six international experiences that may be applied in the local context. This analysis considers six aspects of sustainability: institutional, financial, technological, socio-economic, and environmental (described below). The drawing up of the public policy guidelines to advise the MME in Colombia considers international and national examples and lessons. Defining the objective, determining the target audience, presenting an analysis of the issues, including details of what strategy, legislation, or government policy currently applies, explaining why the research evidence indicates a need for change or improvement, writing them in plain language, prioritizing policymaker information, and convening stakeholder workshops are all steps in developing policy guidelines based on research [20]. The research was limited to analyzing active projects, and due to the COVID-19 pandemic when travel restrictions prevailed, only communities with internet connectivity were involved, excluding case studies in indigenous communities because of their lack of digital access.

To strengthen the findings of the Colombian electrification experience in rural areas and islands, six Latin American projects were analyzed with the objective of identifying actions that could be adapted and adopted by the country in terms of governmental and community participation, innovation, financing opportunities, and technological quality for a long-term functionality of off-grid projects with PV technology. The results of this cross-check analysis were considered to build up the opportunities of the country under a sustainable perspective.

As explained before, the identification of improvement opportunities and policy guidelines are based on the sustainability focus. The United Nations (UN) and the International Atomic Energy Agency (IAEA) have led the development and implementation of national sustainability frameworks, categorizing them in technical, economic, social, organizational, and environmental themes, which remain popular for sustainability classification [21]. However, some of the focuses of these frameworks are more concerned with high-level, country-wide goals or desirable development results than the genuine sustainability difficulties confronted by the implementation of energy projects.

To ensure that the concept of sustainability has a more concrete relationship to the project's survival, this research focuses on a project-centric sustainability analysis, employing the thematic classification of sustainability to detect potential problems and opportunities and respond appropriately. To ensure that the concept of sustainability remains project-centric, this research uses the word "dimensions" rather than "theme category." Therefore, here is presented a summary definition of the sustainability dimensions for better illustration:

- **Institutional sustainability**: Refers to institutions that are stable and long-lasting enough to ensure the project's upkeep. Then, it considers the organizational and management structure, the decision-making capacities, and the adoption and compliance of innovative standards and regulations. In the context of electrification, several investigations conclude that, for effective sustainable energy development, it is imperative to open the decision-making process to the participation of various parties, including local communities [22–24].
- **Financial sustainability:** This term takes the project's long-term financial viability into account, analyzing financing to cover the total duration of the project, facilities for the user, and finance mechanisms to ensure the project's sustainability. To guarantee the financing, it is highly recommendable to make the project's strategies flexible and adaptable to changing local conditions as well as optimize the resources from the project design phase. At the same time, the electrification projects shall contribute to the improvement in family incomes [23,25–27].
- **Technological sustainability:** This section examines the functionality of the technology and the feasibility of the projects to supply the promised energy service. It is explained by the implementation of quality technologies, adapted to the context. When the technological solution implemented covers the needs of the population, the sustainability of the projects and their appropriation by the users/beneficiaries are assured [23,28,29]. Moreover, it involves the creation of a local market to ensure the availability of spare parts and technical assistance [23,30,31].
- **Socio-economic sustainability**: Considers thinking about how to get people involved, how to get their voices heard, and acceptance of the off-grid initiative as part of the local social structure as factors in socioeconomic sustainability. The component of acceptance includes gathering social-economic variables such as affordability, livelihoods, payment culture, and ability to pay, which are critical in the project maintenance analysis. Then, identifying local capacities, assets, and activities necessary for a means of living rather than income poverty avoids confining the socio-economic dimension to one component of deprivation and recognizes that community realities are local, complex, diverse, and dynamic. This dimension also includes equal

distribution; the study emphasizes gender equality, assessing equitable access to rights, resources, and opportunities for women, and recognizing gender equality as a development condition based on human rights and social justice principles. This highlights the importance of having beneficiaries as change-makers with active participation to promote social cohesion and reduce inequalities, especially on gender. It goes beyond the introduction of technology and requires the provision of an affordable service for all [23,28,29].

- **Environmental sustainability**: Takes into account the potential for adverse effects on the environment and other people as a result of the project's implementation and maintenance. For example, the potential of photovoltaic projects in rural and insular environments as a solution to mitigate climate change by replacing polluting energy sources. Furthermore, it tackles the inclusion of project strategies to ensure the final disposal of equipment that has reached its lifetime.

Using this framework and the project-centric approach to sustainability, analysis, assures that the study is interconnected to provide insights into long-term sustainable solutions.

4. Description of Case Studies in Colombia

Rural electrification in NIZ is implemented where the conventional grid cannot be expanded, mainly through three energy solutions: stand-alone photovoltaic systems, mini-grids with diesel generator sets, and hybrid renewable mini-grids. Nowadays, more than 44,000 users have one of these systems through the use of FNCER, of which 39,000 were installed in the last four years. Stand-alone photovoltaic systems are defined in Colombia as Individual Photovoltaic Systems (SFVI). They are SHSs, the preferred solution for the widely dispersed population. As for hybrid mini-grids, this has been the preferred solution for the islands. For the purpose of this paper, as explained in Section 3, six case studies on the Colombian electrification experience were evaluated. They are described below: stand-alone photovoltaic systems located in Acandí, the Chocó region, Aguachica, the César region, Cartagena del Chiará, in the Caquetá region. The hybrid mini-grids are located on IslaFuerte, El Islote, and Isla Múcura (municipality of Cartagena, in the Bolivar region).

4.1. Stand-Alone PV Systems

In the municipalities in which PV systems are installed, this solution is characterized by difficult access, a small population, and temperatures of more than 25 °C. These municipalities have agriculture and cattle raising as their main economic activities. As regards the technical specifications, in general, the 2nd Generation SHS (2G-SHS) has an installed power capacity higher than 500 Wp, a lead-acid battery, a Maximum Power Point Tracker (MPPT) controller, and an inverter of between 500 and 1000 W. At the time of this evaluation, the beneficiaries of the projects did not pay for the electricity service.

4.1.1. Acandí-Chocó

The project was installed in 2016 in the villages of Titiza and Tibirre of Acandí for 136 households. A total of 59 SHSs were installed, whose features involve a solar generator of 500 Wp, a battery bank of 255 Ah/12 Vdc, an MPPT controller, and an inverter of 600 W. This project included the internal electrical installation in each house.

4.1.2. Aguachica, Cesar

The project was installed in 2016 and has 473 households energized located in different villages north of Aguachica. The system has a solar generator of 750 Wp, a battery bank of 200 Ah/24 Vdc, an MPPT controller, and an inverter of 1000 W.

4.1.3. Cartagena del Chairá, Caquetá

The project was installed in 2016 in different villages and towns and 190 households had access to electricity service. The system has a solar generator of 705 Wp, a 230 Ah/12 Vdc battery bank, an MPPT controller, and an inverter of 500 W.

4.2. Hybrid Mini-Grids

The photovoltaic mini-grid solutions were installed in the Bolivar Department on islands and islets that mainly depend on tourism and have a high-density of population.

4.2.1. Isla Fuerte, Bolívar

The island has 2000 inhabitants, and the main economic activity is tourism. In 2009, two diesel generators of 135 kVA each were installed, together with a solar generator of 25 kWp. Later in 2013, the system was reinforced with an installation of 150 kWp and two trackers of 12.5 kWp each. The mini-grid hybrid has an AC coupling with 14 solar inverters and 27 battery inverters.

The mini-grid had 24 h of service in 2013, while in 2020 just 3–4 h because of obsolete diesel generators. These were replaced in 2020. The Cooperative Community of Public Services of Isla Fuerte is in charge of collecting the tariff.

4.2.2. Isla Múcura. Bolívar

Is an island with 100 people that live from tourism. In 2013 a mini-grid hybrid was installed with AC coupling for 43 users. The mini-grid has a solar PV generator of 30 kWp, a storage system with flood batteries, a diesel generator of 116 kVA, solar inverters, and battery inverters.

The mini-grid was designed to ensure 16 h of service and in 2020 the system delivered between 9 and 16 h due to the high price of fuel. The management and maintenance of the system are the responsibility of the Community Council of Múcura. There are only 35 users connected to the mini-grid because most of population do not have the capacity to pay for a service without subsidies.

4.2.3. Santa Cruz del Islote, Bolívar

This is the islet the greatest population in the world, 1200 people per hectare. Inhabitants depend on fishing and tourism. In 2013, two diesel generators were replaced with a hybrid mini-grid for 120 users. The system has a solar generator of 68 kWp, a genset of 116 kVA, a storage system with lead acid batteries (OPZS), and solar and battery inverters. The system is managed by the Islet Community Council. As in the previous case, it does not count on a fuel subsidy.

The purpose of the project was to deliver 24 h of energy service, 6 with diesel and 18 with solar energy, even though in 2020, the energy service was between 1 and 20 h and there were just 80 households connected because of the lack of payment capacity of the users.

The following matrix (Table 2) is a summary of the SWOT analysis of the Colombian case studies. The insights provided by the SWOT analysis are those that identify the potential for improvement. Even though gender equality is a component of the socioeconomic sustainability dimension, the SWOT analysis highlights gender equality aspects due to their direct impact on the project's sustainability and as a condition for sustainable development. Then, the SWOT analysis examines the following aspects: management, technical, environmental, socio-economic, and gender-based aspects, and the impact of the project:

Table 2. SWOT analysis. Own elaboration.

Item	Strengths	Opportunities	Weaknesses	Threats
Management	(i) Public sector leadership to broaden the electric coverage in NIZ with renewable energies. (ii) Promotion of investment in rural electrification projects through funds. (iii) Tool to calculate tariffs and subsidies, so that projects are financially viable.	(i) Improving the management and the interaction between public bodies and service providers, and between these institutions and users. (ii) Possibility of public–private partnerships with local stakeholders to strengthen the business model. (iii) Setting the tariff and charging the users according to the context.	(i) Lack of formal assignment of responsibilities to the body that carries out the OAM. (ii) Lack of funds to pay for the house installations of the new users. (iii) Lack of subsidies to PV Systems users to help in the projects' OAM.	(i) Decisions based on political interests.
Technical	(i) Availability of solar resources. (ii) A more suitable option for scattered populations. (ii) Capacity to cover every basic need: lighting, charging of mobiles, small appliances, entertainment and, sometimes, refrigeration and ventilation. (iii) Electrical installations inside every dwelling.	(i) Implementation of PV Systems whose capacity is adapted to the energy needs of users. (ii) Promoting the buying of efficient household appliances in rural areas with sound policies. (iii) Implementation of pre-paid metering systems in the most scattered communities.	(i) Lack of verification of compliance with technical standards in bid proposals. (ii) Average availability of just 4 h for basic needs. (iii) Low quality of the installed equipment, mainly of batteries and inverters.	(i) Unawareness of the replacement costs of equipment by the population. (ii) Increase in the electricity demand due to the use of high-powered equipment. (iii) Lack of development of a local network of companies to replace equipment.
Environ-mental	(i) Reduction of CO_2 emissions and noise pollution of generators.	(i) Creation of collection points for electronic waste and hazardous material such as batteries.	(i) Frequent replacement of batteries. Old ones are thrown away instead of being recycled.	(i) Household energy solutions based on fossil fuels.
Socio-economic	(i) Household savings when families switch from traditional energy sources of generation (candles, oil lamps, thermoelectric generators) to PV sources.	(i) Training families in the "culture of payment". and sectoral tariff application. (ii) Strong social cohesion and community alliances. (iii) In energy cooperatives, there is a lack of methods for reducing user debt.	(i) Lack of general awareness about the importance of the efficient use of energy. (ii) The subsidy for the hybrid mini-grid is the same as it was for the prior system (diesel generator), hence it is insufficient to keep the system operational.	(i) Users with low incomes, who are unable to pay a service charge. (ii) armed conflict. (iii) There are no subsidies allocated to the SHS.
Gender equality	(i) Community councils are led by women. (ii) Women's participation in energy cooperative structure.	(i) Women can open businesses to sell frozen products, for example. improving households' livelihoods.	(i) Low interest in women's participation in decision-making regarding energy.	
Impact	(i) Improvement of the quality of life thanks to the replacement of the use of fossil fuels for lighting, and the possibility of refrigerating food.	(i) Generation of local business based on the availability of electricity such as the sale of frozen foods.	(i) Decline of trust in governments to manage the projects.	(i) Widespread rejection of the population of NIZ to photovoltaic energy solutions, if they are not carried out with the proper technical quality.

The fact that the public sector leads the process is one of the biggest strengths in the implementation of PV technologies to improve the energy access rates in NIZ. In this case, public funding to install the systems is preferred. However, one of the main barriers is the difficulty of building horizontal partnerships (local agencies) and to reinforce local management (local responsibility over the systems). Added to that is the fact that the local communities do not usually take part in the decision-making, which implies distrust in the community leaders. The bright side of the case studies is the strong social and community cohesiveness. The population (especially young people and leaders) is willing to change, to become active agents in the development of energy solutions, and to be part of monitoring and control committees. In order to do so, they need to be trained in every aspect—technology, information analysis, management, tariffs, and subsidies, among others, and, of course, to be listened to. At the same time, this would offer the possibility of implementing innovative business models, such as SDG 7 and 17 of the 2030 Agenda, in which the political agenda is unable to influence either the decision-making or the continuity of the projects.

The politicization of PV projects is a factor of high concern, especially for rural communities. On the other hand, island communities complain about the lack of interest and support from local agencies, mainly due to the limited resources these entities have. Likewise, the changes in government and of government officials in national institutions hinder the normal development of projects.

As for the technical aspect, the high availability of the energy source (solar) stands out, which facilitates the implementation of PV systems throughout the country. It is also important to mention that the newest part—the PV module or the solar module—is functioning in every case study. That is, the failures reported are mainly due to different problems with the storage system or the electronic equipment of power conditioners, and not with the solar modules. This factor is closely linked to the low quality of the equipment and the scarce compliance with quality standards in technical parameters and guarantees. Furthermore, the evaluation of the island cases shows that basic OAM works (e.g., fuel and oil change in generator sets, module cleaning) can be completed by local workers, but for complex works, it is necessary to look for trained staff from outside the island, which directly affects the cash flow of the service providers.

The socio-economic aspect is one of the most sensitive factors. Household economies are highly vulnerable to the seasonality of income, agriculture being the main source in the rural context, and tourism on islands. In both cases, the households' economic well-being is very susceptible to external factors that severely affect their incomes, as was the pandemic and the armed conflict in some rural areas. An added factor is that, in most cases, there are no set tariffs. The exception is the case of mini-grids, where customers are being charged according to different tariff models, but this is not enough to pay for the operations, administration, and maintenance of the systems despite the community devoting a great amount of resources to it. This shows that the electricity service is not affordable for NIZ populations. Likewise, the economic sustainability is also threatened by the lack of a "culture of payment" among users, due mainly to the fact that the first public service that reaches these areas is electric power, and the communities are not aware that they need to pay to guarantee a service. Lastly, the greatest weakness in the environmental chapter is the lack of defined policies for electronic waste recycling and the disposal of batteries. Therefore, the creation of collection centers for this type of waste in the urban areas of the municipalities would be an opportunity for improvement.

Leaving aside weaknesses and threats, we must also highlight that the implementation of this type of project (PV and hybrid systems) has had a positive impact on the community since the quality of life has improved thanks to the development of its economy and its businesses, most of them led by women. People may engage in different activities after dark, replace other energy sources such as batteries, oil lamps, or candles, save some money, and have access to other services apart from just lighting: communication, information, food conservation (although with limitations), and a better level of education among children and young people. Despite these positive aspects, electrification strategies in the country still require innovative proposals and proposals to adapt projects to current conditions, in which multi-stakeholder partnerships are a potential alternative so that no one is left behind.

5. Description of International Electrification Experiences in Latin American Countries

The objective of this section is to present summarized information on Latin American electrification projects, in both rural and islands contexts in order to identify those characteristics that could be applied in the Colombian electrification case, such as the definition of sustainability, the core of that identification as explained in Section 3. International projects are commonly cited as successful experiences in the literature.

To do that, six Latin American rural PV electrification projects have been analyzed. All of them illustrate the importance of governmental commitment and the involvement of the local population and the relevance of innovation and technological quality. These experiences also reveal that access to financing is one of the major barriers for the region. Hence the relevance of the 2030 Agenda's urge to include every stakeholder, which provides a clear guideline for the formulation of public policies both nationally and regionally. The referenced projects are summarized below:

5.1. Perú: Luz en Casa (Light at Home) Project

In Peru, the project *Luz en Casa* ("Light at Home") [23,32,33] is being implemented by acciona.org Peru, which has developed a solid management model that ensures self-sufficiency to finance the projects and their sustainability once they are implemented. The *Luz en Casa* management model guarantees that access to electricity is affordable for users, and compliance with technical quality criteria thanks to a rigorous verification process. The creation of a multi-stakeholder alliance has been the key to implementing it, with an ESCO (energy service company) management model. However, the concession (also applied for rural electrification) has become a barrier to expanding the project to new areas.

This project is supported by the FOSE (Electric Social Compensation Fund) that helps to cover 80% of the electricity tariff. The commercialized equipment considers second generation and third generation solar homer systems, 2G-SHS and 3G-SHS, respectively. Furthermore, communities are involved through the implementation of microfranchises to commercialize the photovoltaic systems, spare parts and provide technical assistance, these are known as light home centers (CLCs).

5.2. México: Luz en Casa (Light at Home) and Iluméxico Projects

In the cases of Iluméxico (promoted by Iluméxico) [34–36] and "Light at Home" (promoted by acco.org Mexico) [23], community involvement as one of the central axis of project development is very relevant. The community is involved from the project development phase to the installation and capacity-building processes, ensuring project ownership.

In particular, the case of the "Light at Home" program shows the success of the PPARD model (Public–Private Alliance for Rural Development), which has not only provided access to energy to low densely populated areas in the region of Oaxaca but also, thanks to the recent interest shown by the government, it can be applied to water supply systems and other services such as health and cooking. Furthermore, in both cases, it has become clear that adapting the business model to the economic situation of the beneficiaries allows the contribution of tailor-made technological solutions, according to their payment capacity, thus having low default rates.

As regards subsidies, the commercialized equipment includes a subsidy to the users that varies from 20% to 50% in the Iluméxico and Light at Home projects, respectively. Again, the Light at Home project stands out since offers microcredits to users that are not in the capacity to make the purchase in a single installment.

5.3. Brazil: Light for All (Luz para Todos)—Electrobras Amazonas Energía

The electrification in remote rural areas in Brazil is part of the Plan for the Universalization of Access and Use of Electricity, the "Light for All" Program. The performance of the program has improved through the implementation of pilot projects, which allows the Department of Mines and Energy to make the necessary adjustments and introduce innovative mechanisms in its policy. One of the pilot projects that allowed the introduction of these innovations was led by Eletrobras Amazonas Energía-Guascor [32,37–40]. In this project, several hybrid microgrids were installed in some Amazonian communities. After the implementation of this pilot project, the government defined the technical quality standards for electrification projects, the energy consumption control, the provisions of credits, the alliances with local stakeholders to strengthen the capacities, and the design of inclusive materials for the indigenous communities. However, this did not fully fit the complexity of the Amazon. Furthermore, the government measures regarding the privatization of energy service operators have destabilized the program, because the most remote areas of the Amazon are not attractive for the companies.

The cost of the installations (PV diesel microgrids) is assumed by the federal government whereas the community pays for the electricity consumption. The funds come from the National Energy Development Account (to cover 90% of the installation costs) or the Fuel Consumption Account.

5.4. Bolivia: The Microfranchises for Access to Clean Energy Project

In Bolivia, Energética, a private company, has acted as an intermediary in the transition towards sustainability through the project "Microfranchises for Access to Clean Energy" [23,41–43], catalyzing the knowledge transfer, the integration of stakeholders, and the development of a model that was gradually born as a response to the social, socio-economic and institutional characteristics of the area in which they work. Key to institutional sustainability has been: (i) the transfer of powers to local authorities (decentralization) so that they can implement the PV Systems; (ii) a microfranchise model based on the inclusion of the local workforce in the business model; and (iii) the use of international aid to develop the potential of the community, rather than just importing foreign knowledge and technology. Fundamental to achieving economic sustainability has been: (i) the payments system adapted to harvest time, the season in which the users have income, and (ii) the close relationship of the microfranchise with the population. The offer of basic standard products to the users, the availability of local technical workers and the after-sale service to communicate providers and users have ensured the operation and maintenance in the long term. This project was based on a PPARD, combined with a microfranchising, and pay-as-you-go (PAYG) model (the latter for better efficiency in maintenance works).

5.5. Chile: The Coquimbo Project

In Chile, in the Coquimbo region, a rural electrification project was implemented based on the installation of SHSs in 15 municipalities funded by the National Fund for Regional Development (FNDR) and led by the National Electric Power Company (CONAFE).

The Coquimbo project [27,44] was designed based on a PPA (private–public alliance), which has been a success in the long term, not only because of the rate of electricity coverage achieved in the region, but also thanks to the way the OAM of the systems is carried out: by handing over the management of the equipment to the local energy distribution company, the operation of the systems and, above all, the continuity of the service is guaranteed. Furthermore, the bottom-up approach of this experience allowed the community to take part in the design of the project, thus contributing to the empowerment of the beneficiaries and to the good use of the equipment. For this project, the government assumes 75% of the electricity tariff while the remaining value is charged to the users.

However, the project lag between project formulation and implementation remains a barrier to achieving 100% of electricity coverage in the medium term. The same happens with the direct allocation of resources to electrification projects by regional governments, which generates uncertainty about the ownership and the replacement of the PV systems' equipment.

5.6. Ecuador: The Floreana Hybrid Mini-Grid Project

The case of Floreana, Ecuador, an example of a mini-grid on islands, is marked by the high amount of funds provided by international cooperation entities to finance the renewable energy projects as a contribution to the national initiative "Zero Fossil Fuels" for the Galapagos. In fact, this public policy whose objective is decarbonization to preserve the ecological value of the environment has been the key to boosting the use of renewable energy on the islands, with the help of donor countries. Although there are still some challenges, such as the availability of biodiesel for electricity generation in order to maximize the introduction of renewable energy on the island, it should be noted that the combination of different technologies (diesel + biodiesel + PV + batteries) guarantees an electricity service on a permanent basis, thus improving the quality of life of the islanders thanks to the boosting of their economy [45,46]. The system is operated by the local public company (ELECGALAPAGOS) and there is a regulated tariff. Nonetheless, the fixed tariff does not cover the real operational and maintenance costs that increases the tariff deficit. Beyond that, the Ecuadorian government continues to reinforce the power system given the increasing electricity demand and following the Galapagos Energy Plan.

To summarize, in Latin American countries, there is a great variety of strategies for rural and insular electrification, in which business models, stakeholder involvement, technological solutions and user financing options vary widely among regions. The challenge of rural and insular electrification cannot be taken up by the public or the private sector alone. The strategies promoted by the 2030 Agenda seek to join forces in order to work towards a common purpose: "universal access to energy". This also fosters the exchange of experiences in the different regions to strengthen present and future initiatives. Many of the characteristics and appropriate strategies of every one of these projects are considered to outline the recommendations for the improvement of the Colombian management model, illustrated in Section 6. Figure 3 details some of the features of the aforementioned projects in Latin American countries:

Figure 3. Successful Latin American case studies in rural electrification. Own elaboration.

6. Results

The present section details the main results of this research and is organized as follows: Section 6.1. summarizes the lessons learned from the Colombian case studies in different NIZ and Section 6.2. recommends the key aspects to be taken into consideration to strengthen the national policies and strategies when it comes to the electrification of remote areas by applying the lessons learned and the evaluation of international experiences.

6.1. Lessons Learnt from the Colombian Case Studies

This section shows what can be learned from the successes and failures of PV electrification projects in Colombia's rural areas. These eight lessons learned are a useful source of information to anticipate problems and key factors in the development of future projects:

- **Lesson 1.** Active participation of local community leaders and organizations in all the project's stages helps increase commitment and problem-solving. The community's participation in actions such as family selection, coordination, and monitoring increased the commitment to equipment and infrastructure maintenance and enabled the communities to contribute to the efforts to solve problems during the project's approval and implementation.
- **Lesson 2**. Horizontal communication and transparency build trust between institutions, companies, and communities. This allows communities to work together to solve problems, reduce conflicts, and facilitate an effective decision-making process.
- **Lesson 3**. The design and management of electrification projects must be born from co-creation, and the users' community must be the pillar of this stage. PV solutions and OAM plans with sustainability issues share a common thread: they were not created in close cooperation with the local communities. It leads to static solutions that do not account for the dynamism and needs of communities or the complexities of places, failing to maintain the service and meet future demands.
- **Lesson 4**. Establish the OAM business model early on with stakeholders involved. PV solutions with poor service did not build an OAM business model that included communities and other stakeholders. Faced with issues such as unpaid tariffs, communities acknowledge but are unaware of the tariffs they are required to pay and an OAM scheme with no measures to collect payments and prevent communal default.
- **Lesson 5**. Local capability is needed for effective OAM. Local leaders counseled the community on energy options through a few capacity-building activities. Women, children, and adolescents should share knowledge. Storage systems and generators demand technical understanding. Some aspects of management require training, such as dispute resolution (nonpayment of public service bills), developing skills that allow locals to take part in initiatives, and managing alliances and businesses.
- **Lesson 6**. Discussing how energy may impact the community helps prevent disagreements and maintain the financing. It assumes energy systems are beneficial. Energy access has transformed ethnic and rural dynamics, especially among young people. Communities must consider the benefits and drawbacks of energy solutions to avoid downsides and appreciate the positive change in long-term project financing.
- **Lesson 7**. PV solutions must include women from idea to implementation to decrease gender inequality. Functioning PV projects encouraged women's participation in the decision-making process and capacity building, as in the situations of Isla Fuerte and Acandí. There is an erroneous belief, from technical and government staff, that women are not interested in participating in technical projects. Women, on the other hand, are most interested in energy sustainability. Women do not want to be exposed to the pollution caused by burners and candles; instead, they want to enjoy wonderful light longer, start small businesses with their home energy, and reduce domestic labor. Gender disparity occurs in rural electrification projects when the actions and methodologies do not encourage women's participation at all stages of the project.
- **Lesson 8.** Coordination between programs and alliances. Sustainability entails coordinating local and national programs and stakeholders. The coordination of programs and the coalition have allowed the use of energy to generate income, which is a key factor in rural development. In some locations, alliances have reached peace agreements with armed groups, allowing the service to operate. Lack of cooperation impacts the service. This is the situation with IPSE and the Superintendency of Domiciliary Public Utilities, so communities and companies are unable to communicate service difficulties. Then, inter-institutional coordination is needed, but agenda-sharing is not easy.

6.2. Identification of Opportunities for Improving Electrification Projects with PV Technology in NIZ of Colombia

Ensuring access to affordable, sustainable, and modern energy for all is a major challenge for developing countries, in particular for Latin American countries, due to the geographical dispersion and remoteness of their rural communities compared to other regions. Limited access to financing, conservative policies, lack of government support, and lack of capacity building to ensure the operations and maintenance works are some of the many and diverse barriers to the universalization of energy in the region. Thus, this section describes opportunities for improvement in rural PV electrification in Colombia under the sustainability concept.

6.2.1. Institutional Sustainability

This dimension reflects the integration of the efforts made to develop the Colombian legal framework on electricity access under the following considerations: (i) the government leadership to guarantee the financing of energy access programs; (ii) the allocation of subsidies to the most impoverished, isolated, and low-income communities, and (iii) the inclusion of the communities in the implementation and operation phases of energy solutions to achieve co-creation. In this sense, the drafting of a new law that deals exclusively with energy access would be advisable. It should be based on these principles: subsidiarity and sustainable development, as well as technological adaptation and diversification. These principles have greatly improved institutional efficiency, especially the management and the speed of implementation and revision of projects, and the easy access to long-term financing. The simplification and integration of regulations build on the work already carried out by the Colombian government in terms of energy access laws, e.g., Decree 1623 (2015) and Decree 884 (2017), and must contemplate the principles of the well-established laws: Law 143 of 1994, Law 1715 of 2014 and Law 2099 of 2021.

This complementarity would foster the development of electrification projects of public interest, thanks to the coordinated action of the separate levels of government (national, regional, and local) for rural and insular areas, an action that should differentiate the characteristics of both contexts. The subsidiarity, which enables the State to intervene in electrification projects with a subsidiary role to ensure the efficient management of resources, would allow the participation of communities and other private entities as electricity service providers or rural operators, made possible under Law142 and 143 (1994), Law 2099 (2021) and the Resolution MME 40239 (2022). Sustainable development would promote socio-economic development, which would complement the projects with different productive and employment generation initiatives, which in turn would contribute to the overall sustainability of the projects. These aspects could be perfectly integrated into the National Development Plans related to energy as part of the goal of social and productive inclusion through productivity and legality. Technological adaptation and diversification imply efficient management of energy and economic resources, the security of energy supply in NIZ, the prioritization of renewable energy sources, and the application of energy efficiency measures in parallel.

Therefore, integrating the regulatory framework and drafting an Energy Access Law would also promote the ideas proposed by the Mission for Energy Transformation, in its Focus 4, on the focalization of financing facilities and the standardization of the criteria to implement projects, which would reduce administrative obstacles.

6.2.2. Financial Sustainability

"The combination of several business models based on adequate financing mechanisms, subsidies and technological innovation is a key element in encouraging the implementation of renewable energies in vulnerable regions: islands and rural areas" [23]. In this regard, and considering the successful implementation of several business models in other Latin American countries, the following alternative models are proposed:

- Energy Service Company (ESCO)

The energy service company provides energy services—mostly using renewable energy sources—to the electric installation of a particular user, who, in turn, must pay for this service. The ESCO is the owner of the electricity generation facilities. The goal of this kind of company is to guarantee the user a quality and reliable electricity supply. In a regulated and participative market, this financing model guarantees investment, implementation, and operations and maintenance works of the off-grid technology in exchange for a tariff. Additionally, and more importantly, it ensures the affordability of the service in the last mile. Tariffs would be differentiated according to the geographical area, the type of modules implemented, and to the kind of investor (state, private companies, or other entities). This model builds on a fee-for-service model (cross-subsidization). The subsidies come from a social compensation fund that is fed by users of the whole grid-connected users. This social fund would unify those already existing in the Colombian model and goes hand in hand with the proposal of the Mission for Energy Transformation.

- Solar Auctions

In order to achieve that both rural areas and islands have different tariffs because of their particular contexts, the implementation of solar energy auctions is recommended. The great potential of this model, especially in developing countries, where it is already possible to ensure low electricity generation costs, has been proven [7,45]. This instrument is implemented by the national government through public service companies that acquire PV capacity through power purchase agreements. Keeping prices low and ensuring that quality regulations are met in projects depends on several factors: low equipment prices, low capital cost, risk-free investment climate, and other factors such as particular project development strategies. Generally speaking, developing countries where the solar PV resource is large, such as the Caribbean region in Colombia, are well-positioned to boost the general introduction of PV energy. Well-designed auctions are an especially unique opportunity to expand solar photovoltaic energy into the profitably of many new markets [47]. For instance, this kind of model was implemented in the Spanish island El Hierro [7,45], whereas, in Galapagos, the contracting power process began in 2020.

- Microfranchises

This model is an alternative to NIZ, defined by their economic vulnerability, and would allow, on the one hand, to keep the cash flow within the energization projects, and, on the other hand, to increase the income in the communities, as it benefits employment generation. The microfranchise is a model in which a small business and the owner of a company or patent reach an agreement. For the sector of energy access and in some Latin American countries, microfranchises are positioned as a strategy with great potential to involve the population (with or without business) in the commercialization of equipment compatible with solar systems (e.g., household appliances or appliances with productive purposes), in the provision of maintenance and repair services, in the collection of payments, and as a communication channel between the promoters and the communities [7,23]. In Colombia, the role of microfranchisees may be assumed mainly by the locals. Here, the focus must be put on the participation of both women—as entrepreneurs and regional governments. One of the most relevant characteristics of this model is its flexibility to adapt to the context easily.

- Pay-As-You-Go (PAYG)

The use of cell phones has driven this technological model, which allows the user to pay for the service provided (electricity) or to purchase some equipment. This model simplifies the management of work orders for equipment maintenance and of payment collections and invoices. To implement it, the installed equipment (solar system) must have an electronic system to facilitate their monitoring, as is mostly the case in third generation solar home systems (3G-SHSs) [23]. In the Latin American context, the PAYG model is clearly a key factor in improving the efficiency of both human and economic resources to support sustainability and cash flow in electrification projects.

6.2.3. Technological Sustainability

To achieve technological sustainability, not only the technical design and the quality of equipment and implemented technologies must be considered, but also the adaptation of the energy solution to the local context. Therefore, the flexibility of power systems, the reliability of the service, the social acceptance of technology, access to basic services in households and small businesses, and the community infrastructure must be analyzed. Technological sustainability comprises several key points: (i) adapting the technological solutions to the user's energy need, that is, to the characteristics of the demand. This, in turn, will help the diversity of regions and contexts as much as flexibility. For instance, in the cases of acciona.org in Mexico and Peru, and the case of Energética in Bolivia, 3G-SHSs cover the basic needs of lighting and communication devices, which, in Colombia, would be applicable to the indigenous communities. (ii) Promoting energy efficiency to create a market for efficient appliances in NIZ. That way, those impacts on demand that condition the operation of implemented solutions would be avoided. The Caribbean Energy Efficiency Program Sustainable Energy (PEECES, its Spanish acronym) is an example [48]. It was implemented in the Atlántico, Córdoba, and Bolívar departments to replace domestic refrigeration systems and could be reproduced in the rural and insular NIZ. (iii) Guaranteeing the technical quality of equipment for stand-alone and mini-grid solutions according to International Electrotechnical Commission (IEC) [49], many of which have already been adapted to the Colombian context. Technical quality ensures the useful life of the equipment and the social acceptance of technology, thanks to a low failure rate and the reliability of its operation. (iv) Including the household installations in the design to ensure the smooth operation of generation systems. (v) Guaranteeing the operations and maintenance work in the region. Microfranchises are a good solution because thanks to the proximity of the promoter to the user, the maintenance and repair works within the communities are easier.

6.2.4. Socio-Economic Sustainability

This aspect highlights the value of bottom-up strategies when designing projects. The implementation of participatory methods fosters regional development and inclusion, by recognizing the communities as changemakers of their own development, especially women, because of their extensive leadership skills for initiatives with a social impact. This would help to strengthen the community spirit, to minimize the inequality gap, and promote a real implication in projects in the medium and long term. Additional actions would be required: first, the generation of employment opportunities (e.g., microfranchises, with a positive impact on the household economy), the promotion of capacity building in technology and management (data collection and analysis, entrepreneurship, business, tariffs, and subsidies, among others) so that communities can contribute to the general projects' management. Second, the creation of a payment culture in these areas through awareness-raising campaigns; and third, ensuring the affordability of the electricity service once the economic vulnerability of rural communities and islands has been determined.

6.2.5. Environmental Sustainability

The environmental dimension integrates two key factors in the improvement of rural electrification strategies in Colombia. First, synergies between the energy and environment sectors have to be established. There is a great potential for initiatives because the introduction of quality renewable technologies [50–53], the suitable installation of equipment and the promotion of energy efficiency to reduce CO_2 emissions into the atmosphere would help to achieve a circular economy [54]. The second factor has to do with the use of sustainable finance as a new opportunity for funding, in which access to energy must be considered a goal [55]. In other words, we propose the integration of the Country Objectives for this area and the local NDC (National Determined Contribution) [56] to make investments more attractive and to reduce the risk with national and international support based on financial and technical cooperation, as other countries are already doing.

In short, Colombia has a great challenge ahead: the design of an energy policy that favors appropriate holistic planning aiming at long-term sustainability. There are multiple factors that contribute to the improvement of energy access, but the will of decision-makers and the establishment of synergies among stakeholders are vital. Furthermore, the actions to be implemented must respond above all to the needs of the population and the context. This translates into the development of a process of incremental innovation in terms of organization, financing, technology, socio-economy, and the environment. Organizational innovation, since institutional quality is essential to the management of natural resources. Financing innovation allows the participation of new stakeholders, the emergence of new business models, and access to new sources of financing, putting people and the environment at the center of decisions. Socio-economic innovation to reduce inequalities regionally and to generate opportunities for employment, taking into account the role of women as part of this process of change is fundamental. Environmental innovation is also an answer to the negative effects of climate change (which has an impact on every development process) and a way of accessing new sources of financing and cooperation. Figure 4 summarizes the opportunities for Colombia to reinforce off-grid solar PV initiatives, integrating a sustainable perspective:

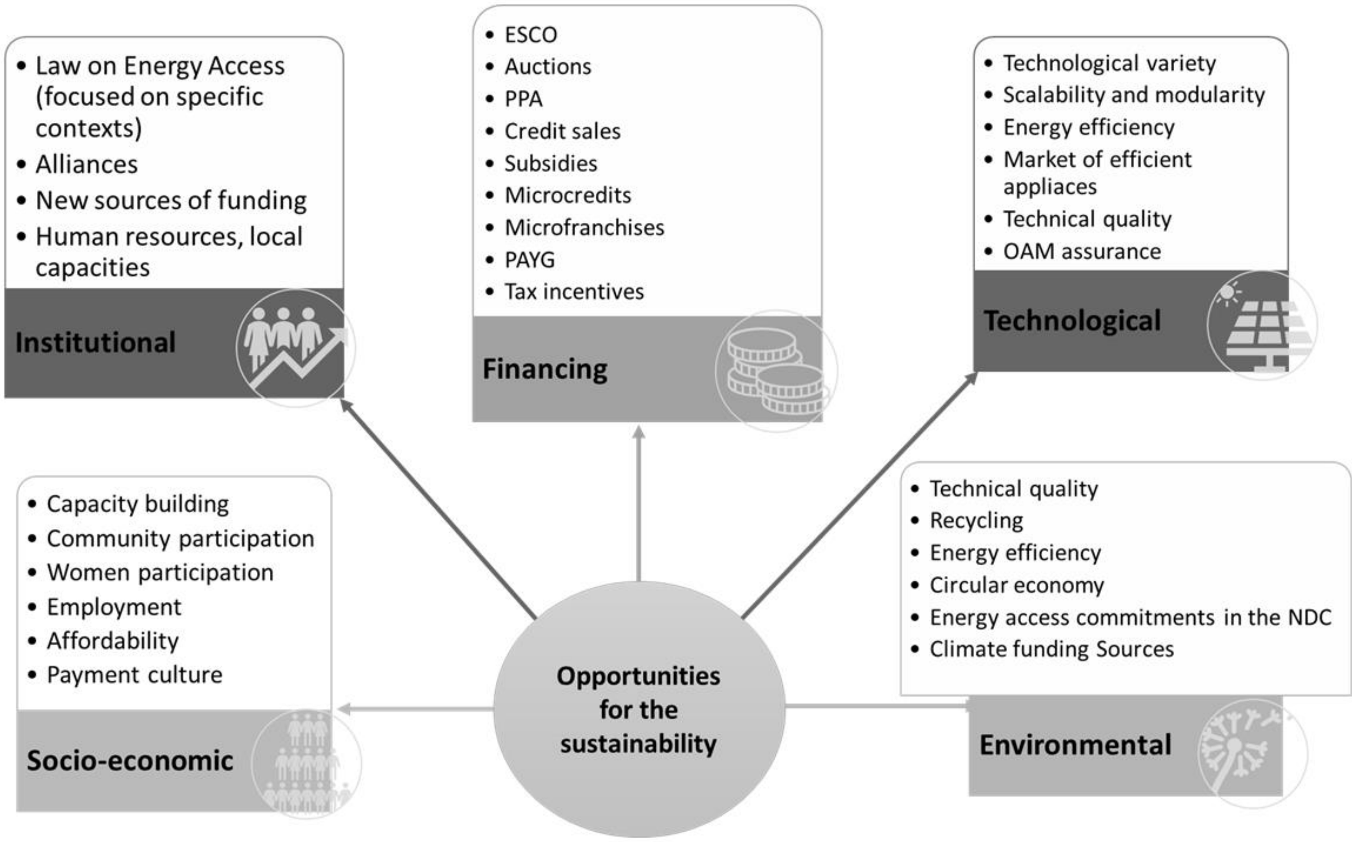

Figure 4. Opportunities for improving electrification projects with PV technology in the NIZ of Colombia. Own elaboration.

7. Public Policy Guidelines for the Sustainability of Rural Electrification Projects in NIZ

This section includes nineteen recommendations for the electrification public policy guidelines to achieve sustainability and coverage in the NIZ. Recommendations for public policy are carried out on two levels: at the structural level, which implies the formalization of public policy and includes the bases for adoption, implementation, and the generation of information for decision-making, and at the operational level, which includes the implementation of public policy. At a strategic level, to improve the efficiency, efficacy, relevance, and coherence of electrification project planning and implementation, allowing for long-term sustainability.

7.1. Structural Guidelines

In the short term, it is important to construct a public policy on energy access in NIZ through the National Council for Social and Economic Policy (CONPES—*Consejo Nacional de Política Económica y Social*), and in the long term, the National Energy Access Law should be created.

It is necessary to formulate a public policy, in the form of a strategic CONPES document that compiles existing regulations and includes the necessary guidelines to mobilize stakeholders, actions, and resources to ensure the sustainability of the service. This recommendation arises from the fact that, in Colombia, public policy on energy access is carried out through projects. The unsustainable projects had problems with validation by the community or lacked commercial models for the delivery of the service.

Beginning with the Colombian Constitution Court's recognition of the link between public services and the materialization of fundamental rights, and that the absence of energy access has a negative influence on the living conditions of the most vulnerable populations [57], and that, in the NIZ, illegal forces and criminals are violating human rights. This research also takes into account the recommendations included in the national strategy for the protection of human rights. It is recommended that policies incorporate the human rights-based approach, the provisions of the peace agreement, and the government's pursuit of innovation in public policies. The goal of proposing a differential and territorial approach based on UNHCR (United Nations Refugee Agency) is to guarantee energy access according to the necessities and characteristics of every community.

Furthermore, innovation in public policy is essential and consistent with the Colombian government's OECD agreements (Organization for Economic Co-operation and Development). Through the integration of Colombian renewable energy and rural development policies and programs, renewable energy must be promoted as a rural development accelerator.

Provide accessible, transparent, and uniform information on projects and rural electrification regulations by integrating multiple information sources and allowing registration and project traceability. This information should be disaggregated and be of interest to public policy decision-making.

7.2. Strategical Guidelines for Plans

These guidelines recommend the inclusion of actions aimed at achieving sustainability in the PNER, integrating institutional, technological, environmental, and financial aspects.

The policy, instruments, PNER, and strategies should integrate gender mainstreaming, i.e., actions to empower women. The PNER recommends women-specific training. However, it is recommended that this action go beyond promoting women's participation and lead the women, as a collective, to make their needs visible within the community, releasing their capacities towards empowerment. Electrification projects should include programs of interest to women as well as a capacity building plan for technical staff, public entities, and private companies responsible for project operation locally to eliminate narratives and behaviors that justify violence against women and girls, reinforced gender roles, and those of primary victims/survivors, and secondary victims (family members/community).

Including guidelines that promote the articulation and coalitions needed to develop territorial and differentiated projects. This means that different parts of the Department of Mines and Energy need to work together, that the finance facilities need to be unified, that the criteria for putting projects into action need to be standardized, and that the local level needs to work together with territorial planning and programs that are important to the communities, such as connectivity, health, education, and rural development.

Another important guideline is to expand local capacity for conflict resolution, alliances, and internal awareness campaigns, as well as carry out the formation in accordance with the traditions of the communities, symbols, language, and channels of communication. Regarding technical and institutional organizations, it is necessary to develop skills in participatory design, co-creation, inclusive language, and protocols for working with survivors of violence. In the education sector, it is important to support the incorporation of new energy and project management technologies, with a regional approach, at the professional and technical levels.

7.3. Strategical Guidelines for Projects

Implementation of co-creation and co-production methodologies to ensure the sustainability of projects. These methodologies offer solutions to complex problems in an innovative and agile manner, which would stimulate local idea generation and empower the community through active participation, listening, and validation.

To design flexible technical solutions to meet the demands and the socio-economic realities of users. The flexibility of the systems must allow a household to increase its energy demand and, furthermore, let the users access solutions for lower demands when their needs or context require a lower demand than that of the standard design.

It is important to promote adaptable business models designed with the broad consensus of all stakeholders in the NIZ, in particular local ones. The models will depend on the needs and resources of each area, but they could include microfranchises, auctions, ESCOs, public–private alliances for development, social enterprises, and community enterprises.

To encourage collaboration with technology centers, universities, and innovation centers that can evaluate the technical parameters of the main components, carry out research, development, and innovation (R+D+i), and pilot projects on technologies and service operation plans. Furthermore, the quality parameters for evaluating the projects must be based on the quality of the equipment and on the support and experience of the manufacturer.

Another proposed rule is the use of monitoring systems, such as remote or on-site data collection technology or community monitoring systems, as well as information analyses that include the users.

7.4. Recommendations for Financing Mechanisms

To promote the cross-subsidization from the SIN to NIZ with high poverty levels. This means that analyzing and defining energy needs is critical.

Given the difficulties encountered in the operation, administration, and maintenance of isolated photovoltaic systems (particularly mini-grids), it is necessary to design incentives to attract new operators, ensuring a return on investment by establishing a tariff that covers the costs of NIZ coverage. Companies and social impact funds should be linked to enable the integration of system components that are difficult to finance, such as metering equipment. Additionally, project approval timelines should be shortened to improve the relationship between businesses and communities.

Finally, it is critical to determine the NIZ tariff based on local features, demand, operational and administrative costs, solar radiation availability, and technology employed. This means that, in the case of solar systems, the tariff must be based on electricity generated rather than power.

7.5. Guidelines and Actions by Sustainability Dimensions

To enable a complete approach to policy implementation, the recommendations are organized into actions relating to each sustainable dimension. Differentiated by activities for plans, projects, and finance methods (Table 3, Table 4, and Table 5, respectively).

Table 3. Guidelines for plans (PNER and capacity building plan).

Guideline	Institutional	Technical	Financial	Socio-economic	Environmental
Promoting the integration of sustainability in PNER	• Entities' commitment	• Introduction of technological innovations	• Inclusion of innovative business models	• More capacity building • Design validation • Generation of entrepreneurship initiatives	•Prioritization of RE projects
Integration of the gender perspective in PNER and in energy projects	• Cross-cutting gender actions • Articulation of actions and programs • Awareness-raising of technical staff • Dissemination of the gender guidelines of the Department of Mines and Energy	• Co-creation and co-production spaces with women • Necessities and interests of the women affected by the armed conflict	• Business models in the energy sector for women	• Productive projects and service projects • Indicators for gender equality	
Promotion of cross-sectoral articulation, complementarity and coordination	• Coordination of government agencies • Promotion of articulation and communications from the Department of Mines and Energy • Consolidation of information • Building of local capacities	• Consolidation of projects' approval • Territorial Planning Kit: KPT, with instrumental update		• Coordination for actions prioritization	• Alliances for energy efficiency
Fostering local multi-stakeholder partnerships	• Alliance training • Agreements and systematization	• Co-creation and co-production		• Awareness-raising of the importance of alliances	• Efficient stoves • Efficient appliances

Table 4. Guidelines for electrification projects (PV system).

Guideline	Institutional	Technical	Financial	Socio-economic	Environmental
Introduction of co-creation and co-production in projects	• Collective innovation spaces	• Co-creation and co-production • Publication of innovation methods			
Flexible technical solutions for user communities		• Community participation in the validation • Company design: grid operator • Different technological solutions according to the local demand (energy steps) • Open innovation pilots			
Identification and implementation of adaptable business models	• Alliances for projects	• Open innovation skills	• Different business models • Attracting impact investors	• Involvement of communities in OAM from the start • Incentives for social entrepreneurship	• Promotion of investments in RE
Technical quality of systems	• Promotion of the R+D+i ecosystem	• Local quality assessments		• Parameters for quality assessments at community level	

Table 4. *Cont.*

Guideline	Institutional	Technical	Financial	Socio-economic	Environmental
Plan for capacity building on isolated electrification with renewable energies	• Including the study of RE in Engineering education programs • Increasing of the programs offered by the National Learning Service (SENA) • Involvement of women's organizations	• Voluntary national certification system • Innovation skills • Awareness-raising on Human Rights		• Strengthening of community capacities • Gender-differentiated approach learning	• Energy efficiency capacities • Awareness campaigns about efficient energy use • Waste disposal
Monitoring and supervision of investments	• Alliances for Information and Communication Technology (ICT) coverage and innovation • Dissemination of generated knowledge	• Development of monitoring systems with R+D+i • Definition of useful indicators		• Communication channels for complaints • Design of local monitoring systems	

Table 5. Guidelines for financial mechanisms.

Guideline	Institutional	Technical	Financial	Socio-economic	Environmental
Incentives for new grid operators		• Metering systems • Flexible solutions	• Tariff setting that covers the cost of coverage in NIZ • Including the transport costs according to the area • Private investors from the start • Attracting social impact investors	• Reducing the duration of projects' approval	
Targeted subsidies				• Subsidies to cover the cost of equipment replacement and OAM •Cross-subsidization with certain focus	
Tariff calculation	• Setting of a tariff according to the subsidies that the state can provide	• Adjustment of the tariff to the local situation, the demand, the technology, and the availability of solar radiation	• Setting of the tariff according to the energy as opposed to power to ensure an equal access to energy • Adjustment of the tariff to the operative and administrative costs of the NIZ		

8. Conclusions

This document presents an evaluation study of isolated photovoltaic solar systems and their sustainability schemes, in order to outline lessons learned and policy recommendations to reinforce energy access strategies in NIZ of Colombia, as part of the fulfillment of the SD7. The NIZs are characterized by having a low population density, low levels of electricity consumption compared to the urban environment, and a low level of income, which decreases their ability to pay for electricity services.

In general, the NIZ tariff framework has shown significant weaknesses. In fact, in the projects financed with public funds, the users are not paying for the electricity generated with isolated photovoltaic systems designed for domestic use.

The methodology of the research employs a mixed-methods approach to collect primary and secondary information, both of which are required to identify gaps and strengths in sustainability schemes, lessons learned, opportunities, and the required actions to strengthen the national regulation towards sustainable electrification projects with PV technology in NIZ. The identification of lessons learned is through reflection and critical examination of success and failure factors affecting the sustainability of solar projects in Colombia's NIZ. The identification of opportunities for improvement in the Colombian mode considers the findings of the SWOT analysis, the lessons learned from the national case studies, and the most positive aspects of six international experiences that may be applied in the local context. It should be noted that the identification and solution of the barriers to achieving full access to electricity in Latin America will serve as a reference to outline adaptable solutions to the context conditions of Asia and Africa, which will still lack access to electricity in the medium and long term. This is because Latin America is attempting to connect the last mile population, which is located in the most difficult-to-reach zones, and its lessons learned and current strategies could provide insightful guidelines to other regions.

Leaving aside weaknesses and threats, we must also highlight that the implementation of this type of project (PV and hybrid systems) has had a positive impact on the community since the quality of life has improved thanks to the development of its economy and its businesses, most of them led by women.

In light of this, the research generated policy recommendations are to promote sustainability in the electrification projects for NIZ. At the structural level, the recommendations are focused on formalizing public policy and providing decision-making information. In the context of Colombia, public policy must be designed with a human rights-based approach, coherent with the peace agreement, promoting innovation and transparency, and meeting the community's needs. At the operational level, the emphasis is on the implementation of plans, projects, and finance mechanisms.

The guidelines for plans include the integration of institutional, technological, environmental, socio-economic, and financial factors; empowering women through training and capacity building, and the articulation and participation of many components of the Ministry of Mines and Energy. Furthermore, it underlines expanding capacities at the community scale in conflict resolution and awareness, at technical and institutional organizations in participatory design, co-creation, and inclusive language, as well as including new energy technologies and project management technologies in professional and technical education programs.

The guidelines for projects include the implementation of co-creation and co-production methodologies for better involvement of the community in the project and response to complex problems. Furthermore, it emphasizes the design of flexible technical solutions that meet the demands and socio-economic realities of users. Additionally, adaptable business models that involve local stakeholders, collaboration with technology and innovation centers, and the use of monitoring systems are recommended. It is suggested that the quality of the projects will be based on both the quality of the equipment, the application of standards, and the support and experience of the project's promoters.

The main suggestions for financing mechanisms are to encourage cross-subsidization from low-income areas, come up with incentives to bring in new operators, work with companies and social impact funds to pay for hard-to-finance system parts, shorten the time it takes to approve projects, and set the NIZ tariff based on the amount of electricity produced instead of the amount of power, taking into account local factors, demand, costs, solar radiation, ability to pay and the technology being used.

In summary, Colombia has a great challenge ahead: the design of an energy policy that favors suitable holistic planning aiming at long-term sustainability. Multiple factors contribute to the improvement of energy access, but the willingness of decision-makers and the establishment of synergies among stakeholders are vital.

Finally, further research could be aimed at applying the mixed-methods approach to research to other Latin American countries with low rates of electricity access, considering the five dimensions of sustainability: institutional, technological, environmental, financing, and socio-economic. It also involves giving value to diversity and cultural differences within a country to outline rural electrification strategies according to the context's needs and ensuring a long-term appropriation of projects by the indigenous people, rural communities, and islanders. Along the same line, other regional experiences could be studied to open the perspective to the current implementing actions with PV technology and cutting-edge solutions, incorporating new business models and innovations in creating local human resources for supporting projects' sustainability.

Key Definitions

CREG: Regulates public power services, fuel gas, and liquid fuels, in harmony with public policy. Furthermore, it promotes the availability of a reliable and suitable energy supply.

IPSE: This institution identifies, implements, and monitors sustainable energy solutions in NIZ. Furthermore, it verifies the technical requirements of the projects for NIZ that seek to obtain resources with public funds.

FAZNI: Is a public fund that seeks to promote investment projects in energy infrastructure in NIZ. The projects are mainly based on the installation of diesel generators, distribution networks, hybrid mini-grids, and SHS.

MME: Formulates and adopts energy policies for the country. IPSE and UPME are dependent on the MME. They develop plans and programs to satisfy the mining and energy requirements of the country.

PEN: Is the umbrella plan. There have established the foundations for the structuring and implementation of the energy policy in the country. It also assigns resources for public funds such us FAZNI. The document is prepared by the MME and UPME.

PNER: The document focuses on expanding the energy coverage in rural areas, prioritizing energy solutions with FNCE. Additionally, it gives technical assistance to the communities in the maintenance, training, and sustainably of the projects.

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Abbreviations

2G-SHS	Second generation solar home systems
3G-SHS	Third generation solar home systems
CLC	Centro Luz en Casa (Light at Home Centers)
CONAFE	National Electric Power Company
CONPES	National Council for Social and Economic Policy
COP	Colombian Pesos
CREG	Energy and Gas Regulation Commission
ESCO	Energy service company
FAZNI	Financial Support Fund for the Electrification of Non-interconnected Areas
FNCER	Non-conventional renewable energy sources
FNDR	National Fund for Regional Development
FOSE	Electric Social Compensation Fund
GEF	Global Environment Fund
IAEA	International Atomic Energy Agency
ICT	Information and communication technology
IDB	Inter-American Development Bank
IEC	Electro-technical Commission
IPSE	Institute for Planning and Promotion of Energy Solutions for Non-
NIZ	Interconnected Zones
KPT	Territorial Planning Kit
MPPT	Maximum Power Point Tracker
MME	Ministry of Mines and Energy
NDC	National Determined Contribution
NIZ	Non-interconnected zones
OAM	Operation, administration, and maintenance
OECD	Organization for Economic Co-operation and Development
PAYG	Pay-as-you-go
PEECES	Caribbean Energy Efficiency Program Sustainable Energy
PEN	National Energy Plan
PERS	Sustainable Rural Energization Plan
PIEC	Energy Coverage Expansion Plan
PDET	Development Plans with a Territorial Focus
PNER	National Plan for Rural Electrification
PPA	Public–private alliance
PPARD	Public–Private Alliance for Rural Development
PTSP	Plan Todos Somos PAZcífico
PV	Photovoltaic
RAP	Administrative and Planning Region
RE	Renewable energies
R+D+i	Research, development, and innovation
SENA	National Learning Service
SHS	Solar home system
SIN	National Interconnected System
SFVI	Individual Photovoltaic Systems
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UN	United Nations
UNHR	United Nations Human Rights Council
UPME	Mining and Energy Planning Unit

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