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Techno-economic and environmental impact of a photovoltaic system to improve energy quality in isolated areas

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Abstract---The lack of access to electricity in isolated areas represents a significant obstacle to the economic development of their inhabitants. Solar photovoltaic technology emerges as a promising solution to address electrification challenges in these areas; However, its implementation faces technical, economic and environmental barriers. The objective of the research was to carry out a technical, economic and

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environmental analysis of a photovoltaic system designed for an isolated community. The bibliographic review, qualitative and quantitative method was used as a methodology, in addition to PvSyst 7.2, the result was the estimation of energy demand, the analysis of solar potential in the region, the design of the photovoltaic system and the evaluation of energy losses energy. The system has a power of 180 kWp, the system is designed to meet the energy needs of the community, improve the stability of the electricity supply and reduce dependence on fuel-powered generators. The economic analysis shows a recovery period of 16 years and a generation cost of $0.0826 USD/kWh, competitive with traditional rates. In addition, it is projected that the system will avoid the emission of 2,446.1 tons of CO_2 in 30 years, thus contributing to sustainability and reducing the carbon footprint.

Keywords---rural electrification, solar energy, sustainability, carbon footprint.

Introduction

The transition towards sustainable energy, focused on improving energy efficiency and the use of renewable sources, has been a pillar of global sustainable development, promoted by events such as the United Nations Conference and the Climate Change Conference (Miravet et al., 2022). These initiatives have led many countries, including those in Latin America, to seek solutions to reduce their dependence on fossil fuels.

In Ecuador, electricity production capacity has grown significantly in recent years, reaching 5,395 MW from renewable sources in 2023, which represents the 65% of the country's total generation (Energía Estratégica, 2023). However, this expansion presents a marked dependence on hydroelectric energy, which contributes 69.1% of total electricity generation; In contrast, other renewable sources have a minimal participation: biomass contributes only 0.87%, wind energy 0.57%, photovoltaic plants 0.11% and biogas plants 0.1%. (Zambrano, 2023).

These results highlight the urgency of diversifying renewable energy sources in Ecuador through distributed generation. Although hydroelectric infrastructure makes a significant contribution, the limited participation of other sources reveals the little use of renewable resources.

Photovoltaic solar energy has established itself as one of the main sources of renewable energy in the world. Its ability to generate electricity from solar radiation, an inexhaustible and widely available source, makes it an important option in the global energy transition. (Guanacunga et al., 2022).

According to the Atlas of Ecuador for electricity generation purposes, the country has an average global solar insolation potential of 4,575 Wh/m^2/day, divided into a direct insolation of2,543 Wh/m^2/day and a diffuse insolation of 2,032 Wh/m^2/day (Ministry of Energy and Mines, 2019). In the province of Manabí, this resource is particularly abundant, with radiation levels ranging between 1,478 and 1,874 kWh/m^2/year in different cantons (Navas et al.,2022). These high solar potential positions the region as an ideal area for the development and expansion of photovoltaic energy projects, offering important alternatives to take advantage of this solar source efficiently.

The growing demand for energy in rural areas, together with the strong dependence on conventional sources, the rise in fuel prices and their progressive depletion, has generated significant limitations for socioeconomic development (Valencia, 2018). These areas suffer from problems of instability in the energy supply, high operating costs and a lower quality of life due to limited availability of electricity.

Under these circumstances, photovoltaic systems represent a feasible solution to satisfy the energy needs of isolated rural areas (Salau et al., 2023). The Solar energy not only offers a renewable and sustainable source, but also has the potential to improve energy quality in these areas by stabilizing supply, reducing operating costs and minimizing environmental impact (Barasa and Akanni, 2021).

Materials and methods

To carry out the study, a bibliographic review was carried out, the inductive-deductive method was applied, the research is qualitative-quantitative, for the design of the employment system the PVSyst (PVSyst 7.2, 2024) that allows calculations, analysis referring to economic and environmental feasibility.

Analysis and discussion of the results

In the province of Manabí there are communities in rural areas that have difficulties with the energy service, (Mera, Rodríguez, 2024), these authors carried out a study where they proposed the use of solar potential with the use of photovoltaic technology, because In this province there are high rates of solar irradiance (Rodriguez, Vázquez, 2018), these conditions are appropriate to invest in rural electrification to improve the living conditions of the populations that today have these needs.

The study was carried out in the Las Aldeas community, located in the San Eloy sector, in the Rocafuerte canton, province of Manabí. This community, shown in Figure 1, is made up of approximately 22 homes that, although they are connected to the electrical distribution network, face a series of problems related to the quality of supply. The distance from the main grid generates significant voltage drops and unforeseen power outages, both due to technical and non-technical failures, resulting in intermittent and unreliable service.

Figure 1. Las Aldeas Community, San Eloy Sector, Rocafuerte Canton

Due to these deficiencies, 45.5% of households have resorted to using fuel generators as an alternative source to guarantee a constant electricity supply. This dependence on generators reflects not only the high operating costs that these families must assume, but also the environmental impact associated with the use of fossil fuels. The remaining 55.5% of homes depend exclusively on the electrical grid, which makes them vulnerable to service interruptions and fluctuations.

Energy demand estimation

Through a standardized consumption estimate for typical equipment in rural homes, complemented with specific information from the community, it was possible to obtain the results that allow identifying the energy consumption pattern of the sector, as presented in Table 1.

The study focused on a representative sample of 22 homes, where data collection was carried out on the electrical equipment present and its average use. Based on the data obtained, an estimate of energy consumption was made for the most common equipment, using an analytical approach that considers the nominal power of each device and the average hours of daily use.

The results show that, on average, each household consumes approximately 4.67 kWh/day. When projecting this consumption at the community level, taking into account the total number of homes, an estimate of energy consumption of 102.74 kWh/day was obtained for the entire Las Aldeas sector.

Table 1
Estimation of daily energy consumption per home

Equipment	**Power (IN)**	**Number Average Per Dwelling**	**Time of use daily**	**Daily consumption per team (Wh)**	**Total consumption per home (Wh)**
Light bulbs	25	5	4	100	500
Lamps	25	2	2	50	100
TV	100	2	3	300	600
Fridge	115	1	24	2760	2760
Fans	30	2	4	120	240
Radios	5	1	2	10	10
Recorders	45	1	1	45	45
Washing machines	180	0,5	0,5	90	45
Planks	1000	0,2	0,5	500	100
Cell Phones	5	3	2	10	30
Devices Internet	10	1	24	240	240
Total consumption per home (kWh/day)					**4,67**
Total daily consumption for the community (kWh/day*22)					**102,74**

A detailed analysis of energy consumption by type of equipment in homes, the results reveal that the greatest consumption is concentrated in equipment such as fans, refrigerators, televisions and light bulbs, which have continuous use and are essential for the daily needs of the home, in addition It is observed that intermittently used equipment, such as irons and washing machines, although they are not in constant operation, generate significant peaks in energy demand when they are used.

Solar irradiation of the study area

The table in Figure 2 shows the monthly data of global horizontal irradiation, diffuse horizontal irradiation and average temperature in the study area. The annual average global horizontal irradiation is 4.60 kWh/m^2/day, while the annual average horizontal diffuse irradiation is 2.57 kWh/m^2/day. This indicates that approximately 56% of the global irradiation is direct irradiation, which is favorable for the efficiency of photovoltaic systems that require a higher proportion of direct irradiation for better generation.

	Irradiación horizontal global	Irradiación difusa horizontal	Temperatura
	kWh/m²/día	kWh/m²/día	°C
Enero	5.07	2.70	25.9
Febrero	5.04	2.78	26.0
Marzo	5.40	2.79	26.2
Abril	5.76	2.44	25.7
Mayo	4.84	2.36	25.7
Junio	4.12	2.54	24.4
Julio	3.99	2.62	24.1
Agosto	4.02	2.81	23.7
Septiembre	3.83	2.42	23.3
Octubre	3.80	2.54	23.8
Noviembre	4.53	2.51	23.7
Diciembre	4.78	2.31	25.1
Año	**4.60**	**2.57**	**24.8**

Figure 2. Monthly solar irradiation data in the study area

As can be seen, the month with the highest global irradiation is April, with 5.76 kWh/m²/day, and the month with the least irradiation is July, with 3.99 kWh/m²/day, which shows a significant seasonal variation. The average annual temperature is 24.8°C, with a maximum of 25.9° in January and a minimum of 23.1°C in December. These temperatures are stable and favorable for the modules

Photovoltaic system

As evidenced in Table 1, it is estimated that the community's electricity consumption demand is approximately 102.74 kWh/day. Based on this demand, a photovoltaic system has been designed that not only covers the current energy needs, but also allows a margin of flexibility in the face of possible increases in consumption, therefore, the system design will have a planned installed capacity of 180 kWp.

Figure 3 presents the schematic of a grid-connected photovoltaic system, which includes photovoltaic modules, inverters, as well as control and measurement devices. This configuration not only provides the necessary energy supply for the community, but also contributes to distributed generation by injecting surplus energy into the electrical grid, which can improve the stability and quality of service in the region.

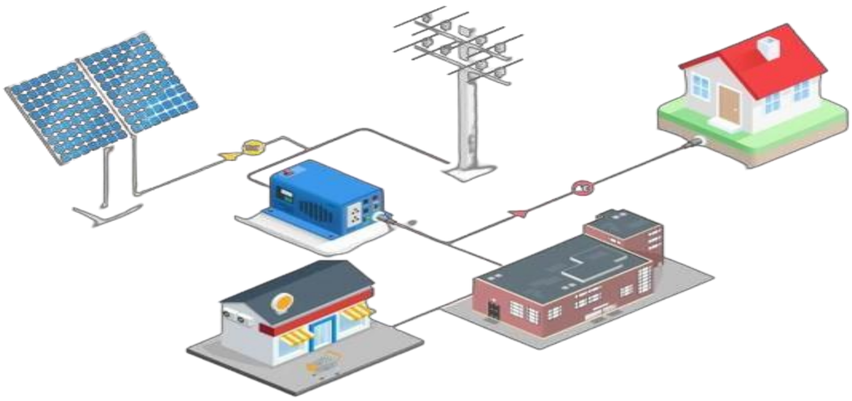

Figure 3. Grid connected photovoltaic array

Photovoltaic module

For the design, a photovoltaic module from the Heckert Solar brand has been selected, with a capacity of 400 Wp and an output voltage of 40 V under standard conditions. This module has a maximum power voltage (Vmpp) of 40.8 V at a temperature of 60°C, and an open circuit voltage (Voc) of 60.8 V. These specifications ensure robust performance under conditions of high irradiance and elevated temperatures, typical characteristics of the region. Based on demand analysis, it has been calculated that a total of 450 panels will be required, covering an estimated area of 877 m^2. This surface was sized considering both the necessary generation capacity and the space available in the community.

Investor

To convert the direct current generated by the panels to alternating current usable in the network, a Huawei Technologies brand inverter with a nominal power of 40 kW has been selected. This inverter has an input voltage range of 200 - 1000 V, and a maximum input voltage of 1100 V, giving it great flexibility to operate with variations in input voltage without compromising efficiency. The inverter output is designed to provide 400 V at 60 Hz, suitable for connection to the local medium voltage grid.

To meet the total required system capacity, 4 inverters will be used in parallel, resulting in a combined power of 160 kW alternating current (AC). This approach allows for better load management and greater overall system efficiency, ensuring continuous supply to the community.

Energy Analysis

The analysis of the normalized production per kWp installed in Figure 4 shows that the collection losses reach 0.61 kWh/kWp/day, which indicates that a significant part of the energy that could be captured by the panels is affected due to various factors, such as the presence of partial shadows. On the other hand, system losses (due to components such as cables, inverters and other energy conversion and transmission elements) are relatively low, with a value of 0.07 kWh/kWp/day, which suggests that the system is optimized to minimize conversion losses.

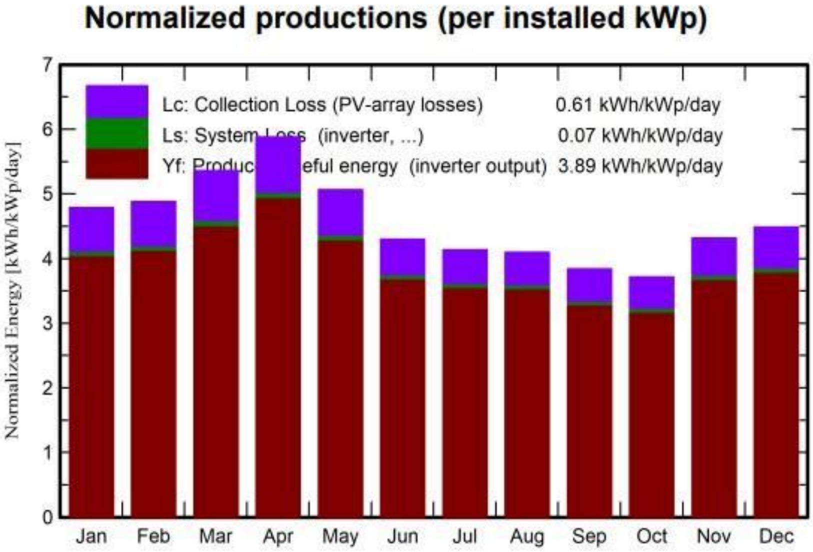

Figure 4. Normalized productions per installed kWp

The performance index shown in Figure 5, with a value of 0.85 (equivalent to 85%), reflects a system with relatively high performance. This index indicates that the system is operating at 85% of its optimal capacity, which can be interpreted as good performance, although there is room for improvement. The possible causes of this slight decrease in performance may be factors such as losses due to partial shading, low efficiency of some system components or operating conditions, which could be optimized through adjustments in orientation, maintenance or updating of the components.

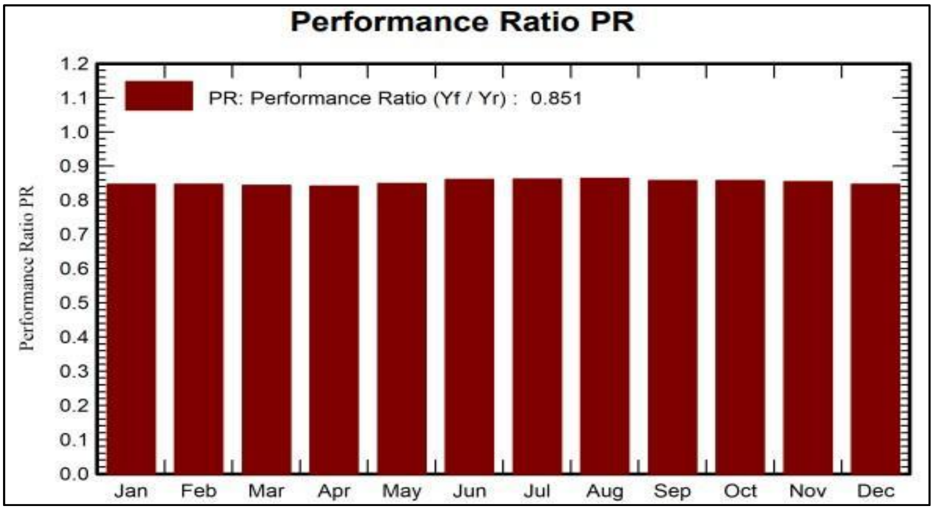

Figure 5. Performance index

The loss diagram presented in Figure 6 is a detailed breakdown of the different conversion stages and energy losses of the photovoltaic system. At the top, the global horizontal irradiation is observed (1678 kWh/m²) which is then reduced to the incident in the plane of the collectors due to losses due to inclination and orientation (1624 kWh/m²). Subsequently, the efficiency of the photovoltaic modules is shown, which is 20.57% under standard conditions (STC). After applying various factors such as irradiation losses, temperature and quality of the modules, the nominal energy generated by the modules is 292,791 kWh.

However, additional losses occur due to module misalignment, wiring, and inverter efficiency factors, resulting in a virtual energy at the maximum power point of 260,052 kWh. Finally, after the losses in the inverter and night consumption, the energy available at the inverter output and ready to be injected into the grid is 255,599 kWh.

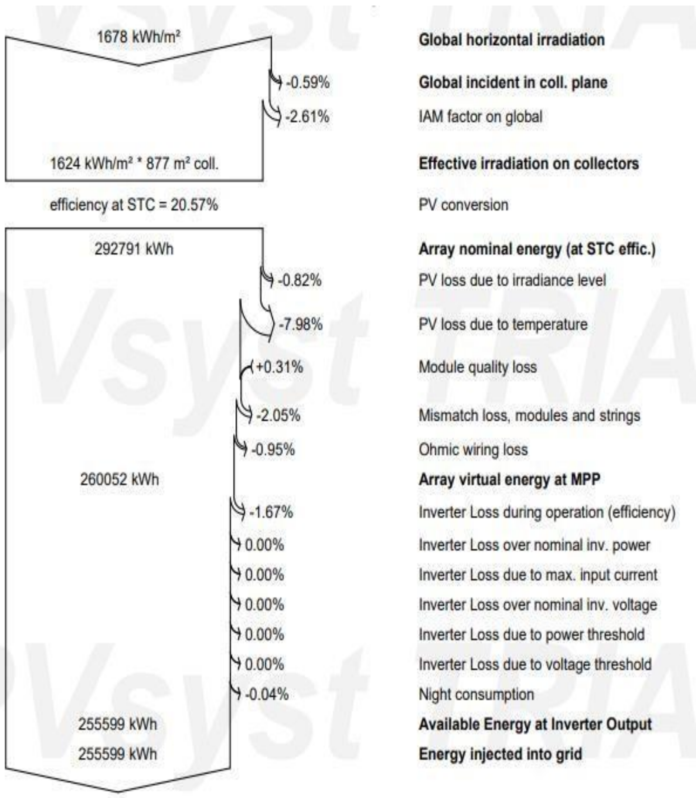

Figure 6**.** Photovoltaic system loss diagram

The daily input/output diagram presented in Figure 7 shows a direct relationship between the global irradiation incident on the collector plane and the useful energy of the system for each day of the year, in the period from January 1 to January 31. of December. The graph presents a clear linear correlation between these two parameters, which indicates that as the available solar irradiation increases, the useful energy generated by the photovoltaic system also increases.

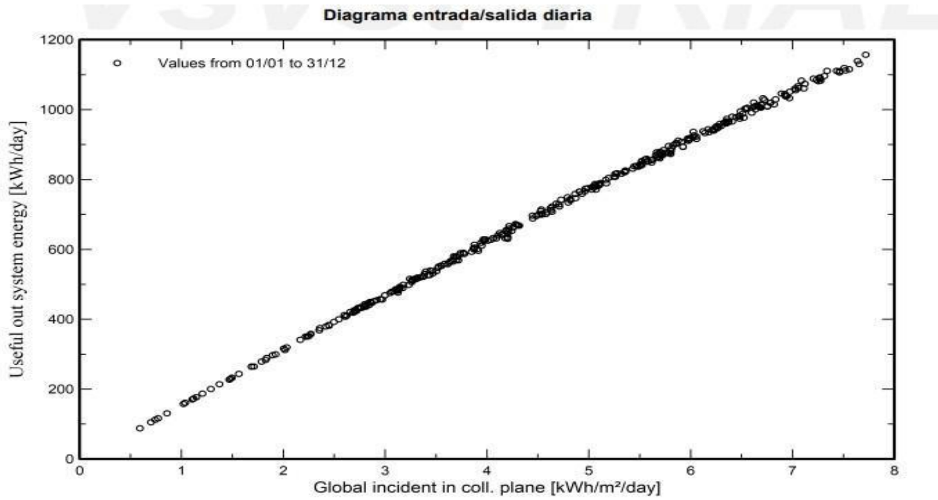

Figure 7. Daily input/output diagram

This linear behavior is typical in photovoltaic systems where losses are relatively constant, and energy production is mainly affected by the amount of irradiation received. The diagram suggests good efficiency of the system, with no indications of saturation or significant loss of performance under high irradiation conditions.

The system output power distribution diagram in Figure 10 shows the frequency with which the PV system achieves different levels of useful energy production, measured in 2 kW intervals. This diagram relates the useful energy of the system to the number of hours in which the system has operated at each power level.

It is observed that the curve has an asymmetric shape with a peak in the intermediate zone, around 100 kW, which indicates that the system operates more frequently in that power range. This suggests that, during the year, most of the time the system generates between 80 kW and 120 kW reflecting moderate irradiation conditions.

It is also notable that there are fewer hours at the extremes of the graph, that is, the system rarely produces very little power or reaches its maximum capacity, which is consistent with cloudy days or with the lowest available irradiation, as well as with the days of maximum irradiation.

Economic Analysis

The economic analysis detailed in Figure 11 reveals the initial investment of $68,600.00 USD in the depreciable assets, which include the main components of the photovoltaic system: photovoltaic (PV) modules, inverters and accessories. This figure represents only a part of the total investment, which amounts to $358,440.00 USD, including maintenance costs, additional equipment, installation, land acquisition, technical and environmental analysis, among others.

In operational terms, the system has operating costs of $3,200.00 USD per year, which cover maintenance and other recurring expenses associated with the operation of the system. The energy produced is estimated at 256 MWh per year, resulting in an energy production cost of $0.0826 per kWh, a competitive value compared to average electricity grid rates.

From a financial perspective, the payback period of the project is estimated at 16 years, which means that the income generated will cover the initial investment in that time. The net present value (NPV), calculated at $88,959.45 USD, indicates that the project is profitable once future cash flows are discounted. However, the internal rate of return (IRR), which is 2.22%, suggests that, although the project has a positive return, its profitability is not particularly high. However, with a return on investment (ROI) of 24.8%, it is evident that, in the long term, the system will provide additional benefits after the recovery period.

Therefore, although the IRR and payback period indicate a moderate financial performance, the competitiveness in the cost of the energy produced, together with the environmental benefits and the reduced dependence on non-renewable energy sources, make the project be viable and attractive, especially in environments where sustainability and mitigation of environmental impacts are prioritized.

Environmental Analysis

The system has an annual generation capacity of 2,556 MWh and is estimated to operate for 30 years, with an annual degradation of 1%. This system generates CO_2 emissions during its life cycle, calculated at 318.71 tons of CO_2, mainly due to the manufacturing of the modules, supports and inverters, with a specific emissions breakdown for each component: 308,290 kg of CO_2 for the modules, 9,575 kg for the supports and 843 kg for the inverters.

On the other hand, the avoided emissions are calculated at 2446.1 tons of CO_2, considering that the emissions will replace the conventional source of the network that produces 319 gCO_2/kWh. This cumulative CO_2 savings, the emissions balance line, grows over time, exceeding the emissions generated after a few years and remaining positive until the end of the system's useful life period.

This shows that, over 30 years, the photovoltaic system will largely offset the emissions generated in its manufacturing and installation, contributing significantly to the reduction of the total carbon footprint.

Conclusions

The implementation of the photovoltaic system allows improving the quality of electrical service in isolated rural areas such as Las Aldeas. This is achieved by stabilizing the supply and reducing voltage drops and interruptions, which directly benefits the quality of life of the inhabitants.

The economic analysis shows that the system is viable in the long term, with a payback period of 16 years and a competitive cost of energy generation. Although the IRR is moderate, the ROI and savings in fossil fuel consumption make the project profitable and attractive from a sustainability perspective.

The proposed photovoltaic system avoids a large amount of CO_2 emissions compared to the use of fossil fuel generators, achieving a positive balance in its carbon footprint. Throughout its useful life, the system will contribute significantly to the reduction of emissions and the mitigation of climate change.

The Manabí region has a high solar potential, which supports the implementation of similar projects in other rural communities in the country. The experience in Las Aldeas can serve as a model to expand the use of photovoltaic systems in areas with similar challenges, promoting the diversification of renewable energy sources in Ecuador.

References

Barasa, M., & Akanni, O. (2021). Sustainable energy transition for the generation and supply of electricity from renewable and low-carbon sources. *frontiers, 9*(1), 1-8. doi.org/10.3389/fenrg.2021.743114

Guanacunga, A., Iza, M., & Lasluia, D. (2022). *Solar Projects in Ecuador*. Cotopaxi Technical University. https://repositorio.utc.edu.ec/

Mera, Jean. P, Rodriguez, M. (2024). Feasibility for rural electrification with photovoltaic technology 593 Digital Publisher, Vol. 9, No. 3 (Issue dedicated to: Multidisciplinary), pp. 1139-1153, https://dialnet.unirioja.es/servlet/articulo?codigo=9535938

Ministry of Energy and Mines. (September 3, 2019). *resource and energy*. Retrieved from https://www.recursosyenergia.gob.ec/manabi-tendra-la-central-de-energia- photovoltaic-largest-in-the-country/#:~:text=The%20Aromo%20is%20a%20new,the%20production%C3%B3n%20of%20energ%C3%ADa%20el%C3%A9ctrica.

Miravet, B., Garcia, A., Yuli, R., Inostroza, A., Fernandez, G., & Apesteguia, A. (2022). Solar photovoltaic technology in isolated rural communities in Latin America and the Caribbean. *Energy Reports, 8*(2), 1238-1248. doi.org/10.1016/j.egyr.2021.12.052

Navas, W., Durango, R., & Landivar, E. (2022). The potential of photovoltaic energy as a source of electricity in Manabí. *Digital Science, 6*(1), 91-115. doi:doi.org/10.33262/cienciadigital.v6i1.1956

PVSyst, (2024). Design and simulation software for your photovoltaic systems. https://www.pvsyst.com/

Rodriguez, M., Vázquez, A. (2018). Photovoltaic Energy in the Province of Manabí. UTM Publishing. ISBN: 978-9942-948-20-5. https://utm.edu.ec/ediciones/libros-de-texto/713-la-energia-fotovoltaica-en-la-provincia-de-manabi

Salau, A., Khan, B., & Gidey, I. (2023). Techno-Economic analysis of distributed generation for power system reliability and loss reduction. *International Journal of Sustainable Energy, 42*(1), 873-888. doi:10.1080/14786451.2023.2244617

Strategic Energy. (2023). Ecuador strengthens regulatory instruments for distributed generation and self-supply. *News*, p. 12-15. Retrieved from https://www.energiaestrategica.com/ecuador-fortalece-instrumentos-regulatorios-para- distributed-generation-and-self-sufficiency/

Valencia, P. (2018). https://dialnet.unirioja.es/servlet/articulo?codigo=4547088Distributed generation: democratization of electrical energy. *Free Criterion, 2*(1), 105-113.

Zambrano, L. (2023). Electric Energy Situation in Ecuador 2024. *elements*, pp. 1-2. https:///www.elementsgroup.com.ec/situacion- electric-energy-in-ecuador-2024/