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Research Article

Energy equity in the integration of photovoltaic systems: A case study of Armenia, Colombia

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Abstract. This study evaluates the technical and economic potential of a hybrid photovoltaic system aimed at promoting energy equity in the Colombian Andean region (La Tebaida), using a meteorological database with a five-minute temporal resolution. The methodology integrated a probabilistic characterization of the solar resource, a generation estimation based on a sensitivity analysis with restrictive irradiance thresholds (600, 650, and 700 W/m²), and financial modeling through ten-year projected cash flows that incorporate the volatility of electricity rates and local credit conditions. The probabilistic results demonstrate a high robustness of the resource: during the time frame of greatest operational interest (09:00 to 14:00 h), 80% of the records exceeded the 600 W/m² threshold, ensuring an annual generation of over 700 kWh per panel in all evaluated scenarios. In the economic component, it was evident that self-consumption supported by storage is the dominant strategy compared to grid injection, due to the low remuneration for surpluses within the regulatory framework. Under a representative macroeconomic scenario, access to preferential financing lines dilutes the initial investment barrier, allowing the cash flow to reach its break-even point in 62 months with a positive Net Present Value (NPV), an Internal Rate of Return (IRR) of 16.94%, and a Levelized Cost of Energy (LCOE) of 487 COP/kWh, a value substantially lower than the average commercial grid rate (900 COP/kWh). It is concluded that distributed self-generation is consolidated as a feasible and necessary instrument to mitigate the economic burden on rural households in the face of the sustained increase in the cost of commercial electricity.

Keywords: Energy models, Economic analysis, Sensitivity analysis, Economic barrier



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1. Introduction

Energy equity is an essential element of sustainable development (Fu *et al.*, 2021), as it relates to the real possibility of households accessing secure, continuous, and affordable energy services (Guerrero *et al.*, 2021; Jiao & Tan, 2024; Raman *et al.*, 2025). In vulnerable populations, economic limitations and living conditions increase exposure to energy poverty (Chan & Delina, 2023; Esquivel García & Toro-García, 2024; Wang & Zhan, 2022), which translates into a high proportion of income allocated to energy payments, restrictions on the use of basic equipment, and difficulties in maintaining adequate levels of thermal comfort, lighting, and connectivity (Cong *et al.*, 2022; Huang *et al.*, 2023).

Energy constitutes not only a productive input but also a determinant of well-being and opportunities (Amoah *et al.*, 2020; Liao *et al.*, 2021); consequently, decisions regarding infrastructure, tariffs (Ansarin *et al.*, 2022; Hancevic *et al.*, 2022), and technological alternatives directly impact the quality of life and households' capacity to reduce social gaps (Bayona-Velásquez *et al.*, 2023; Esquivel García & Toro-García, 2024).

Furthermore, the energy transition acquires a distributive dimension (Bragolusi & Righettini, 2022; Gürtler, 2023; Heffron, 2022); it is not enough to decarbonize the system if the economic, environmental, and resilience benefits are concentrated in the highest-income segments (Vanegas Cantarero, 2020; Wahlund & Palm, 2022). In this regard, energy equity applied to renewable energies requires evaluating the extent to which available technologies and financing schemes enable or restrict access for vulnerable households (Brito Cedeno & Wei, 2024; Mungai *et al.*, 2022).

In the context of this study, the definition and quantitative evaluation of energy equity rest upon financial affordability and credit access. This framework evaluates the capacity of a user in a state of socioeconomic vulnerability (strata 1, 2, and 3) to assume and fulfill a credit obligation destined for the acquisition of a photovoltaic system. The financial design must restrict the monthly installment to an amount lower than the monetary savings reflected on the electric power invoice. This approach permits economic viability analysis, calculated through a cash flow, to constitute the primary metric to determine whether the

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technology acts as an equity enabler or as an energy burden that causes the decapitalization of the user.

Distributed solutions based on local renewable resources can offer relevant advantages by reducing grid dependency (Bamisile *et al.*, 2019; Islam & Hossain, 2022), stabilizing energy expenditure, and increasing resilience against service interruptions (Diaz Motta, 2020). Among them, solar photovoltaic energy stands out due to its modularity, the sustained reduction in technological costs (Ramasamy *et al.*, 2023), and its potential for adoption at a residential scale (Arefeen & Dallas, 2021; Nijse *et al.*, 2023). However, its effective contribution to equity depends on variables that are often underestimated in simplified analyses (Garnica *et al.*, 2018), such as the intra-day and seasonal variability of the solar resource (Perez *et al.*, 2018), conversion-associated losses, the mismatch between generation and demand, and, especially, the conditions of access to capital that determine economic viability in households with liquidity constraints.

Financial institutions have improved access conditions through preferential rates and, in parallel, the performance and technological availability of photovoltaic systems have enhanced (Nijse *et al.*, 2023; H. Wang, 2023; Wu, 2023). Under this scenario, it is pertinent to quantitatively examine whether these conditions translate into a real improvement in affordability and, therefore, into a contribution to energy equity. In response, this research proposes to evaluate the integration of a solar photovoltaic generation system using data measured near the municipality of Armenia, Colombia. This is with the objective of strengthening the activities of peasant populations and, based on this, identifying opportunities for improvement and gaps to be closed with a view to increasing energy equity in the region.

The objective of this research is to evaluate the financial viability and the impact on energy equity of integrating solar photovoltaic systems, through the development of a 10-year economic model that assesses the Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE) under comparative scenarios of interest rates, financing terms, and electricity tariffs. The novelty of this approach lies in evaluating how local financing schemes and cross-subsidies specific to Colombia (such as the Solidarity Fund for Subsidies and Income Redistribution - FSSRI) interact with Andean solar variability to facilitate or block access for vulnerable rural populations. This goes beyond a standard technical feasibility analysis, providing a replicable methodological perspective for the integration of renewable energies in developing country contexts. The results allow for the identification of the financial and tariff conditions under which the investment constitutes a viable alternative or, conversely, an additional barrier for users. Furthermore, they enable sensitivity analyses and the construction of scenarios useful for guiding public policy decisions and the design of inclusive financing strategies and programs.

2. Methodology

The methodology employed was structured into three consecutive phases and utilized a high-resolution temporal database consisting of records taken every five minutes during the year 2017. To mitigate the climate uncertainty associated with using a single year of measurement, the obtained irradiance averages were contrasted with multi-year satellite databases, which validated that 2017 represents a typical meteorological year for the Colombian Andean region. The database includes the date, hour, minute, irradiance (W/m^2), and ambient temperature ($^{\circ}C$).

The first phase corresponds to a descriptive analysis of irradiance and ambient temperature, oriented toward exploratory inspections and internal consistency verifications. An hourly violin plot was constructed with the temperature data, while thirteen box-and-whisker plots (twelve monthly and one annual) were generated for irradiance. Additionally, two duration curves (Lin *et al.*, 2012; Nasir, 2024; ScienceDirect, n.d.) were prepared (one annual and one monthly) considering only records between 10:00 and 16:59; these results allow for characterizing the probabilistic behavior of the resource and demonstrating its variability throughout the year.

The second phase presents the estimation of the energetic potential of the photovoltaic system. The mathematical modeling was divided into two approaches: the first presents a probabilistic reliability model based on strict thresholds, and the second is a real continuous generation model utilizing the irradiance data for financial evaluation; both models were implemented in the R environment. The selection of a simplified model based on panel efficiency is grounded in the work of (Galindo, 2017), where it is demonstrated that this approach records a maximum discrepancy of 6.5% compared to complex four-parameter models or commercial software (such as PVsyst or SAM) for the equatorial strip region.

- *Probabilistic Reliability Approach*

To establish a safety baseline and evaluate the reliability of the solar resource against credit risks, the thresholds of 600, 650, and 700 W/m^2 were analyzed discretely. The expected theoretical effective power (P_T) in each module for a given threshold was calculated using Equation 1:

$$P_T = P_{STC} \frac{T}{G_{STC}} \quad (1)$$

Where P_{STC} is the nominal power of the panel under standard test conditions (610 W), T is the evaluated irradiance threshold (600, 650, or 700 W/m^2), and G_{STC} is the reference irradiance (1000 W/m^2). Subsequently, the conservative monthly energy (E_{Umbra}) guaranteed exclusively by records exceeding said threshold was quantified using Equation 2:

$$E_{Umbra} = \frac{N_{\geq T} * P_T * \Delta t}{1000} \quad (2)$$

Where $N_{\geq T}$ is the number of records in the month where the irradiance equals or exceeds the threshold T , and Δt is the recording interval expressed in hours ($\Delta t = 5\text{min} / 60\text{min/h} = 0.0833\text{h}$). This conservative approach does not seek to predict total production but rather to demonstrate the minimum and immediate energy with which the user will mitigate the financial risk of the debt under unfavorable climate scenarios.

- *Continuous Generation Approach*

For the 10-year economic projection of the cash flow, the modeling in R did not filter the data by peak thresholds; instead, it calculated the net energy yield by dynamically and continuously applying Equation 3 to each of the real variations in irradiance (G_i) recorded every 5 minutes throughout the year:

$$E_i = A * \eta_{panel} * \frac{G_i * \Delta t}{1000} * \eta_{inv} * k_p \quad (3)$$

Where E_i is the real electrical energy generated in the interval i (kWh), A is the catchment area of the photovoltaic array (m^2), η_{panel} is the nominal efficiency of the module under STC conditions, G_i is the recorded instantaneous irradiance (W/m^2), and Δt is the fraction of an hour (0.0833h). The real technical

Table 1
Capital Expenditure (CAPEX) Estimation of the Photovoltaic System.

Component	Technical Specification	Quantity	Unit Cost (COP)	Total Cost (COP)
Photovoltaic Modules	Bifacial Solar Panel 610W	4	\$ 510,00	\$2,040,000
Hybrid Inverter	Growatt Grid Inverter MIN 6000TL-XE	1	\$2,198,500	\$2,198,500
Inverter Charger	Growatt Inverter Charger SPF 3000	1	\$2,122,000	\$2,122,000
Battery Bank	2.4 kWh Lithium Battery	3	\$2,695,259	\$8,085,777
Electrical Kit	Structure, solar wiring, and protections	1	\$1,500,000	\$1,500,000
Labor	Installation and commissioning	1	\$2,000,000	\$2,000,000
Total Initial Investment (CAPEX)				\$17,946,277

coupling and global losses were modeled by separating the conversion efficiency of the hybrid inverter (η_{inv}) and a dimensionless coefficient of additional losses (k_p) due to wiring, dirt, and mismatches. Regarding losses due to the temperature coefficient, although the local records show instantaneous thermal peaks exceeding 30 °C, the Andean microclimate of La Tebaida is predominantly temperate. Consequently, the cumulative thermal impact on voltage is not statistically disruptive in the annual balance and is considered safely absorbed within the k_p factor.

The third phase corresponds to the economic evaluation of the project. To guarantee financial transparency and justify the initial capital investment (CAPEX), the sizing and budgeting were based on a real hybrid commercial kit available in the Colombian market. The configuration of the array was optimized by reducing the original photovoltaic block to four (4) panels of 610 W. This sizing (2.44 kWp installed) was specifically established to cover 100% of the average monthly demand of a rural household in Quindío, avoiding oversizing and facilitating the system's affordability. The system consists of a 6000 W on-grid inverter, a 4500 W inverter-charger, and three (3) 2.4 kWh lithium batteries. Storage is technically and socially necessary to provide autonomy and resilience against electricity service interruptions, which are recurrent in Colombian rural areas. The detailed breakdown of the initial investment, which amounts to a total cost of 18,000,000 COP, is presented in Table 1. The analyses will be maintained in Colombian currency due to the volatility that the dollar has shown in recent months.

The viability of the project was determined using a cash flow model projected over a 10-year time horizon, which aligns with the maximum term of the evaluated credit obligations. During this decade, the model assumes that there are no replacement costs for major equipment (inverters or batteries), based on the commercial guarantees of the manufacturers that ensure capacity retentions higher than 80% in lithium cycles. However, to guarantee full rigor and financial transparency, the cash flow incorporates an annual degradation rate of photovoltaic modules of 0.5% (reducing energy generation year by year) and a provision for Operation and Maintenance (O&M) costs. This provision is set at a baseline value of 200,000 COP for the first year, executed in two constant semi-annual interventions of 100,000 COP, with a compound annual increase of 5% associated with inflation.

Finally, the economic performance of the business case is evaluated using standard financial indicators: Net Present Value (NPV), Internal Rate of Return (IRR), and the Levelized Cost of Energy (LCOE). The economic analysis is structured around three comparative variables: (1) interest rate, (2) financing term, and (3) electricity price. For each variable, three scenarios are proposed with low, average, and high values of the evaluated parameter. The results are presented through graphs of the cash

flow and the behavior of the acquired debt (Behar, 2026; King *et al.*, 2025).

3. Results

Data acquisition was carried out in the municipality of La Tebaida (Quindío), located in the Andean region of western Colombia at an average altitude of 1,483 m a.s.l. The topography of this area directly influences cloudiness and precipitation regimes, introducing high intra-day variability in the solar resource. Consequently, it is necessary to evaluate the viability of photovoltaic technology through a probabilistic approach that guarantees affordability and the mitigation of financial risk for the rural economies of the region.

3.1. Solar radiation and ambient temperature

Figure 1 presents the violin plot of hourly ambient temperature, compiled from records measured every five minutes over a full year. The analysis of this distribution allows for evaluating the impact of the surrounding thermal conditions on the technical performance of the panel. During the early morning hours (0:00 to 6:00 h), a high probability density is observed with values homogeneously concentrated between 18 °C and 19 °C, accompanied by prolonged lower tails reaching minimum records between 8 °C and 10 °C. In the morning interval between 7:00 and 10:00 h, the distribution shows a progressive and linear thermal increase, a behavior directly conditioned by the absorption of the incident solar irradiance flux.

In the period of maximum insolation, located between 11:00 and 13:00 h, the daytime temperature exhibits its greatest dispersion and is frequently situated above 30 °C, recording

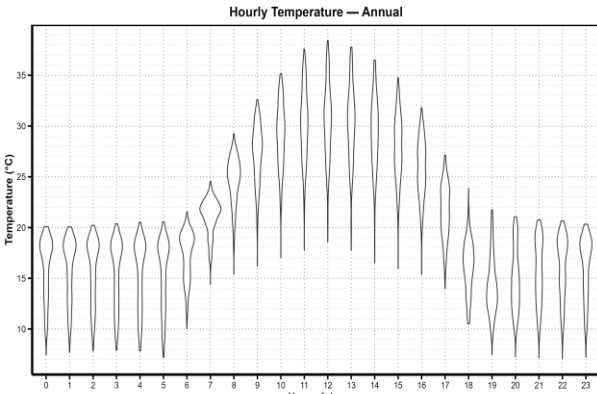


Fig.1 Violin plot of hourly temperature data.

maximum values exceeding 34 °C. This variability is due to the effects of cloudiness, relative humidity, and local climate seasonality. This thermal increase transiently reduces the open-circuit voltage and the conversion efficiency of the modules relative to Standard Test Conditions. Between 16:00 and 23:00

h, a gradual decrease in the thermal profile is identified, converging towards a new stable concentration around 18 °C and 19 °C, consistent with the nocturnal pattern of atmospheric stabilization.

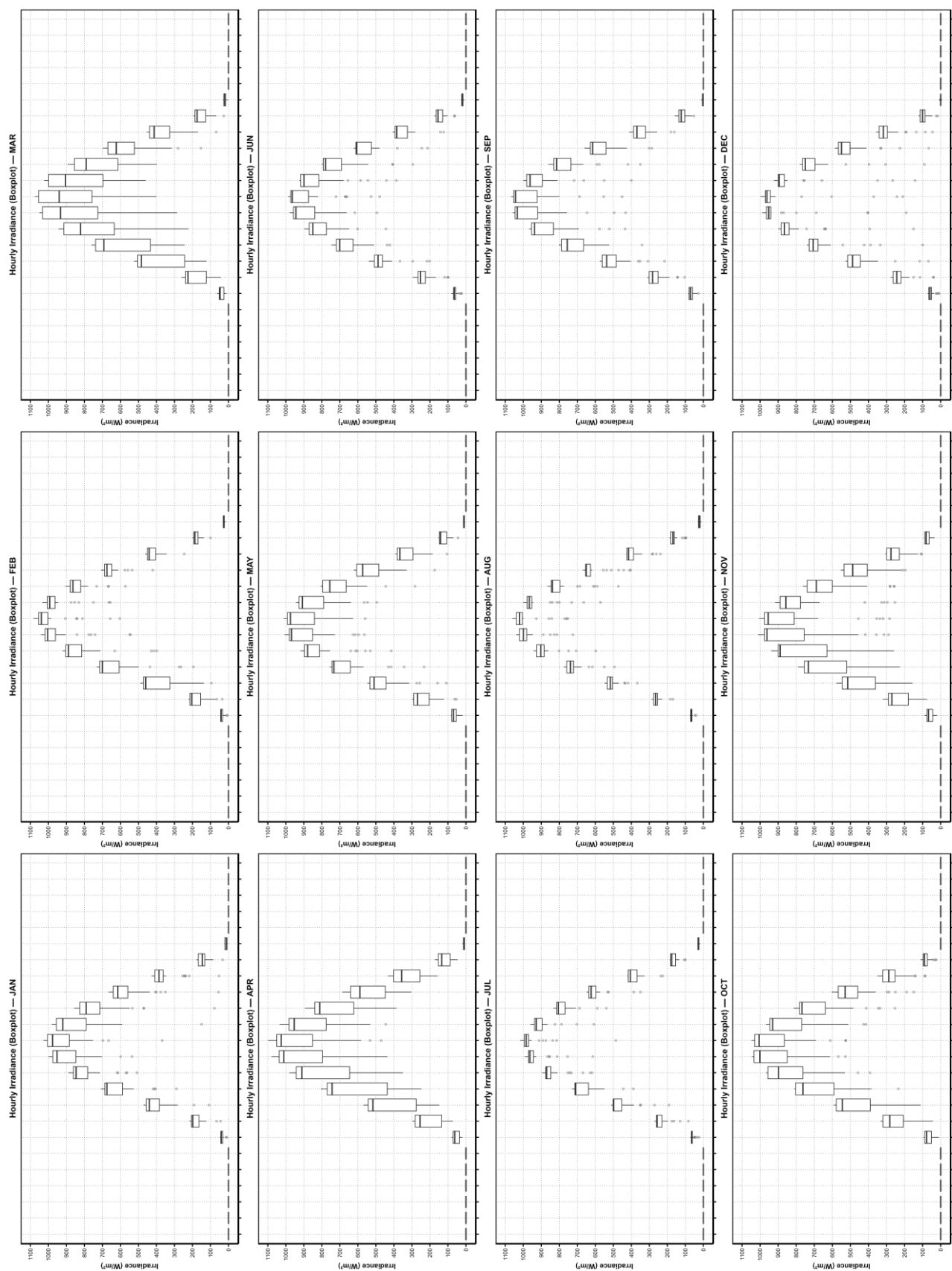


Fig.2 Box-and-whisker plot of hourly irradiation data for each month.

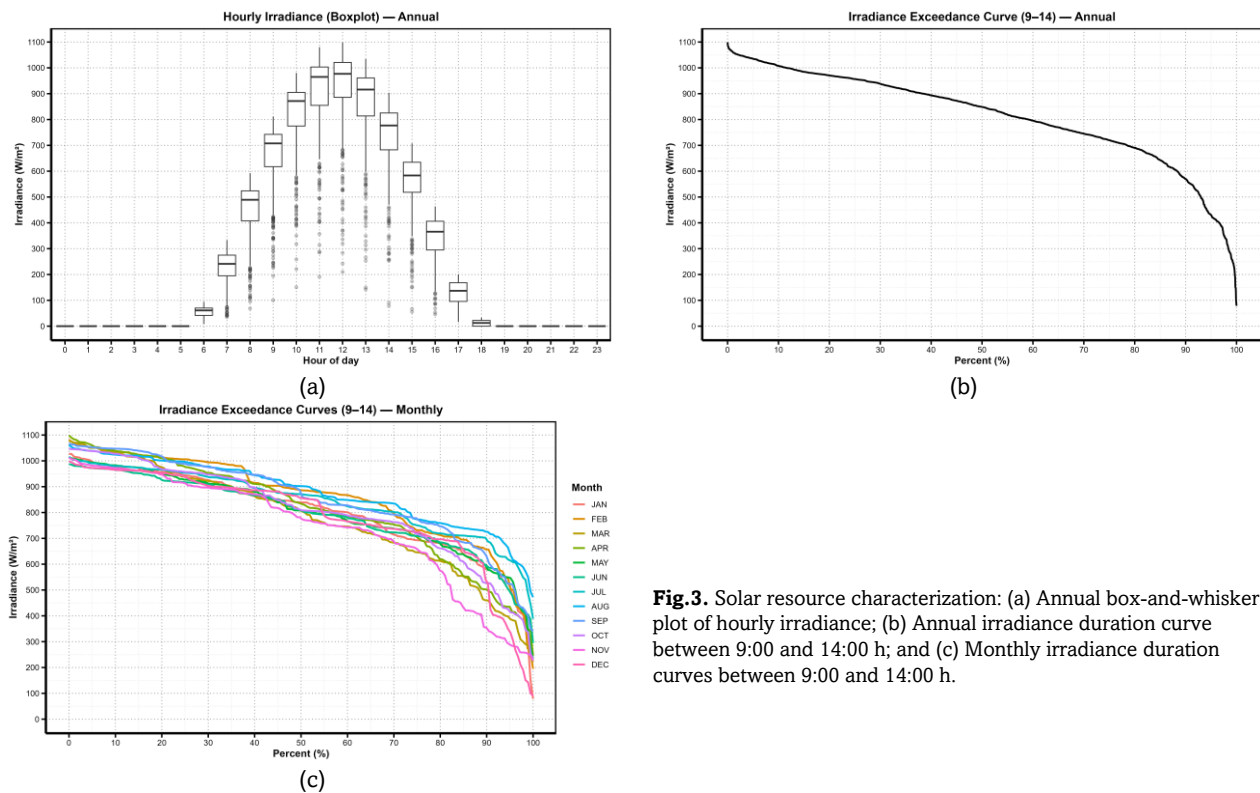


Fig.3. Solar resource characterization: (a) Annual box-and-whisker plot of hourly irradiance; (b) Annual irradiance duration curve between 9:00 and 14:00 h; and (c) Monthly irradiance duration curves between 9:00 and 14:00 h.

However, the general meteorological conditions of the area limit the accumulated impact of this thermal degradation on the annual balance, validating that these instantaneous losses are considered absorbed within the system's global loss coefficient. To characterize the available solar resource, Figure 2 presents the box-and-whisker plots of hourly solar irradiance (W/m^2) for each month of the year, structured from the five-minute resolution records.

Through the inter-monthly variability analysis of Figure 2, it is identified that the months of July, August, and December present the most compact dispersion plots, which is associated with the atmospheric stability characteristic of the dry season in the Andean region. Conversely, the lower outliers recorded in the maximum irradiance windows of these periods evidence episodes of intermittent attenuation due to the presence of local cloudiness. With the purpose of evaluating the general and consolidating behavior of the solar resource, Figure 3a exhibits the annual box-and-whisker plot of hourly solar irradiance.

The annual distribution presented in Figure 3a determines that the start of the useful daytime period occurs from 6:00 h with low, but non-zero, initial values. Between 7:00 and 10:00 h, a marked increase in irradiance is recorded, a period in which the median shifts at an accelerated pace and the interquartile dispersion widens, indicating the high variability imposed by changing atmospheric conditions during the mornings.

The maximum typical energy availability is concentrated around solar noon, specifically between 11:00 and 13:00 h, a time frame that records the highest annual medians and upper whisker values reaching or exceeding the order of $1000 \text{ W}/\text{m}^2$. In this same central interval, a high density of outliers towards the lower limit of the distribution is observed, which quantitatively confirms the intermittent reductions in solar flux caused by the influence of cloudiness and the intra-day dynamics inherent to the local climate. From 14:00 h onwards, a monotonous and gradual reduction of the medians is observed, maintaining a notable dispersion during the early afternoon, until concluding the useful solar period between 17:00 and 18:00 h with accelerated drops towards values close

to zero. To analyze the probabilistic stability of the photovoltaic resource, Figure 3b exhibits the annual irradiance duration curve, strictly restricted to the time interval of greatest operational interest (09:00 to 14:00 h).

The curve exhibits a monotonously decreasing trend that describes the cumulative frequency of the resource; the behavior indicates that very high irradiance levels, exceeding $1000 \text{ W}/\text{m}^2$, present an annual probability of 10%. In contrast, the overall shape of the curve suggests remarkable stability in the intermediate and high ranges; the lower tail reveals that only 10% of the annual records fall below the $600 \text{ W}/\text{m}^2$ threshold. This indicator delimits the probability of occurrence of variable meteorological alterations during the hours of maximum theoretical catchment. Figure 3c disaggregates the irradiance duration curves on a monthly scale for the same time interval of interest (09:00 to 14:00 h).

Figure 3c presents the monthly profiles; it is observed that they maintain the same monotonously decreasing morphology but exhibit vertical shifts and slope variations that evidence the seasonality of the resource and the monthly fluctuations in the frequency of clear skies. The months of March and April typically record the highest irradiances of the period.

When evaluating the 50th percentile (P50) as an indicator of central tendency, it is identified that, in all months of the year, with the sole exception of November, the irradiance remains steadily above $800 \text{ W}/\text{m}^2$. Likewise, setting a reference level of $600 \text{ W}/\text{m}^2$, the probability of exceedance surpasses 80% in all periods, again excepting November. These results allow us to rigorously foresee that the month of November will consolidate as the critical or lowest-yield period for the subsequent photovoltaic generation analyses.

3.2. Photovoltaic Solar Generation Potential

The energy potential was quantified through a sensitivity analysis based on irradiance thresholds, applied to a nominal 610 W module. Table 2 details the estimated monthly generation, the relative frequency of records exceeding the

Table 2
Estimation of generation and effective time according to irradiance threshold.

Units	600 W/m ²			650 W/m ²			700 W/m ²		
	kWh	%	h/day	kWh	%	h/day	kWh	%	h/day
Jan	64,84	23,81%	5,72	63,77	21,62%	5,19	61,63	19,40%	4,66
Feb	64,14	26,08%	6,26	63,70	23,91%	5,74	62,27	21,70%	5,21
Mar	60,88	22,36%	5,37	57,99	19,66%	4,72	54,87	17,27%	4,15
Apr	59,90	22,73%	5,46	59,81	20,95%	5,03	58,32	18,97%	4,55
May	65,39	24,01%	5,76	62,71	21,26%	5,10	59,99	18,88%	4,53
Jun	63,74	24,19%	5,81	62,28	21,82%	5,24	58,00	18,87%	4,53
Jul	71,55	26,28%	6,31	70,94	24,05%	5,77	69,25	21,80%	5,23
Aug	74,21	27,25%	6,54	74,28	25,18%	6,04	73,27	23,06%	5,53
Sep	66,80	25,35%	6,08	66,28	23,22%	5,57	65,26	21,23%	5,09
Oct	62,83	23,07%	5,54	62,28	21,11%	5,07	60,49	19,04%	4,57
Nov	54,20	20,57%	4,94	53,73	18,82%	4,52	51,1	16,62%	3,99
Dec	63,23	23,22%	5,57	62,65	21,24%	5,10	60,81	19,14%	4,59
Annual	771,71	24,07%	5,78	760,42	21,89%	5,25	735,26	19,66%	4,72

reference value, and the equivalent average daily hours under restrictive operating conditions.

The results presented in Table 02 consolidate the inversely proportional relationship between the stringency level of the threshold and the effective operating window. The increase in the threshold reduces the operating time from 5.78 h/day (for 600 W/m²) to 4.72 h/day (for 700 W/m²). However, the annual energy yield evidences high systemic reliability: the annual accumulations reach 771.71 kWh, 760.42 kWh, and 735.26 kWh for the 600, 650, and 700 W/m² thresholds, respectively. In all evaluated scenarios, the annual production per module exceeded the technical barrier of 700 kWh. These probabilistic indicators are determining factors from the perspective of financial viability and investment risk mitigation.

When projecting the most unfavorable scenario—corresponding to the month of November under the strict threshold of 700 W/m², with a theoretical production of 51.1 kWh per panel—the final configuration of four modules guarantees a minimum generation of 204.4 kWh/month. This volume of available energy comfortably exceeds the average electricity demand characteristic of a rural household in the study area, which ranges between 130 and 150 kWh/month. Consequently, it is quantitatively demonstrated that the proposed sizing possesses the necessary robustness to strictly cover self-consumption requirements and ensure the user's

operational cash flow, even in the face of adverse weather scenarios.

3.3. Economic evaluation of the generation system

The viability of the energy transition in rural areas depends intrinsically on the financial conditions of access to technology. This third methodological phase simulates the financial behavior of the proposed technical sizing, with an initial investment of 18,000,000 COP, using a cash flow model projected over a 10-year horizon. This analysis is based on parametric evaluation and sensitivity analysis of three determining variables: electricity price, credit interest rate, and debt amortization term.

3.3.1. Electricity price behavior in Quindío

Within the Colombian regulatory framework, the cost of electrical energy billed to residential users is conditioned by socioeconomic stratification and cross-subsidy mechanisms administered through the Solidarity Fund for Subsidies and Income Redistribution (FSSRI). In the municipality of La Tebaida, whose grid is operated by the Empresa de Energía del Quindío (EDEQ), users classified in strata 1, 2, and 3 (corresponding to vulnerable populations and peasant economies) receive tiered subsidies on the Unit Cost (UC) of

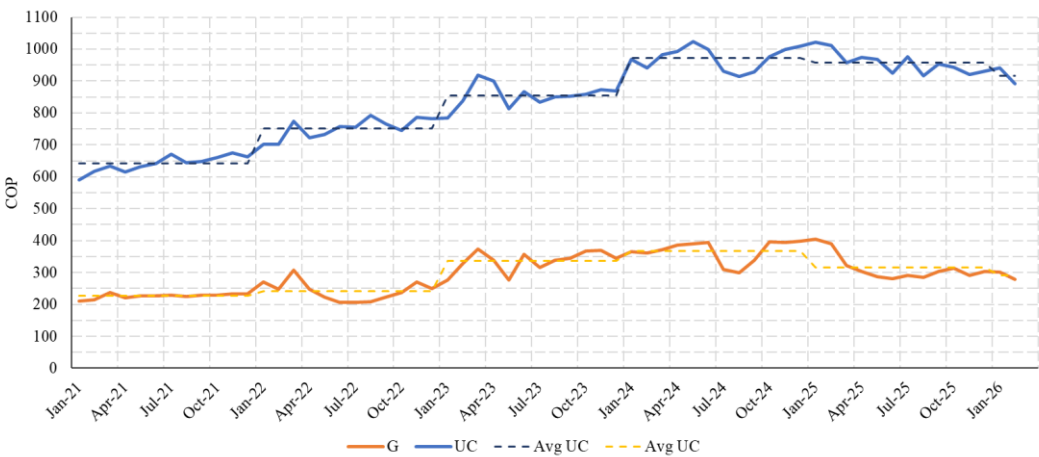


Fig.4 Evolution of the unit price of electricity in COP in Quindío from 2021 to 2026.
Source: (EDEQ, 2026)

service provision (MinEnergia, 2026). However, this state benefit is restrictive and strictly applies up to the basic or subsistence consumption level, set at 130 kWh/month for altitudes equivalent to the study area; any kilowatt-hour exceeding this threshold is billed at the full commercial rate. Added to this tariff structure is the historical instability of the UC in the region, which has exhibited a sustained upward trend in recent years.

Figure 4 evidences an increase in the electricity price, which reaches its maximum in May 2024 with a value of 1,022.80 COP/kWh. In 2021, the lowest values are recorded, with an average of 640.85 COP/kWh. The overall behavior shows a marked increase, followed by a slight decrease in 2025 and a further reduction in 2026, reaching an average value of 915.96 COP/kWh. Meanwhile, the generation cost presents high volatility, with a maximum value of 366.91 COP/kWh. On the other hand, the contribution surcharge implies a 20% increase, which means that for a value of 900 COP/kWh, 1,080 COP/kWh would be paid, increasing the pressure on the energy acquisition cost.

According to Colombian regulations, the value of kWh consumed from the grid is determined based on the unit cost, while kWh injected into the grid is remunerated based on the generation value. Considering the behavior of UC and G observed in Figure 4, it is proposed that the energy price could exceed 1,000 COP/kWh; in an optimistic scenario, this value could decrease and settle around 850 COP/kWh. Regarding the generation value, although it presents significant variations, a value of 400 COP/kWh is taken as an upper limit reference.

3.3.2. Financing in Colombia for renewable energy projects

The Colombian financial market has green credit lines aimed at small-scale self-generation projects, offering preferential rates and amortization terms of up to 10 years. Interest rates for these financial instruments are usually indexed to the Reference Bank Indicator (IBR) or the Fixed Term Rate (DTF), adding a commercial intermediation margin ranging between 2.5% and 3.5% (OPS, 2025).

Macroeconomic indicators in Colombia have shown high volatility. Following the economic reopening after the health crisis, the IBR experienced a significant increase (Banco de la República, 2026b), going from stabilization levels close to 1.7% to peaks of 11.8%, recently settling in a range between 8.8% and 10.7%. Likewise, the DTF, which reflects the weighted average of effective 90-day deposit rates, stands around 9.59% according to reports from the Bank of the Republic (Banco de la República, 2026a). Under this macroeconomic context, effective lending rates for solar technology are situated in an estimated range of 11.5% to 15% annually. To evaluate the credit viability of the investment (18 million COP), Table 3 presents a

simulation matrix of fixed amortization installments under different term and interest rate scenarios.

To validate the project's affordability in the rural context and quantify the economic burden (*energy burden*) transferred to the user, the Current Legal Minimum Monthly Wage (SMLMV) projected for 2026, estimated at 1,750,905 COP, was taken as a reference. Assuming financial indebtedness capacity indices of 20% and 30%, a user belonging to the base peasant economy could assume a credit obligation as long as the fixed monthly installment does not exceed 350,181 COP and 525,272 COP, respectively. By cross-referencing these budget restrictions with the results of Table 03, it is quantitatively demonstrated that a user with an income equivalent to one SMLMV can afford the debt of 18,000,000 COP, guarantee a minimum amortization term of 5 years and access interest rates that do not exceed 1.4% per month. Based on these affordability boundaries, the economic cash flow analysis was structured considering the sensitivity of three independent variables: (1) the cost of capital, comparing monthly interest rates of 1.0%, 1.3%, and 1.4%; (2) the amortization horizon, evaluating terms of 5, 6, and 7 years; and (3) the equivalent income scenario, varying the price of substituted electricity at 400, 850, and 1,000 COP/kWh. While the first two variables directly affect debt service, the third determines profitability and the net savings perceived by the user.

3.3.3. Influence of interest rate

Figure 5a exposes the sensitivity analysis of the cumulative net cash flow and the evolution of the debt balance throughout the 10-year planning horizon. For this simulation, the initial capital investment was fixed at 18,000,000 COP, an amortization term of 6 years (72 months), and an energy substitution rate of 850 COP/kWh, parametrically varying the monthly interest rate across three levels: 1.0%, 1.2%, and 1.4%.

Figure 5a shows that the credit interest rate acts as the main compression factor of the net cash flow during the amortization period. Under the highest evaluated rate (1.4% monthly), the cost of debt service absorbs almost all the economic savings generated by substituting the purchase of energy from the grid. Under these restrictive conditions, the cumulative cash flow and the debt balance reach the break-even point simultaneously in month 72, coinciding exactly with the extinguishment of the financial obligation. In this scenario, the project registers an NPV of 802,687 COP, an IRR of 12.90%, and an LCOE of 531 COP/kWh.

The gradual reduction of the monthly interest rate mitigates the financial burden and accelerates the recovery of the invested capital. By decreasing the rate to 1.0% monthly, the lower value of the fixed monthly installments immediately frees up liquidity in favor of the user. Consequently, the break-even point of the cumulative cash flow advances to month 64,

Table 3.
Installment value according to interest rate and term.

APR	MPR	3	4	5	6	7
12,0%	1,0%	-\$ 597.858	-\$ 474.009	-\$ 400.400	-\$ 351.903	-\$ 317.749
13,2%	1,1%	-\$ 608.227	-\$ 484.684	-\$ 411.401	-\$ 363.237	-\$ 329.416
14,4%	1,2%	-\$ 618.700	-\$ 495.496	-\$ 422.571	-\$ 374.770	-\$ 341.310
15,6%	1,3%	-\$ 629.278	-\$ 506.445	-\$ 433.909	-\$ 386.500	-\$ 353.429
16,8%	1,4%	-\$ 639.959	-\$ 517.530	-\$ 445.413	-\$ 398.424	-\$ 365.767
18,0%	1,5%	-\$ 650.743	-\$ 528.750	-\$ 457.082	-\$ 410.540	-\$ 378.321
19,2%	1,6%	-\$ 661.630	-\$ 540.104	-\$ 468.913	-\$ 422.845	-\$ 391.086
20,4%	1,7%	-\$ 672.619	-\$ 551.590	-\$ 480.905	-\$ 435.335	-\$ 404.058
21,6%	1,8%	-\$ 683.709	-\$ 563.208	-\$ 493.055	-\$ 448.006	-\$ 417.232

allowing the rural household to perceive a positive net balance prior to the total settlement of the loan. This favorable scenario optimizes the overall profitability indicators of the project, reaching an NPV of 3,279,447 COP, an IRR of 15.82%, and an LCOE of 473 COP/kWh. The intermediate scenario (1.2% monthly) consolidates stable performance with an NPV of 2,059,736 COP, an IRR of 14.36%, and an LCOE of 501 COP/kWh.

These results confirm that access to preferential financing lines in the Colombian market that do not exceed 15% E.A. (Effective Annual rate) constitutes a vital condition for the project's socioeconomic viability. Reducing the cost of capital not only lowers initial economic barriers for vulnerable rural populations but also optimizes the NPV and IRR, transforming a cost substitution scheme into a financially sustainable technological asset in the long term.

3.3.4. Influence of time

Figure 5b presents the cash flow analysis projected over 10 years to evaluate the impact of the amortization horizon on the viability of the investment (18,000,000 COP). To isolate the time effect, financing terms of 5, 6, and 7 years were evaluated, keeping the electricity tariff scenario fixed (850 COP/kWh) along with a restrictive monthly interest rate of 1.4%, which allows for observing the sensitivity of financial leverage with greater clarity.

Based on the behavior observed in Figure 5b, the 6-year term consolidates as the optimal reference scenario, given that under these conditions the total debt amortization and the net cash flow recovery reach their break-even point simultaneously in month 72. This balance ensures positive profitability with a Net Present Value (NPV) of 802,687 COP, an Internal Rate of Return (IRR) of 12.90%, and an LCOE of 531 COP/kWh. When evaluating the contraction of the credit horizon to 5 years, the value of the fixed monthly installment increases, exceeding the direct economic savings derived from energy substitution.

Consequently, the user's cash flow remains negative during the term of the loan, and the break-even point shifts to month 68, eight months after the debt has been extinguished. However, by drastically reducing exposure to compound interest, this scenario maximizes the overall financial performance of the project, obtaining the highest yield with an NPV of 2,013,186 COP, an IRR of 14.26%, and an LCOE of 497 COP/kWh.

In contrast, expanding the amortization horizon to 7 years decreases the monthly installment value, which appears to reduce short-term liquidity pressure. Nevertheless, prolonged exposure to the cost of capital severely penalizes the economic model. The accumulated weight of interest destroys the project's value, yielding a negative NPV of -359,974 COP, an IRR of 11.59%, and an LCOE of 566 COP/kWh, placing it below the reference discount rate (12%). These results show that, for the predominant interest rates in the Colombian consumer market, extending the term does not constitute a recommendable financial alternative for photovoltaic systems of this scale. To ensure an affordable and profitable integration into the peasant economy, debt sizing must be structured over horizons close to six years, ensuring that the economic value of generated electricity acts as an equitable hedge against the assumed monthly installment.

3.3.5. Influence of electricity price

Figure 5c presents the sensitivity analysis of the 10-year projected cash flow regarding variations in energy tariffs. To isolate the effect of this variable, the initial investment of 18,000,000 COP, the 6-year amortization horizon, and the 1.4% monthly interest rate (the highest financial demand scenario) were kept constant, evaluating three electricity price levels: 400, 850, and 1,000 COP/kWh.

Taking the intermediate scenario of 850 COP/kWh as a baseline, which reaches the break-even point in month 72 with a Net Present Value (NPV) of 802,687 COP and an Internal Rate of Return (IRR) of 12.90% the high sensitivity of the model to

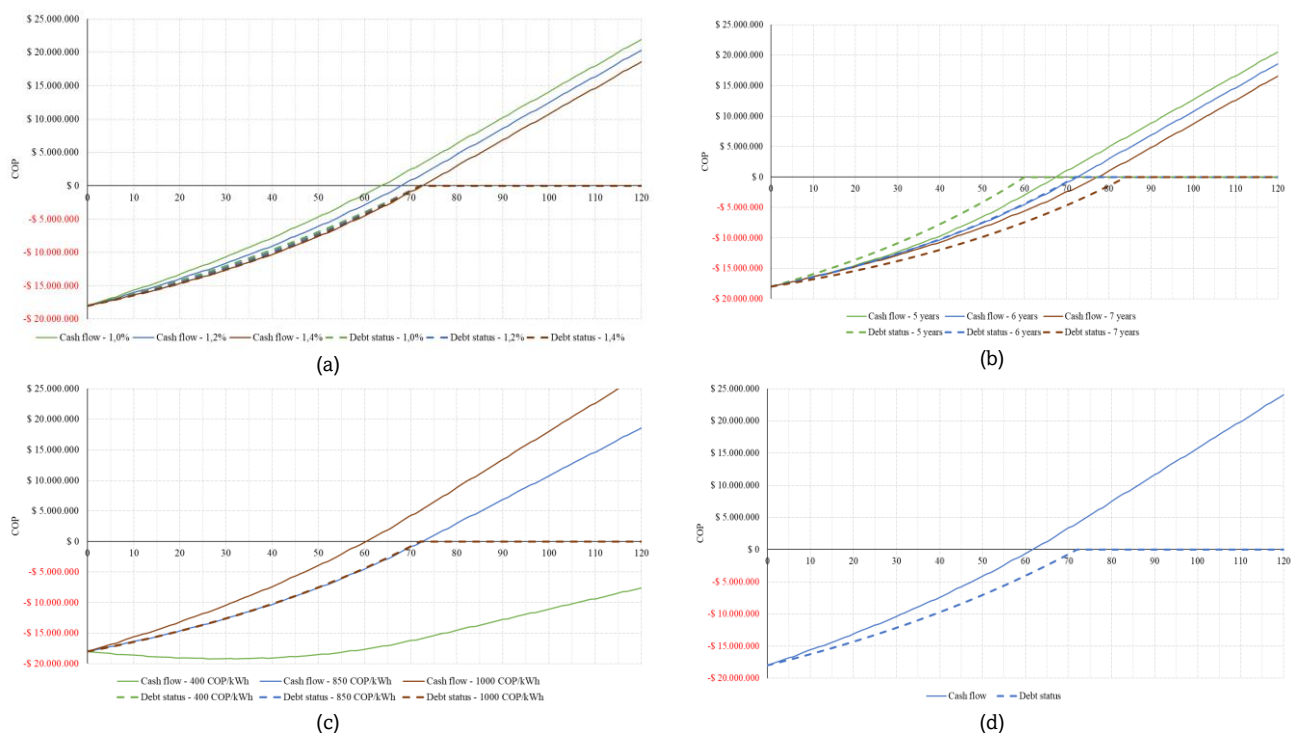


Fig. 5. Sensitivity analysis of the cumulative net cash flow and break-even point: (a) Influence of the monthly interest rate; (b) Influence of the financing amortization term; (c) Influence of the electricity tariff variations; and (d) Financial behavior under representative average market conditions.

energy devaluation is evidenced. By reducing the price to 400 COP/kWh, a scenario simulating exclusive remuneration for injecting surpluses into the grid at the generation cost, the cash flow is unable to reach the break-even point within the evaluated horizon. This drastic decapitalization yields a negative NPV of -14,000,714 COP and an IRR of -6.43%. This result quantitatively shows that, under current regulations, selling energy to the grid does not constitute a viable economic model for residential systems of this scale, justifying the technical necessity to prioritize self-consumption through battery storage.

Conversely, facing an upward tariff scenario to 1,000 COP/kWh, the system's economic performance experiences substantial improvement. The higher value of monthly energy savings accelerates capital recovery, advancing the break-even point to month 60, and generates profitability with an NPV of 5,737,153 COP and an IRR of 18.29%. Considering that in the study area the Unit Cost of electricity tends to remain above 900 COP/kWh and exhibits a historical growth trend, the economic viability of the photovoltaic system tends to strengthen over time. This profitability is maximized particularly for rural users who lose the state subsidy benefit upon exceeding the subsistence consumption limit, or who are subject to the additional 20% contribution tax burden. In all three cases, the LCOE equals 531 COP/kWh because they share the same investment, maintenance, and energy production conditions. The self-generation system solidifies not as a profit mechanism from energy sales, but as a robust instrument for financial protection against continuous tariff escalation.

3.3.6. A scenario with representative average conditions

To consolidate the project's viability under the most probable macroeconomic conditions of the current market, Figure 5d presents the cash flow analysis structured under a representative or central tendency scenario. This 10-year projected model assumes the 18,000,000 COP investment financed under the optimal 6-year term. For this case, a monthly interest rate of 1.1% was applied, equivalent to an effective annual rate of 13.2%, which aligns with the real banking average for green credit lines, and a stabilized electricity price of 900 COP/kWh.

Based on the behavior observed in Figure 5d, the cumulative net cash flow reaches its financial break-even point in month 62 (5 years and 2 months). This indicates that the economic value of energy savings fully compensates for the initial investment and cumulative operational costs ten months before the end of the debt amortization horizon. The fact that the system begins to report a positive financial balance while the user still maintains credit obligations evidences a highly favorable, low-risk economic performance condition. Under these real average conditions, the project maximizes its certainty and demonstrates its solidity as an investment asset, consolidating an NPV of 4,319,155 COP, an IRR of 16.94%, and an LCOE of 566 COP/kWh. These indicators largely exceed the required discount rate, guaranteeing long-term profitability, protection against tariff inflation, and an effective improvement in energy affordability for the evaluated rural household.

The model's results establish a configuration with battery storage, wherein the energy generated is not injected into the electrical grid to ensure self-consumption during periods without solar radiation. Previous studies (Chaurasia *et al.*, 2022; Darling, 2022; Lai & McCulloch, 2017), report low profitability for hybrid systems due to the high initial capital expenditure associated with batteries; furthermore, the work of (Guerrero *et al.*, 2021) identified the difficulty users face in assuming the investment installments. The current model achieves better

outcomes driven by technological improvements such as increased panel power, enhanced storage capacity, and reduced equipment acquisition costs. This allows the user to effectively offset the value of their generation against the energy not consumed from the grid.

Although the LCOE calculated for this model might be considered high compared to other technologies (Manzolini *et al.*, 2025; Uranbold & Lima, 2025; Yin *et al.*, 2025); its economic viability, specifically for residential users in Colombia, must be primarily evaluated against the billing value due to their inability to negotiate favorable supply conditions. Under Colombian regulations, users with energy consumption equal to or greater than 55 MWh are classified as non-regulated users (CREG, 2025); since residential households do not fall into this category, their tariff is calculated using a strictly established formula, whereas non-regulated users have the option to negotiate their energy supply conditions directly (CREG, 2013).

According to the results obtained, this calculated cost is substantially below the local commercial grid tariff; 37% lower compared to the current price of 900 COP/kWh, and 19% lower for a price of 700 COP/kWh. Both scenarios present clear savings and considering the upward trend in electricity prices (Shah *et al.*, 2022), long-term savings can be estimated at over 30%. This decentralized generation model with storage proves to be not only a technical alternative but also a highly profitable financial shield against sustained tariff escalations, actively strengthening energy equity for vulnerable rural populations (Guerrero *et al.*, 2021; Vanegas Cantarero, 2020).

4. Conclusions

This study demonstrated the technical and economic feasibility of integrating residential photovoltaic systems in the Colombian Andean region, using a high-resolution meteorological database. The methodology presented an analysis using a probabilistic reliability model to evaluate risk against climate variability and a continuous generation model to structure a ten-year projected cash flow. This integration allowed evaluating the technology not only as a distributed generation solution but as a financial equity instrument for rural households.

The solar resource analysis evidenced that, although the Andean topography introduces high thermal dispersion and intermittent irradiance during central hours of the day, the predominant microclimate works in favor of the system. Probabilistic characterization showed notable resource robustness in all months of the year; at least 80% of records corresponding to the productive time frame (09:00 - 14:00 h) meet or exceed the conservative threshold of 600 W/m². Under the most restrictive sensitivity scenarios (600, 650, and 700 W/m²), the theoretical annual generation per module comfortably surpassed the 700 kWh barrier. This certainty guarantees that the four-panel array (2.44 kWp) possesses the necessary energy robustness to fully cover a rural household's demand, ensuring the baseline savings required to protect its cash flow against adverse climate scenarios.

The economic evaluation indicates that the hybrid design oriented towards self-consumption with battery storage constitutes the dominant strategy over injecting energy into the grid. Colombian regulations remunerate surpluses at a generation cost far below the commercial Unit Cost; thus, selling energy proves unviable for residential systems. Additionally, the sensitivity analysis showed that, to ensure affordability of the initial investment, access to green financing lines with preferential rates below 15% Effective Annual (E.A.) is necessary. Under these conditions, a six-year amortization

horizon achieves the optimal balance between energy savings and monthly debt service, without overloading the user's payment capacity.

The simulation under average conditions showed successful results. The structured model generated a positive Net Present Value (NPV) of 4,319,155 COP, an Internal Rate of Return (IRR) of 16.94%, and a Levelized Cost of Energy (LCOE) of 487 COP/kWh. Contrasting this self-generation cost with the commercial grid tariff (900 COP/kWh) shows a structural reduction in expenses. The system achieves its financial break-even point in 62 months, fully compensating for the initial investment and injecting direct liquidity to the user even ten months prior to the total extinguishment of the loan.

It is concluded that adopting photovoltaic technology does not impose a regressive economic burden; rather, it financially shields vulnerable strata against the market's escalating tariffs. This economic benefit naturally intensifies for high-stratum and industrial users due to the evasion of surcharges from tax contributions. The study ratifies that self-generation with storage is a feasible, affordable, and indispensable tool to consolidate a just and equitable energy transition in the Colombian rural sector.

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References

- Amoah, A., Kwablah, E., Korle, K., & Offei, D. (2020). Renewable energy consumption in Africa: the role of economic well-being and economic freedom. *Energy, Sustainability and Society* 2020 10:1, 10(1), 32. <https://doi.org/10.1186/S13705-020-00264-3>
- Ansarin, M., Ghiassi-Farrokhfal, Y., Ketter, W., & Collins, J. (2022). A review of equity in electricity tariffs in the renewable energy era. *Renewable and Sustainable Energy Reviews*, 161, 112333. <https://doi.org/10.1016/J.RSER.2022.112333>
- Arefeen, S., & Dallas, T. (2021). Low-cost racking for solar photovoltaic systems with renewable tensegrity structures. *Solar Energy*, 224, 798–807. <https://doi.org/10.1016/j.solener.2021.06.020>
- Bamisle, O., Olubiyo, F., Dagbasi, M., Adun, H., & Wole-Osho, I. (2019). Economic Analysis and Performance of PV Plants: An Application in Kurdistan Region of Iraq. *International Journal of Renewable Energy Development*, 8(3), 293–301. <https://doi.org/10.14710/ijred.8.3.293-301>
- Banco de la República. (2026a, April). *DTF_Indicador Bancario de Referencia*. https://suameca.banrep.gov.co/estadisticas-economicas/informacionSerie/220003/tasas_interes_cdt_dtf
- Banco de la República. (2026b, April). *IBR_Indicador Bancario de Referencia*. https://suameca.banrep.gov.co/estadisticas-economicas/informacionSerie/241/tasas_interes_indicador_bancario_referencia_ibr
- Bayona-Velásquez, E., Nuñez-Alvarez, J. R., Pirela-Ríos, A., & Marín-Giraldo, E. (2023). Measurement of energy poverty in the Colombian Caribbean region: a comparative analysis. *International Journal of Electrical and Computer Engineering (IJECE)*, 13(6), 6016–6024. <https://doi.org/10.11591/ijece.v13i6.pp6016-6024>
- Behar, O. (2026). Financial and economic metrics for assessing renewable energy systems using discounted cash flow analysis. *Reference Module in Materials Science and Materials Engineering*. <https://doi.org/10.1016/B978-0-443-29210-1.00105-9>
- Bragolusi, P., & Righettini, M. S. (2022). Dimensions of Social Acceptance in Energy Transition. *Lecture Notes in Networks and Systems*, 482 LNNS, 1780–1789. https://doi.org/10.1007/978-3-031-06825-6_172
- Brito Cedeno, R. C., & Wei, J. (2024). Investigating factors to promote energy: Socio-political barriers to renewable energy sector in India. *The Electricity Journal*, 37(2), 107366. <https://doi.org/10.1016/j.tej.2024.107366>
- Chan, C., & Delina, L. L. (2023). Energy poverty and beyond: The state, contexts, and trajectories of energy poverty studies in Asia. *Energy Research & Social Science*, 102(3), 103168. <https://doi.org/10.1016/j.erss.2023.103168>
- Chaurasia, R., Gairola, S., & Pal, Y. (2022). Technical, economic feasibility and sensitivity analysis of solar photovoltaic/battery energy storage off-grid integrated renewable energy system. *Energy Storage*, 4(1), e283. <https://doi.org/10.1002/EST2.283;PAGEGROUP:STRING:PUBLICATON>
- Cong, S., Nock, D., Qiu, Y. L., & Xing, B. (2022). Unveiling hidden energy poverty using the energy equity gap. *Nature Communications* 2022 13:1, 13(1), 2456-. <https://doi.org/10.1038/s41467-022-30146-5>
- CREG. (2013). *Concepto 12018 de 2013*. https://gestornormativo.creg.gov.co/gestor/entorno/docs/concepto_creg_0012018_2013.htm
- CREG. (2025). *Concepto 14534 de 2025*. https://gestornormativo.creg.gov.co/gestor/entorno/docs/concepto_creg_0014534_2025.htm
- Darling, R. M. (2022). Techno-economic analyses of several redox flow batteries using levelized cost of energy storage. *Current Opinion in Chemical Engineering*, 37, 100855. <https://doi.org/10.1016/J.COCHE.2022.100855>
- Diaz Motta, A. (2020). *Estudio de factibilidad técnico-económica de un sistema de generación híbrido para zonas no interconectadas de Colombia*. <https://hdl.handle.net/2445/169560>
- EDEQ. (2026, April). *Tarifas de energía*. <https://www.edeq.com.co/clientes-y-usuarios/tarifas/tarifas-de-energia>
- Esquivel García, C. L., & Toro-García, G. L. (2024). Multidimensional energy poverty in Colombia: A department-level review from 2018 to 2022. *Heliyon*, 10(14), e34395. <https://doi.org/10.1016/j.heliyon.2024.e34395>
- Fu, F. Y., Alharthi, M., Bhatti, Z., Sun, L., Rasul, F., Hanif, I., & Iqbal, W. (2021). The dynamic role of energy security, energy equity and environmental sustainability in the dilemma of emission reduction and economic growth. *Journal of Environmental Management*, 280, 111828. <https://doi.org/10.1016/J.JENVMAN.2020.111828>
- Galindo, A. (2017). Otimização do projeto de um sistema híbrido Diesel-Ciclo Orgânico Rankine (ORC) / fotovoltaico. Universidade Federal de Itajubá.
- Garnica, J. E. G., Mora, S. B. S., & Jaimes, J. F. (2018). Viabilidad técnico-económica de un sistema fotovoltaico en una planta de tratamiento de agua. *Inge CuC*, 14(1), 41–51. <https://doi.org/10.17981/INGECUC.14.1.2018.04>
- Guerrero, J. W. G., Rios, C. J., Villar, L. M. del, Carreño, E. G., & Turyol, J. B. (2021). Equity and renewable energy: An analysis in residential users in the department of Atlántico-Colombia. *International Journal of Energy Economics and Policy*, 11(4), 107–112. <https://doi.org/10.32479/ijeeep.11092>
- Gürtler, K. (2023). Justice in energy transformations as a spatial phenomenon: A framework for analyzing multi-dimensional justice claims. *Energy Research & Social Science*, 105, 103277. <https://doi.org/10.1016/J.ERSS.2023.103277>
- Hancevic, P. I., Nuñez, H. M., & Rosellón, J. (2022). Electricity Tariff Rebalancing in Emerging Countries: The Efficiency-equity Tradeoff and Its Impact on Photovoltaic Distributed Generation. *Energy Journal*, 43(4), 69–93. <https://doi.org/10.5547/01956574.43.4.PHAN;WEBSITE:WEBSITE:SAGE;WGROU:STRING:PUBLICATON>
- Heffron, R. J. (2022). Applying energy justice into the energy transition. *Renewable and Sustainable Energy Reviews*, 156, 111936. <https://doi.org/10.1016/J.RSER.2021.111936>
- Huang, L., Nock, D., Cong, S., & Qiu, Y. (Lucy). (2023). Inequalities across cooling and heating in households: Energy equity gaps. *Energy Policy*, 182(6), 113748. <https://doi.org/10.1016/j.enpol.2023.113748>
- Islam, M. T., & Hossain, M. E. (2022). Economic Feasibility of Solar Irrigation Pumps: A Study of Northern Bangladesh. *International Journal of Renewable Energy Development*, 11(1), 1–13. <https://doi.org/10.14710/IJRED.2022.38469>
- Jiao, L., & Tan, Y. (2024). Social Equity and Renewable Energy Access in Developing Countries. *MEDAAD*, 2024, 27–33. <https://doi.org/10.70470/medaad/2024/005>
- King, M., Popp, M., Anderson, J., Connor, L., & Kee, J. (2025). Solar investment analysis: effects of electricity rate structure and financing terms on financial leverage, after-tax cash flow and

- profitability. *Agricultural Finance Review*, 85(3), 397–415. <https://doi.org/10.1108/AFR-01-2024-0003>
- Lai, C. S., & McCulloch, M. D. (2017). Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Applied Energy*, 190, 191–203. <https://doi.org/10.1016/J.APENERGY.2016.12.153>
- Liao, C., Erbaugh, J. T., Kelly, A. C., & Agrawal, A. (2021). Clean energy transitions and human well-being outcomes in Lower- and Middle-Income Countries: A systematic review. *Renewable and Sustainable Energy Reviews*, 145, 111063. <https://doi.org/10.1016/J.RSER.2021.111063>
- Lin, C. H., Hsieh, W. L., Chen, C. S., Hsu, C. T., & Ku, T. T. (2012). Optimization of photovoltaic penetration in distribution systems considering annual duration curve of solar irradiation. *IEEE Transactions on Power Systems*, 27(2), 1090–1097. <https://doi.org/10.1109/TPWRS.2011.2178619>
- Manzolini, G., Gentile, G., Pilotti, L., Martelli, E., Picotti, G., Binotti, M., & Cholette, M. E. (2025). Limitations of using LCOE as economic indicator for solar power plants. *Renewable and Sustainable Energy Reviews*, 209, 115087. <https://doi.org/10.1016/J.RSER.2024.115087>
- MinEnergia. (2026). Fondo De Solidaridad Para Subsidios y Redistribución de Ingresos - FSSRI. <https://www.minenergia.gov.co/es/misional/energia-electrica-2/subsidios/fondo-de-solidaridad-para-subsidios-y-redistribucion%C3%B3n-de-ingresos-fssri/>
- Mungai, E. M., Ndiritu, S. W., & Da Silva, I. (2022). Unlocking climate finance potential and policy barriers—A case of renewable energy and energy efficiency in Sub-Saharan Africa. *Resources, Environment and Sustainability*, 7, 100043. <https://doi.org/10.1016/j.resenv.2021.100043>
- Nasir, B. A. (2024). Efficiency Assessment of an Inverter based on Solar PV Energy in Baghdad. *Engineering, Technology & Applied Science Research*, 14(2), 13425–13429. <https://doi.org/10.48084/ETASR.6948>
- Nijse, F. J. M. M., Mercure, J. F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P., & Pollitt, H. (2023). The momentum of the solar energy transition. *Nature Communications* 2023 14:1, 14(1), 6542. <https://doi.org/10.1038/s41467-023-41971-7>
- OPS. (2025, November). Financiación de Paneles Solares en Colombia 2026: Créditos, Incentivos y Estrategias de Pago | Blog OPS Colombia. <https://www.opscolombia.com/blog/financiacion-de-paneles-solares-en-colombia-pagos>
- Perez, R., Lauret, P., Perez, M., David, M., Hoff, T. E., & Kivalov, S. (2018). Solar Resource Variability. *Green Energy and Technology*, 0(9783319768755), 149–170. https://doi.org/10.1007/978-3-319-76876-2_7
- Raman, R., Ustenko, V., Filho, W. L., & Nedungadi, P. (2025). Energy justice and gender: bridging equity, access, and policy for sustainable development. *Discover Sustainability* 2025 6:1, 6(1), 558-. <https://doi.org/10.1007/s43621-025-01375-7>
- Ramasamy, V., Zuboy, J., Woodhouse, M., O'shaughnessy, E., Feldman, D., Desai, J., Walker, A., Margolis, R., & Basore, P. (2023). U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2023. *National Renewable Energy Laboratory (NREL)*. <https://www.nrel.gov/publications>
- ScienceDirect. (n.d.). Curva de duración de carga: una descripción general. Retrieved March 12, 2026, from <https://www.sciencedirect.com/topics/engineering/load-duration-curve>
- Shah, I., Iftikhar, H., & Ali, S. (2022). Modeling and Forecasting Electricity Demand and Prices: A Comparison of Alternative Approaches. *Journal of Mathematics*, 2022(1), 3581037. <https://doi.org/10.1155/2022/3581037>
- Uranbold, T., & Lima, L. M. (2025). Energy solutions for data center: Comparative analysis of levelized cost of electricity (LCOE) and recent developments. *Energy Reports*, 14, 3529–3535. <https://doi.org/10.1016/J.EGYR.2025.10.012>
- Vanegas Cantarero, M. M. (2020). Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. *Energy Research & Social Science*, 70, 101716. <https://doi.org/10.1016/j.erss.2020.101716>
- Wahlund, M., & Palm, J. (2022). The role of energy democracy and energy citizenship for participatory energy transitions: A comprehensive review. *Energy Research & Social Science*, 87(3), 102482. <https://doi.org/10.1016/j.erss.2021.102482>
- Wang, H. (2023). Does the financial investment preference of renewable energy firms promote their advance towards sustainable development goals? *Renewable Energy*, 218(2), 119326. <https://doi.org/10.1016/j.renene.2023.119326>
- Wang, Q., & Zhan, L. (2022). How renewable energy alleviate energy poverty? A global analysis. *Renewable Energy*, 186, 299–311. <https://doi.org/10.1016/j.scitotenv.2019.07.170>
- Wu, X. (2023). Achieving renewable energy transition through financial stability of renewable energy companies and banking facility. *Environmental Science and Pollution Research* 2023 30:57, 30(57), 120174–120187. <https://doi.org/10.1007/s11356-023-30134-2>
- Yin, H., Zhang, H., Fan, E., Zhai, C., & Qi, J. (2025). Optimized cost-effective and reliable electricity solutions for remote communities by presenting renewable hybrid microgrid systems. *Applied Thermal Engineering*, 274, 126659. <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126659>

