

Energy, economic, and environmental analysis of a hybrid photovoltaic system for local development

Análisis energético, económico y ambiental de un sistema fotovoltaico híbrido para el desarrollo local

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ABSTRACT: Local development projects in Cuba are strategic for food sovereignty and territorial socioeconomic growth. Their viability is threatened by dependence on an unstable and costly national electrical grid, based on fossil fuels. The photovoltaic system emerges as a technical solution; however, a comprehensive evaluation of its impact is required. The objective of this work is to analyze the energy, economic and environmental impact of a hybrid photovoltaic system designed for La Finca La Suiza in Ciego de Ávila, Cuba, as a model catalyst for local development. A case study with a mixed methodology was employed. A hybrid photovoltaic system was technically sized for the small-scale industry. The annual energy generated, the savings in fossil fuel, and the reduction in CO₂ emissions were quantified. An economic approximation of the monetary savings from displaced diesel generation and the purchase of electricity was made, contrasting it with the investment. The system eliminates daytime energy dependence on the unstable grid, guaranteeing operational continuity. An estimated annual savings from displaced fuel and unpurchased energy amounts to 2500,00 USD. The environmental mitigation avoids the emission of 16 tons of CO₂ annually. Socially, the project gains greater robustness in the face of contingencies, avoids losses from stoppages, fosters local technical training, and contributes to meeting national renewable energy targets (24% by 2030). The system is a catalyst for local development. Its implementation provides energy security, generates direct and indirect economic savings, reduces the environmental footprint, and strengthens territorial autonomy.

Keywords: photovoltaic solar energy, local development, hybrid system, rural sustainability.

RESUMEN: Los proyectos de desarrollo local en Cuba son estratégicos para la soberanía alimentaria y el crecimiento socioeconómico territorial. Su viabilidad se ve amenazada por la dependencia de una red eléctrica nacional inestable y costosa, basada en combustibles fósiles. El sistema fotovoltaico emerge como una solución técnica; sin embargo, se requiere evaluar su impacto integral. El objetivo del trabajo es analizar el impacto energético, económico y ambiental de un sistema fotovoltaico híbrido diseñado para La Finca La Suiza en Ciego de Ávila, Cuba, como modelo catalizador de desarrollo local. Se empleó un estudio de caso con metodología mixta. Se dimensionó técnicamente un sistema fotovoltaico híbrido para la minindustria. Se cuantificó la energía generada anual, el ahorro de combustible fósil y la reducción de emisiones de CO₂. Se realizó una aproximación económica al ahorro monetario por desplazamiento de generación diésel y compra de electricidad, contrastando con la inversión. El sistema elimina la dependencia energética diaria de la red inestable, garantizando la continuidad operativa. Se estima un ahorro anual por concepto de combustible desplazado y energía no comprada de 2500,00 USD. La mitigación ambiental evita la emisión de 16 toneladas de CO₂ anuales. Socialmente el proyecto adquiere mayor solidez frente a contingencias, se evita pérdidas por paradas, se fomenta la capacitación técnica local y se contribuye al cumplimiento de las metas nacionales de energía renovable (24% para 2030). El sistema es un catalizador del desarrollo local. Su implementación provee seguridad energética, genera ahorros económicos directos e indirectos, reduce la huella ambiental y fortalece la autonomía del territorio.

Palabras clave: desarrollo local, energía solar fotovoltaica, sistema híbrido, sostenibilidad rural.

INTRODUCTION

The economic and social development of Cuba in the current context requires promoting endogenous and sustainable initiatives. Local development projects

have become key instruments in this strategy, as they mobilize territorial resources and capacities to generate goods and services, diversify the economy, and improve quality of life [Correa Soto et al., \(2017\)](#); [Zirufu-Briones y Pelegrín-Entenza \(2023\)](#).

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However, the viability of many of these projects, especially those in the agro-industrial sector such as small-scale food processing industries, is severely compromised by a critical external factor: the instability and high costs associated with the electricity supply (Morcillo-Valencia et al., 2024).

Cuba depends heavily on imported fossil fuels for electricity generation, a situation affecting national energy security and the balance of payments (Rodríguez-Ponce et al., 2020; Gómez-Rodríguez et al., 2021)). Furthermore, the electrical grid suffers from vulnerabilities that translate into frequent service interruptions, particularly acute in rural areas (Cardona et al., 2024). For a local development project, a power outage means production stoppage, loss of perishable raw materials (refrigeration), breach of contracts, and damage to electromechanical equipment, eroding its profitability and sustainability. Consequently, Cuba's policy for the future development of Renewable Energy Sources (RES) and energy efficiency, supported by Decree-Law 345/2019 Escobar-Mendoza et al. (2022), sets the goal of generating 24% of electricity from RES by 2030.

This has driven research and deployment of large-scale solar parks (Álvarez Peña and Sarduy González, 2024). However, there is a growing academic consensus on the need to complement this centralized strategy with a distributed generation model, where energy is produced close to the point of consumption (Presicce, 2019).

In this realm, hybrid photovoltaic systems (grid-connected with backup capability) present unique advantages for the productive sector: they reduce the electricity bill, inject surplus, and, most crucially, provide supply continuity during grid failures (Ureña-Erazo and Martínez-Peralta, 2024). International studies have extensively quantified the economic and environmental benefits of photovoltaics in industry (Vargas Sierra, 2024). However, a significant gap persists in the Cuban scientific literature due to the lack of comprehensive studies that, based on a specific case, jointly evaluate the role of hybrid photovoltaic systems as catalytic infrastructure for local development.

Research is needed that not only presents power and savings calculations, but also analyzes how this technology affects the economic and environmental sustainability of the local development project in fulfilling national development and energy policies. In this sense, this work provides the scientific community with a comprehensive case study that links energy engineering with local development economics.

The arguments presented justify the undertaking of this study, which is necessary to generate solid evidence and an analytical framework to demonstrate the multidimensionality of the impact associated with decentralized solar energy. The objective of this research is to analyze the multidimensional impact (energy, economic, environmental, and on local development) of a hybrid

photovoltaic system designed for the local development project Finca La Suiza in Ciego de Ávila, Cuba.

MATERIALS AND METHODS

The research was approached as an instrumental case study Merlinsky, (2018), using the local development project Finca La Suiza to analyze the role of energy as a catalyst for development. A mixed methodology was employed, combining a technical-quantitative analysis based on the online tool Photovoltaic Geographical Information System (PVGIS) to estimate the photovoltaic system's energy production, and a qualitative impact assessment using a Standard Emission Factor of 0.75 tCO₂/MWh, corresponding to the conditions of the Cuban electricity grid (González-Díaz et al., 2024).

The subject of the case study and initial diagnosis is the local development project "Finca La Suiza," located in the province of Ciego de Ávila and dedicated to food processing (dairy, grains, root vegetables). The central problem identified is high production vulnerability due to frequent interruptions in the national electricity service, with episodes lasting several hours that paralyze the entire operation.

The load analysis conducted over a typical month of operation, based on a detailed record of power and operating schedules of 20 main equipment units (motors, refrigeration, pasteurizer, etc.), indicates a daily electrical consumption of 528.43 kWh, applying a simultaneity factor of 0.70. The project requires a total of 40 panels of 380 Wp (15.20 kWp), coupled to a hybrid SMA inverter of 15 kVA based on local solar irradiation (5.28 kWh/m²/day). The annual energy generated is 21,280.00 kWh/year.

The economic analysis was based on an estimative quantitative method. The financial savings from displaced diesel generation were estimated as the fuel avoided by replacing the operation of a backup generator with photovoltaic energy. The savings from reduced electricity purchase were calculated based on the avoided cost of energy not consumed from the grid. It was assumed that the price of diesel fuel is 1.0 USD/L, 70% of photovoltaic generation is instantly self-consumed, and the average industrial electricity tariff is 0.10 USD/kWh. The equations used were:

$$A_{(Econom_Comb)} = E_{annual} \cdot C_{comb} \cdot P_{comb} \quad (1)$$

$$A_{(Econom_Red)} = E_{auto_consum} \cdot T_{elect} \quad (2)$$

Where $A_{(Econom_Comb)}$ is the economic savings from displaced diesel fuel (USD/year), E_{annual} is the annual energy generated (kWh), C_{comb} is the fuel consumption for electricity generation (0.30 L/kWh), P_{comb} is the price of diesel fuel (USD/L), $A_{(Econom_Red)}$ is the economic savings from reduced electricity purchase (USD/year), E_{auto_consum} is the self-consumed energy by the mini-industry (kWh), T_{elect} is the industrial electricity tariff (USD/kWh).

The investment was estimated from a reference quotation based on international market prices for equipment with similar characteristics (panels, inverter, mounting structure, Balance of System - BOS). The environmental analysis was performed using a quantitative method to determine fossil fuel savings (avoided fossil fuel) and CO₂ emission reduction (avoided CO₂ emissions). The equations used were:

$$A_{comb} = E_{annual} \cdot F_{acf} \quad (3)$$

$$R_{CO2} = E_{annual} \cdot F_{rem} \quad (4)$$

Where A_{comb} is the fossil fuel savings or avoided fossil fuel (t fuel/year), R_{CO2} is the CO₂ emission reduction or avoided CO₂ emissions (t CO₂/year), F_{acf} is the fossil fuel savings factor (0.000086 t/kWh), F_{rem} is the CO₂ emission reduction factor (0.00075 t CO₂/kWh).

For the analysis of impact on local development, an analytical framework based on sustainability dimensions and the guidelines of Cuban local development policy (Sosa-González et al., 2020) was used. The impact of the hybrid photovoltaic system was evaluated in terms of:

- Productive resilience (operational continuity, reduction of losses from stoppages).
- Local energy autonomy and sovereignty (reduced dependence on the national grid).
- Capacity building (need for operation and maintenance training).

- Alignment with national policies for its contribution to the objectives of Decree-Law 345/2019 (Escobar-Mendoza et al. 2022).

RESULTS AND DISCUSSION

The designed system generates 21,280.00 kWh annually, equivalent to covering 100% of the mini-industry's daytime electrical demand on full sun days. This is the most transformative result. As seen in figure 1, the hybrid system acts as a buffer against grid intermittency.

The hybrid capability of the inverter solves the central problem identified related to high productive vulnerability due to frequent national electricity service interruptions. While the grid is functional, the system operates in self-consumption mode with surplus injection. During an outage, its ability to form an "electrical island" (with battery support) prevents total paralysis. This transforms energy from a variable cost into a resilience asset, ensuring food production and the economic viability of the local development project (Ise, 2021).

Table 1 shows the main results of the economic analysis, which, although estimative and subject to price variations, reveal a substantial positive economic impact. It is important to clarify in this analysis that the diesel savings materialize completely only if the photovoltaic system effectively avoids the operation of a generator. The real savings on the electricity bill will depend on the specific tariff and the self-consumption profile.

Although the initial investment for a system of these characteristics could be around 15,000-20,000 USD (depending on import and installation costs),

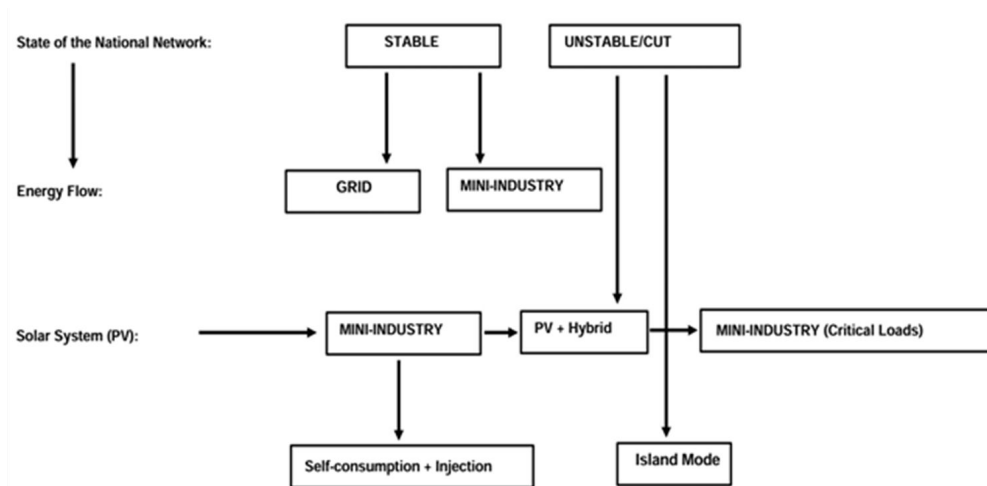


Figure 1. Schematic of the impact of the hybrid photovoltaic system on productive continuity

Table 1. Estimation of annual economic savings and environmental benefits

Concept	Estimated value
Savings from displaced diesel (USD/year).	6,384.00
Savings from reduced electricity purchase from the grid (USD/year).	1,490.00
Total annual economic savings (USD/year).	7,874.00
Avoided fossil fuel (t/year).	1,83
Avoided CO ₂ emissions (t CO ₂ /year).	15,96

the estimated savings suggest an investment payback period between 2 and 3 years, considered very favorable for energy projects. This economic analysis, although preliminary, provides a strong argument for decision-making. The investment should not be seen as an expense, but as the acquisition of a productive asset that reduces operational costs and mitigates risks (Abad-Cevallos and Zapata-Sánchez, 2024).

The environmental results are direct and quantifiable, demonstrating that the system avoids the burning of 1.83 tons of fossil fuel and the emission of 16 tons of CO₂ annually. On a macro scale, replicating this model across all existing local development projects in Cuba would represent a non-marginal contribution to national climate change mitigation commitments and the fulfillment of the 24% RES generation target by 2030 (Lino y Saez, 2022).

This case exemplifies distributed generation as a necessary complement to large solar parks. While parks contribute to the national system, systems in local development projects solve local problems of supply quality and reliability, a critical aspect for territorial development that sometimes falls outside the focus of centralized energy planning (Di Pietro, 2022).

Qualitative analysis reveals impacts that go beyond the quantitative results achieved and are demonstrated in the following aspects:

- Strengthening local autonomy: due to reduced dependence on volatile external inputs (fuel, electricity), gaining autonomy in their production process.
- Capacity building, which is of great importance for the installation and maintenance of the system, thus fostering the development of technical human capital in the territory.
- Integrated sustainability: through the alignment of the economic (savings, productivity), social (employment, training), and environmental (decarbonization) dimensions, operationalizing the concept of sustainable development in practice.
- Attractiveness for investments: a local development project with reliable energy and controlled costs is more attractive for potential economic alliances or financing.

This catalytic role is the main contribution of the present study; access to modern and reliable energy is a key enabler for rural economic development (Billi et al., 2018). In Cuba, this case demonstrates that hybrid photovoltaic systems can serve as infrastructure to consolidate more robust, productive, and sustainable local development projects.

CONCLUSIONS

The implementation of a hybrid photovoltaic system in the local development project Finca La Suiza resolves the central problem of electrical intermittency, ensuring productive continuity and transforming energy instability from a risk factor into an asset of operational resilience.

Tangible economic benefits are generated through savings from displaced diesel generation and reduced electricity purchase, with a favorable estimated investment payback period (2-3 years), addressing the objective of evaluating economic impact.

The environmental contribution is significant by avoiding 1.83 t of fuel and 16 t of CO₂ annually, aligning the project with national renewable energy and climate mitigation goals.

The photovoltaic system catalyzes local development through its comprehensive impact by strengthening autonomy, fostering technical capabilities, and enhancing the overall sustainability of the project.

The relevance of the study lies in providing an analytical model and concrete evidence that links decentralized energy transition with Cuba's territorial development agenda. The results can be used as a basis to justify prioritizing investments in solar energy as critical infrastructure for development. They can also serve as a guide for energy policy planners and for designing specific support programs for distributed generation in the rural productive sector.

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