Techno-economic assessment of a 100 kWp self-consumption photovoltaic system for underground coal mining in Colombia

Luis Alejandro Fonseca Páez1, Héctor Hugo Mora Franco2, Onier Alexander Pinto Torres 3

[1]Universidad Pedagógica y Tecnológica de Colombia. Email: Alejandro.fonseca@uptc.edu.co ORCID: https://orcid.org/0009-0001-4983-1521
[2]Universidad Pedagógica y Tecnológica de Colombia. Email: hector.mora@uptc.edu.co ORCID: https://orcid.org/0009-0006-7711-4913
[3]Universidad Pedagógica y Tecnológica de Colombia. Email: onier.pinto@uptc.edu.co ORCID: https://orcid.org/0009-0006-7859-8024

Abstract

This study evaluates the technical and economic feasibility of implementing a 0.1 MWp (100 kWp) photovoltaic system for self-consumption in a small-scale underground coal mining operation located in the area of Sogamoso, Boyacá (Colombia). The main objective is to reduce energy costs a significant component of operational expenditures (OPEX) by integrating a renewable energy source capable of supplying between 30 % and 40 % of the mine's total electricity demand. The methodology includes detailed electrical design of the photovoltaic system (PV array sizing, inverter selection, cabling, protection coordination and grounding under RETIE/NTC 2050 criteria), load profile modeling of the mining operation, and annual hourly energy simulation (8760 h) to accurately estimate generation, self-consumption, and surplus energy. Additionally, an economic evaluation was conducted based on CAPEX and OPEX broken down by cost items and key financial indicators.

The results indicate an annual energy generation of approximately 144 000 kWh, with a self-consumption rate of 94 % and an energy demand coverage close to 39 %. The economic analysis shows a net annual savings of approximately 98 million Colombian pesos (COP), with a payback period of less than five years (2.5–3 years when considering Law 1715 incentives) and a levelized cost of energy (LCOE) close to 200 COP/kWh, well below the current grid tariff (≈900 COP/kWh). It is concluded that the integration of photovoltaic systems in small-scale underground mining is a technically viable and economically profitable solution, with a significant impact on reducing energy costs and improving the sustainability of the sector.

Keywords: Photovoltaic energy; industrial self-consumption; underground mining; PV electrical design; 8760 simulation; techno-economic analysis.

1. INTRODUCTION

The Colombian mining sector, particularly small-scale underground coal mining, faces increasingly significant challenges arising from the increase in operating costs, the need to improve energy efficiency, and compliance with growing

environmental demands. Thus, electricity consumption constitutes a strategic component of operating expenditure (OPEX), especially in underground operations whose operation depends on ventilation, pumping, air compression, and lighting systems to guarantee adequate safety conditions and production continuity (Choi and Song, 2017).

In departments such as Boyacá, and particularly in the area of influence of Sogamoso, coal mining represents an activity of high relevance for the regional economic dynamics (Vargas Montañez, 2021), however, the cost of electricity supplied by the grid operator, the Boyacá Energy Company (EBSA), has been consolidated as one of the factors with the greatest impact on the profitability of mining operations (Mining and Energy Planning Unit, 2005). Under this scenario, the incorporation of renewable energy sources, especially photovoltaic (PV) systems, acquires interest as a strategy to reduce energy dependence on the grid, optimize operating costs and strengthen the sustainability of extractive activities.

The specialized literature has widely documented the potential of photovoltaic systems in industrial self-consumption schemes (Luthander, et al, 2015), as well as their growing adoption in the international mining industry, both in open-pit operations located in countries such as the United States, Chile, and Australia, and in remote operations traditionally dependent on diesel generation (Nasirov and Agostini, 2018). However, scientific evidence related to the implementation of self-consumption photovoltaic systems in small-scale underground mining remains limited, particularly in developing economies, where technical, regulatory, and financial conditions differ substantially from the contexts widely documented in the literature (Alves, et al, 2020), (Nkambule, Hasan, & Shongwe, 2023).

In response to this knowledge gap, the purpose of this study is to evaluate the technical and economic viability of a 100 kWp photovoltaic system designed to cover between 30% and 40% of the energy demand of an underground coal mine, for this, a comprehensive approach is adopted that articulates the detailed electrical design of the system, including the photovoltaic field, the inverters, the electrical protections and the grounding system, with the hourly energy simulation and the economic evaluation of the project. This approach allows estimating the potential for self-consumption, analyzing its impact on operating costs and verifying the technical compatibility of the proposed solution with the existing infrastructure and with the applicable Colombian regulatory framework, particularly the RETIE (Technical Regulation of Electrical Installations) and Law 1715 of 2014.

METHODOLOGY

The research was developed under an integrated technical-economic approach, aimed at systematically evaluating the viability of the proposed energy solution, the methodology articulated the energy characterization of the case study, the dimensioning and detailed electrical design of the photovoltaic system, the modeling of the load profile of the mining operation, the annual hourly energy simulation (8760 h), the economic evaluation of the project and the definition of a monitoring system for the follow-up of its performance.

The energy characterization allowed to establish the operating and consumption conditions of the mine, while the electrical design provided the necessary technical criteria to guarantee the safe and efficient integration of the photovoltaic system, in a complementary way, the demand modeling and the annual hourly simulation allowed estimating the energy generation, the levels of self-consumption and the interaction with the electricity grid under different operating conditions.

Subsequently, the economic evaluation was carried out in order to determine the financial behavior of the project through the analysis of costs, savings and profitability indicators. Finally, a monitoring system was proposed aimed at verifying the operational performance of the facility, facilitating the management of energy information and validating the estimated results during the design stage, together, this approach allowed the integration of the technical and economic components necessary to develop a comprehensive valuation of the project.

2.1. Description of the case study

The case study corresponds to a small-scale underground coal mining operation located in the area of Sogamoso, department of Boyacá, the exploitation has an average production of 140 tons per day and develops its activities under an operational scheme of six days per week, with shifts between 6:00 a.m. and 6:00 p.m. The annual energy consumption is estimated at approximately 350,000 kWh, energy that is supplied by the local network of the Boyacá Energy Company (EBSA), with an average cost of close to 900 COP/kWh.

The electrical demand of the operation is mainly associated with the operation of the main ventilation, drainage pumping, air compression, lighting and transport systems, essential processes to guarantee production continuity and the safety conditions required in underground exploitation.

Under the current tariff conditions, the annual cost associated with the consumption of electricity is estimated at approximately 315 million Colombian pesos, constituting one of the most representative components of the operating expense of the mining unit, consequently, this value is adopted as a baseline to evaluate the technical and economic impact derived from the incorporation of the proposed photovoltaic system**.**

2.2. Sizing criterion

The photovoltaic system was sized with the purpose of covering between 30% and 40% of the annual energy demand of the mining operation, privileging the self-consumption of the energy generated and minimizing the appearance of significant surpluses during normal periods of operation. Given that the production activities are mainly carried out during daylight hours, between 6:00 a.m. and 6:00 p.m., there is a high correspondence between the solar generation profile and the behavior of the electricity demand, a condition that favors the direct use of the energy produced and improves the overall efficiency of the system. Under these conditions, the incorporation of battery storage systems was not considered necessary in this first phase of the project, since the existing synchronization between generation and consumption allows high levels of self-consumption to be achieved with a configuration of direct connection to the grid.

2.3. Sizing of the photovoltaic system

Monocrystalline modules of 550 Wp (Voc ≈ 49 V; Vmp ≈ 41 V; Imp ≈ 13 A) were adopted, considering the specific production factor of the Sogamoso area (range 4.2–4.8 kWh/kWp/day, with a conservative design value of 4.3 kWh/kWp/day, consistent with the records of the Atlas of Solar Radiation of Colombia (Mining and Energy Planning Unit, 2005) and a design Performance Ratio (PR) of 0.82–0.83, the system was configured in:

- Installed power: 99 kWp (180 modules of 550 Wp).
- Estimated annual production: 144,000 kWh/year.
- Demand Resulting Coverage: ≈ 39%, within the target range (30–40%).

2.4. Detailed electrical design of the photovoltaic system

The electrical design was developed with engineering criteria applicable to Colombia (Resolution 40117 of 2024 of the Ministry of Mines and Energy), which updated the RETIE and modified the way in which the Colombian Technical Standard NTC 2050 is applied, and also considering the specific conditions of an underground mining environment, coal dust, possible explosive atmospheres and operational continuity (Ministry of Mines and Energy of Colombia, 2024).

2.4.1. General system architecture

The proposed system corresponds to a photovoltaic configuration connected to the grid (on-grid) for self-consumption, without incorporating energy storage at this stage of the project, a decision that responds to the high coincidence identified between the periods of solar generation and the hours of operation of the mine. From a functional point of view, the energy generated in the photovoltaic field is directed to the direct current (DC) combiner boxes, then processed by the inverters for conversion to alternating current (AC) and, finally, it is integrated into the electrical system of the operation through the interconnection panel and the general distribution board, maintaining its interaction with the grid of the Boyacá Energy Company (EBSA).

In terms of electrical design parameters, the photovoltaic field operates in a voltage range between 600 and 1000 VDC, while the output of the inverters is set at 400 V three-phase. From this point, the energy is incorporated into the mine's electrical system, which can operate at voltage levels of 220/440 V or, depending on the particular conditions of the connection point, at medium voltage. This configuration ensures technical compatibility between the photovoltaic system and the existing electrical infrastructure, favoring a safe and efficient integration of renewable generation within the mining operation.

2.4.2. Photovoltaic field (DC side)

The field was configured in 10 strings of 18 modules each (180 modules, 99 kWp), the voltage per string is Vmp ≈ 738 V and Voc ≈ 882 V, values within the inverter operating limit (1000 VDC), with a conservative design criterion. The short-circuit current per string is ≈ 14 A.

2.4.3. Investors

2.4.4. DC wiring and protections

For the DC side, 6 mm² Cu photovoltaic cable (capacity ≈ 55 A) was chosen, oversized with respect to the design current (Isc × 1.25 ≈ 17.5 A), which guarantees a voltage drop of less than 1% for an estimated length of 80 m (round trip). Each string is protected with a 15 A fuse, as well as a DC disconnector (1000 V, 32 A) and type II surge arrester (DPS) per inverter.

2.4.5. AC Side Design

The rated current per inverter (50 kW, 400 V three-phase, cos φ ≈ 0.98) is ≈ 75 A. Applying a safety factor of 1.25 and considering grouping and ambient temperature (30 °C), 25 mm² copper wire (capacity ≈ 120 A), with a voltage drop of less than 3% for 50 m in length, was selected. The interconnect AC board includes one 3P–100 A switch per inverter, three-phase bars, DPS Type II AC, 3P–250 A master switch, and bidirectional metering at the point of connection.

2.4.6. Coordination of protections

Table 1. Coordination of electrical protections of the photovoltaic system.

Item	Side	Design Value
Fuse by string	DC	15 A
DC Disconnector	DC	1000 V – 32 A
DPS Type II	DC	1000 V
Inverter switch	AC	3P – 100 A
General switch	AC	3P – 250 A
DPS Type II	AC	400 V

2.4.7. Grounding and power quality

The grounding system (TT/TN-S configuration) was designed for a target resistance of less than 10 Ω (ideally < 5 Ω), using a mesh of 4–6 copperweld rods (2.4 m) interconnected with 35 mm² bare copper conductor, with equipotentiality between structures, module frames, inverters and panels. In terms of power quality, a power factor ≈ 0.98 and a total harmonic distortion (THD) of less than 5% were established as acceptance criteria, in compliance with RETIE.

2.4.8. Physical layout and system losses

The array is distributed in 10 rows of 18 modules, with a south orientation and inclination of 10°–15°, and separation between rows of 2.5–3 m to minimize shading between structures. The total area required is approximately 800 m². The losses of the system, particularly relevant in a mining environment due to the accumulation of coal dust on the modules, are summarized in Table 2.

Table 2. Losses considered in the photovoltaic system (design PR ≈ 0.82–

0.83).

Concept of loss	Range (%)
Temperature	6 – 8
Dirt (coal dust)	5 – 10
Investor	2 – 3
Wiring	1 – 2

In addition, given the mining environment, the following specific criteria were established: segregation of the PV system from areas at risk of explosive atmospheres (firedamp), sealed electrical conduits, a minimum IP65 degree of protection for cabinets, vibration-resistant structures, and a module cleaning program every 15–30 days to mitigate coal dust fouling.

2.4.9. Regulatory compliance

- Technical Regulation of Electrical Installations – RETIE (Resolution 40117 of 2024).
- NTC 2050 (Colombian Electrical Code).
- CREG Resolutions on Small-Scale Self-Generation (AGPE).
- Law 1715 of 2014 and its amendment, Law 2099 of 2021, on the integration of non-conventional sources of renewable energy [6].

2.5. Load profile modeling

The load profile was modeled using a stepwise distribution representative of the mine's operating behavior:

Table 3. Hourly load profile adopted for the mining operation.

Time slot	Charge Level (%)	Power demanded (kW)
6:00 – 8:00	70%	65,8
8:00 – 16:00	100%	94
16:00 – 18:00	80%	75,2

Constant operation on working days, zero or minimal consumption on non-operational days (Sundays), and absence of significant transient peaks were assumed, which is reasonable for predominantly electromechanical loads of continuous cycle (fans, pumps, compressors).

2.6. Hourly energy simulation (8760 h)

A computational model was implemented to evaluate the 8760 hours of the year consecutively. For each hour t, the balance is governed by the fundamental

equation:

$$\boldsymbol{Balance(t) = E_{gen}(t) - E_{cons}(t)}$$

Photovoltaic hourly generation was calculated by indexing values of a typical meteorological year (TMY) of the radiation in the inclined plane of Sogamoso and applying the thermal performance equation:$P_{fv}(t)$

$$\boldsymbol{P_{fv}(t) = P_{stc} \times \frac{G(t)}{1000} \times [1 - \gamma(T_{celda}(t) - 25)] \times \eta_{inv} \times \eta_{suci}}$$

For each hour, the energy flow variables were mathematically defined as:

- Self-consumption: $.E_{auto}(t) = \min\big(E_{gen}(t), E_{cons}(t)\big)\big)$
- Surplus: $.E_{exc}(t) = \max\big(0, E_{gen}(t) - E_{cons}(t)\big)\big)$
- Grid Power: $.E_{red}(t) = \max\big(0, E_{cons}(t) - E_{gen}(t)\big)\big)$

2.7. Economic evaluation

CAPEX was structured by items with reference prices in the Colombian market (2023–2024):

Table 4. CAPEX breakdown of the 100 kWp photovoltaic system.

Departure	Cost (million COP)
Photovoltaic modules (180 × 550 W)	108
Inverters (2 × 50 kW)	80
Support structure	40
DC Electrical System	15
AC Electrical System	25
Grounding	8
Civil works	25
Engineering, design and legalization	15
Installation and assembly	60
Monitoring System	5
Subtotal	381
Contingency (5–10%)	19 – 39
Estimated total CAPEX	400 – 420

The annual OPEX was calculated by real components, considering the critical condition of coal dust fouling typical of the mining activity:

Table 5. Annual OPEX broken down of the photovoltaic system.

Component	Cost (million COP/year)
Module cleaning (24 times/year)	6
Preventive maintenance	4
Corrective maintenance	2
Investor Replenishment Fund	8
Technical supervision (personnel)	3
Monitoring and communications	1
Insurance	2

Administrative costs	1
OPEX total	**27**

The following financial indicators were calculated from CAPEX, OPEX and annual energy production:

- Annual Gross Savings: The difference between the avoided cost of grid energy and the value of the surplus injected.
- Annual Net Savings: Gross savings minus PV system OPEX.
- Levelized cost of energy (LCOE).
- Simple payback period.

The effect of the tax incentives of Law 1715/2014 (income deduction, accelerated depreciation and exclusion of VAT) that reduce effective CAPEX and improve the payback of the project (Law 1715 of 2014) was also considered.

2.8. Monitoring system

A real-time monitoring system is proposed consisting of an energy meter at the point of connection, a network analyzer for mine loads, a bidirectional meter (in case of surplus injection), data logger/data acquisition gateway, remote communication via 4G and a monitoring platform. The variables recorded include power and energy generated, mine consumption, imported/exported energy and, optionally, environmental variables (irradiance, module temperature). The system allows validating the 8760 h simulation, detecting losses due to fouling or degradation and optimizing the operation.

3. Results

3.1. Energy performance

The simulation determined that the 100 kWp photovoltaic system reaches a specific production of 1,440 kWh/kWp/year, consolidating a total annual generation of 144,000 kWh.

3.2. Annual energy balance

Table 6. Annual energy balance of the system.

Balance Parameter	Energy value (kWh/year)	Relative percentage (%)
Total PV generation	144.000	100%
Direct self-consumption	136.000	94,40%
Exported surpluses	8.000	5,60%
Total mine consumption	350.000	100%
Supply from the network (EBSA)	214.000	61,10%

3.3. Performance indicators

- *Self-consumption rate:* The results obtained show that 94.4% of the photovoltaic energy generated is consumed directly by the mining operation at the time of production, a behavior that is explained by the high correspondence between the solar generation profile and the mine's operating hours, which favors the immediate use of the energy produced and significantly reduces the need to export energy to the grid.

- *Self-sufficiency rate (coverage):* The proposed photovoltaic system directly contributes approximately 39% of the annual energy consumption of the operation, evidencing a relevant contribution to the reduction of energy dependence on the conventional electricity grid and the strengthening of the energy autonomy of the mining operation.

- *Surpluses*: The remaining energy represents only 5.6% of the total annual generation, equivalent to about 8,000 kWh/year, a situation that reflects an adequate sizing of the system with respect to the existing demand. These surpluses are mainly concentrated on Sundays, when the mine's operational activity decreases considerably or is non-existent, reducing the absorption capacity of the energy generated by the photovoltaic system.

3.4. Economic performance

From an economic perspective, the implementation of the photovoltaic system made it possible to estimate an annual gross savings of close to 125.6 million Colombian pesos, this result is mainly associated with the high level of self-consumption achieved by the mining operation, which makes it possible to replace a significant proportion of the energy acquired from the electricity grid with locally generated energy. Added to this is the income derived from the surplus generation injected into the grid, although its contribution is relatively limited due to its small volume and the differences between the compensation rate and the cost of the energy consumed.

When incorporating the operation and maintenance costs of the photovoltaic system, the annual net savings were estimated at approximately 98.6 million Colombian pesos, this behavior shows that the economic benefits generated by the reduction in the purchase of energy far exceed the costs required for the operation, supervision and conservation of the photovoltaic infrastructure, which strengthens the financial viability of the evaluated alternative.

Similarly, the analysis of the levelized cost of energy (LCOE) yielded a value close to 200 COP/kWh, significantly lower than the average cost of electricity supply of the grid, estimated at approximately 900 COP/kWh. This difference reflects the economic competitiveness of photovoltaic generation for self-consumption applications in mining environments, particularly in scenarios where there is a high coincidence between generation and demand profiles.

On the other hand, in terms of investment recovery, the results indicate a simple return period of approximately 4.2 years, however, when the tax incentives contemplated in Law 1715 for renewable energy projects are considered, this period can be reduced to a range between 2.5 and 3 years. This behavior highlights the relevance of state promotion mechanisms in improving financial indicators and strengthening the economic attractiveness of this type of

investment within the mining sector.

4. Discussion

The most significant finding of this research lies in the high rate of direct self-consumption (94.4%) without requiring electrochemical storage systems (batteries), which would have doubled the CAPEX of the project severely affecting the financial return, this is explained by the strict synchrony between the dynamics of mining production (shift from 6:00 a.m. to 6:00 p.m.) and the availability of the solar resource in Sogamoso. This operational characteristic makes the case study particularly favorable for a self-consumption scheme without storage, unlike mining operations with night or continuous shifts of 24 hours, where direct solar coverage would be lower (Nasirov and Agostini, 2018).

The application of the 8760 h simulation proved to be a critical methodological step compared to average static estimates, when contrasting the dynamic model with simplified calculations, it was observed that the latter overestimate the savings by omitting that the Sunday generation could be fed into the grid at a compensation price 55% lower (400 COP) than the commercial replacement rate (900 COP). The hourly simulation also allows to capture the seasonal variability and the temporal relationship between generation and consumption with greater precision.

The detailed electrical design (string sizing, inverter selection, wiring and coordination of protections under RETIE criteria) is a relevant contribution to pre-feasibility studies that are limited to energy sizing, as it allows anticipating regulatory and safety restrictions typical of the mining environment (explosive atmospheres, coal dust, vibration).

Likewise, the severe environmental conditions of the coal mining environment make it necessary to conceive a more rigorous soiling factor (Romero Paredes, et al, 1995) in the engineering design, it was identified that the absence of scheduled cleanings twice a month can cause losses due to opacity of up to 15% accumulated monthly, reducing net savings and extending the payback by more than a year. The investment in real-time monitoring instrumentation (≈12 million COP) is fully justified by mitigating these operational and maintenance deviations.

The economic results obtained (LCOE ≈ 200 COP/kWh, payback of less than 5 years) are consistent with the literature on industrial photovoltaic self-consumption (Pedrero, Hernández, & Martínez, 2021) and with studies on the adoption of solar energy in mining in other Latin American contexts (Martínez-Calahorro, et al, 2020) and confirm that, when there is a coincidence between the generation and demand profile, photovoltaic energy constitutes an effective lever for reducing OPEX in small-scale mining, in line with what has been reported for hybrid systems applied to the mining industry (Valikandi & Choi, 2024) (Kadri, et al, 2022).

The limiting factors of the study were identified as the absence of in situ measurements of irradiance and real load curve, which were approximated using typical data (TMY) and a stepped profile, the sensitivity of coal dust fouling, which can vary significantly depending on the location of the mine with respect to haul roads and storage yards, and finally the non-inclusion, in this phase, of battery storage, whose evaluation is proposed as future work.

5. Conclusions

The results obtained indicate that the implementation of a 100 kWp photovoltaic system in an underground coal mining operation located in the Sogamoso area constitutes a technically viable alternative to complement the energy supply of the exploitation. Under the conditions evaluated, the system reaches an approximate annual generation of 144,000 kWh and contributes to cover about 39% of the total electricity demand of the operation, in addition the electrical design developed complies with the technical and regulatory requirements applicable in Colombia, particularly those established by RETIE and NTC 2050, guaranteeing its compatibility with the operational and safety conditions of the mining environment.

The high correspondence between the photovoltaic generation and energy consumption profiles allowed to achieve a self-consumption rate of 94.4%, which shows an efficient use of the energy produced and reduces the need to incorporate storage systems in the configuration analyzed.

From an economic perspective, the project presents favorable indicators, reflected in an estimated annual net savings of 98.6 million COP, a levelized cost of energy close to 200 COP/kWh and a simple payback period of 4.2 years, the incorporation of the incentives contemplated in Law 1715 allows improving these results and significantly reducing the time of return on investment.

Finally, the hourly energy simulation of 8760 hours proved to be a suitable tool to evaluate the technical and economic performance of the system, by allowing a more accurate representation of the interaction between photovoltaic generation, demand behavior and operational variations present throughout the year.

6. Recommendations

In order to maximize the use of the energy generated, it is recommended to evaluate the rescheduling of certain auxiliary activities towards periods of lower operational demand, particularly during Sundays, when most of the photovoltaic surpluses are concentrated, processes such as pumping sewage or recharging equipment could contribute to increasing self-consumption and improving the overall economic performance of the system.

Likewise, it is advisable to initiate in advance the regulatory procedures required for the connection of the system under the figure of Small-Scale Self-Generator (AGPE), in order to guarantee compliance with the requirements established by current regulations and facilitate the proper management of energy surpluses.

From a financial perspective, it is recommended to access the tax benefits contemplated in Law 1715 of 2024, since these incentives can significantly improve the project's economic indicators and reduce the payback period of the investment.

Similarly, it is considered essential to implement a real-time monitoring system that allows supervising the performance of the installation, verifying the projections obtained through energy simulation and timely detecting possible operational deviations, in addition, it is recommended to establish a periodic maintenance and cleaning program of modules, considering the effect of coal dust on the reduction of the energy efficiency of the system.

Finally, as a line of future research, it is pertinent to evaluate the incorporation of energy storage systems, in order to increase the use of photovoltaic generation, expand the coverage of electricity demand and analyze their potential contribution during periods of operation outside the hours of solar availability.

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