Technical and economic analysis of photovoltaic systems installed in the metropolitan area of Cúcuta

Análisis técnico-económico de sistemas fotovoltaicos instalados en el área metropolitana de Cúcuta

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Resumen

El objetivo principal de este trabajo fue realizar un análisis técnico y económico de los sistemas fotovoltaicos instalados en el área metropolitana de Cúcuta por una compañía líder en el sector de energías renovables de la región. Un total de 131 proyectos fueron instalados por esta empresa hasta septiembre de 2024. La potencia instalada promedio fue de 21 kW, con una desviación estándar de 33.14 kW. Con base en la calidad de los datos, se seleccionaron 15 proyectos relevantes para un análisis detallado. Por medio de parámetros estadísticos y visualizaciones, se comparó el desempeño de producción energética y económico de estos sistemas fotovoltaicos. En términos de eficiencia, el Coeficiente de Rendimiento promedio fue de 78.2%, con un máximo de 94.1% y un mínimo de 62.3%. Se incluyó la revisión de literatura especializada y la aplicación de métodos estadísticos para analizar el rendimiento energético y las emisiones de CO_2. Los sistemas analizados contribuyeron a la reducción de 613.61 toneladas métricas de CO_2 durante el tiempo que llevan en funcionamiento cada uno de los proyectos seleccionados, utilizando el factor de emisión de 0.493 tonCO_2eq/MWh. Se destacó la necesidad de mejorar el rendimiento de algunos sistemas, optimizando su operación y mantenimiento. Según el análisis del periodo de retorno de la inversión, se espera que los proyectos se recuperen en un rango de 2.56 a 4.39 años, así como también situarlos en un rango común de rendimiento energético entre los 1000 y 1600 kWh/kW/año.

Palabras clave: coeficiente de rendimiento, sistemas fotovoltaicos, análisis técnico-económico.

Abstract

The main goal of this work was to perform a techno-economic analysis of PV systems installed by a renewable energy leading company in the Metropolitan Area of Cúcuta. A total of 131 active projects were installed by this company up to September of 2024. The average installed power was 21 kW, with a standard deviation of 33.14 kW. Based on data quality, we selected 15 relevant projects for a detailed analysis. Through summary statistics and visualizations, we compared the energy production and economic performance of these PV systems. In terms of efficiency, the average Performance Ratio was 78.2%, with a maximum of 94.1% and a minimum of 62.3%. The study included a review of specialized literature and the application of statistical methods to analyze energy performance and CO_2 emissions. The analyzed systems contributed to the reduction of 613.61 metric tons of CO_2 during their operational lifetime, using an emission factor of 0.493 tonCO_2eq/MWh. The need to improve the performance of some systems by optimizing their operation and maintenance was highlighted. According to the simple payback period analysis, the projects are expected to have a payback period ranging from 2.56 to 4.39 years, and their Energy Yield is expected to fall within the common range of 1000 to 1600 kWh/kW/year.

Keywords: performance ratio, pv systems, techno-economic analysis.

1. INTRODUCTION

Solar energy is one of the key technologies to tackle global warming and to use as an alternative to fossil fuels. Since COP26 in 2021, the participant countries committed to reduce fossil fuels usage aiming to zero emissions by 2050. To achieve this, countries need to limit global warming to 1.5°C and to supply 48% of electricity demand using photovoltaic (PV) solar energy (Maka & Alabid, 2022; Holechek *et al*., 2022). Some examples of how PV technology contributes to sustainability include agrivoltaic systems which reduce irrigation by 20% (Zahrawi & Aly, 2024) and PV rooftops that can decrease global CO_2 emissions by 33% (Yin *et al.,* 2024). Additionally, PV is growing at a fast pace. For instance, United Arab Emirates reached 950 MW of PV capacity in 2022 (Obaideen *et al*., 2023; Mirletz *et al.,* 2022). In Africa, most countries have very low electrification rates; for instance, Mozambique has 57% of electricity access in urban and 13% in rural areas, while Benin has an average of 41% of the population with access to electricity. These countries have a great potential for solar energy, and they aim to increase PV capacity by 2025, but they face infrastructure and financing challenges (Santos et al., 2023; Akpahou *et al.,* 2023). Optimization of microgrids and Positive Energy Districts (PED) are essential to reduce operating costs, CO_2 emissions and to improve energy efficiency (Aldosari *et al.,* 2024; Sertöz, 2024).

Techno-economic assessments of PV systems have shown feasibility around the world. In Pakistan, PV projects in the cities of Multan and Attock had payback periods of 5.2 years and CO_2 reduction of up to 154 tons per year. In Eqlid (Iran), PV system generates 10.66 MWh and avoids 102 tons of CO_2 each year (Aziz *et al*., 2024; Hai *et al*., 2024). In Irak, a hybrid solar system in Diyala is profitable if electric rates are greater than $0.1/kWh (Falih *et al*., 2022). In Cuba, east-west oriented PV systems optimize space and reduce shading losses accounting for 30% of electricity demand of a hotel and avoiding the release of 7535 tons of CO_2 in 25 years (Carrera *et al*., 2023).

In Colombia, 77% of electric energy comes from hydroelectric power plants while solar energy represented only 0.1% in 2018, increased to 1.5% (290 MW) in 2022 and is projected to reach 40% by 2027 (López *et al*., 2020). Some policies have boosted this growth. For example, Law 1955 of 2019 requires 10% of renewable energy in 2023, and Law 2099 of 2021 offers 50% tax deductions for 15 years (Vega Araújo & Muñoz Cabré, 2023). A 2020 study in the city of Manizales revealed that polycrystalline modules were 16% more efficient at high temperatures than monocrystalline ones (Mulcué Nieto *et al.*, 2020). In another Colombian City, Bucaramanga, the cost of residential

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PV system varies between 4000 and 9223 USD, and they make economic sense for high-income households due to government subsidies to the electricity bills for low-income households (Muñoz *et al.,* 2024). In the Colombian State of Chocó, a 20 kW off-grid PV system generated 56581 kWh per year with a Levelized Cost of Electricity (LCOE) between $0.51/kWh and $0.55/kWh (Murillo *et al*., 2023).

In a feasibility study of a PV system located at the municipality of El Zulia, Norte de Santander, Colombia, the authors reported 5.3 Sun peak hours and monthly electricity demand of 2272 MWh. This system would need 56373 solar panels for a total nominal power of 18 MW. It would require an investment of 24390 million COP with a payback period of 4 years, annual savings of 1525 million COP and a total reduction of 250249 tons of CO_2 for 25 years (Galvís Villamizar *et al*., 2023).

The focus of this work is to perform a techno-economic analysis using descriptive Statistics to quantify the profitability and energy production performance of small and medium size PV projects installed by local installer in the Metropolitan Area of Cúcuta (MAC). This analysis will help to optimize the PV system sizing for future projects as well as to track the economic and technical performance of existing projects.

2. METHODOLOGY

Commonly Used Methods for Techno-Economic Analysis of PV Systems

We did a literature review to identify recent methodologies for PV system assessment. We prioritized measuring performance and failure detection, considering shading losses, dirt, module degradation and energy production. We also included financial parameters such as initial and operating costs, Internal Rate of Return (IRR) and payback period. We selected industry metrics and reliable databases (Castro-Maldonado *et al.,* 2022; Hernández-Leal *et al.,* 2022) to analyze power and economic related parameters of the PV projects in the Metropolitan Area of Cúcuta.

Selection of PV Systems

From the literature review, we defined key performance indicators to evaluate the efficiency and profitability of the PV systems. We considered data quality and used common statistical measures such as mean, median and standard deviation. We evaluated the accuracy of the data provided by the inverters, identifying possible bias and atypical values, commonly related to operating interruptions. This allowed us to focus on projects with reliable data, ensuring a clear and complete assessment of the variable's behavior.

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Techno-Economic Performance Using Summary Statistics

We identified inconsistency in some data, likely due to operating interruptions, which led us to focus on PV projects with the largest amount of consistent data and fewest interruptions. We chose these projects for a detailed analysis, evaluating the Performance Ratio, Energy Yield, payback period, and current savings. With this approach we achieved an integral assessment of the technical and economic performance of the PV systems.

Quantifying the environmental benefits based on CO_2 reduction

We investigated if the Grid Operator (Centrales Eléctricas de Norte de Santander, CENS) reports a regional CO_2 factor, but this information is not publicly available. As an alternative, we used the national emissions factor of 0.493 tonCO_2eq/MWh provided by a national government agency called: Unit of Mining and Energy Planning (UPME) through the Resolution 000705 from August 30th, 2024.

3. RESULTS AND DISCUSSION

Parameters to Quantify Technical Performance of a PV installation

The parameters to determine the technical performance of a PV system are presented below.

Availability

This parameter is calculated dividing the number of actual production hours by the calculated production hours. To define whether a specific hour the PV system was available or not, a 5% threshold is established. If the energy production on an hour is below 5% of the calculated production, that hour is not available.

Performance Ratio (PR)

Performance Ratio is a key metric used to evaluate the efficiency and quality of a PV system under real-world operating conditions. It is defined as the ratio of the actual energy output of the system (AC energy delivered to the grid or load) to the theoretical energy output, which is the energy that would be produced if the system operated at its nominal efficiency under standard test conditions (STC).

Clipped Energy

Another parameter to evaluate the performance of PV systems include the concept of "Energy clipped", which refers to the amount of AC energy that could have been used, but it was not due to the limited inverter capacity.

$$E_{clipped} = \int_0^{t_{clipped}} (P_{PV} - P_{inverter}) \cdot dt$$

Where P_{PV} is the power of the PV array and $P_{inverter}$ is the nameplate capacity of the inverter.

Delivered Energy

Similarly, we can quantify the “Delivered Energy” as the difference between the produced energy and the clipped energy.

Regarding economic performance of a PV system, typical metrics are payback period and profitability analysis which compare initial investment with up-to-date savings.

Selection of PV Systems

All active PV projects in the Metropolitan Area of Cúcuta installed by the company are shown in figure 1. System capacity is proportional to the marker size. Visualizing the projects on a map facilitates planning and managing because it helps to identify proximity, assess geographic coverage, optimize logistics and transportation, and assign resources in a more efficient manner.

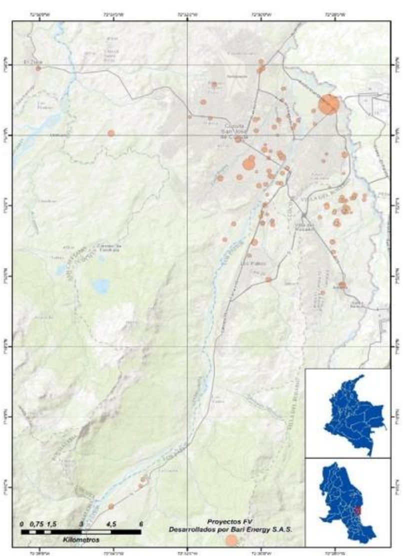

Figure 1. *Geographic distribution of all active PV projects considered in this study*

We identified 131 active projects up to April 2024. The histogram in figure 2 shows the distribution of the installed capacity of all projects. From the right skewed histogram, most of the projects have a capacity below 20 kW and there are two outliers greater than 100 kW.

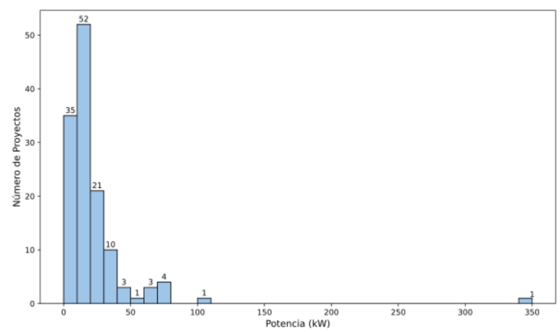

Figure 2. *Distribution of installed capacities of PV systems*

Out of the 131, we selected 15 PV projects based on data quality in terms of consistency and fewer operating interruptions. These projects are displayed in figure 3.

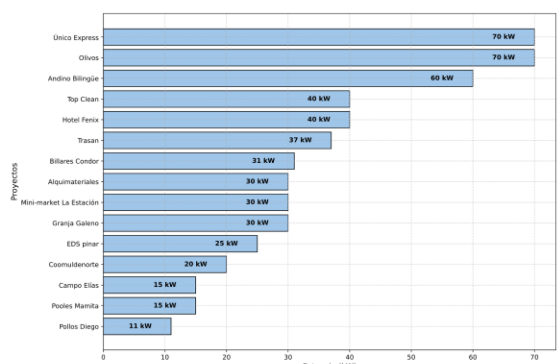

Figure 3. *Selected projects sorted from high to low power (kW)*

Performance Ratio (PR) Analysis

Figure 4 shows Performance Ratio (PR) values for each selected project. PR

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compares actual energy production with estimated production under Standard Test Conditions (1000 W/m^2 and 25 ºC), as defined in IEC EN 61724 standard.

PR can be calculated as:

$$PR = \frac{Actual\ energy\ output\ (kWh)}{Theoretical\ energy\ output\ (kWh)} \cdot 100\%$$

From the 15 selected projects, the minimum PR is 62.3%, the maximum is 94.2%, the mean is 78.25% (see figure 4), and the standard deviation is 7.99%. These values indicate some significant variability among the PV systems, considering that all of them are in the same geographic region and were installed by the same company.

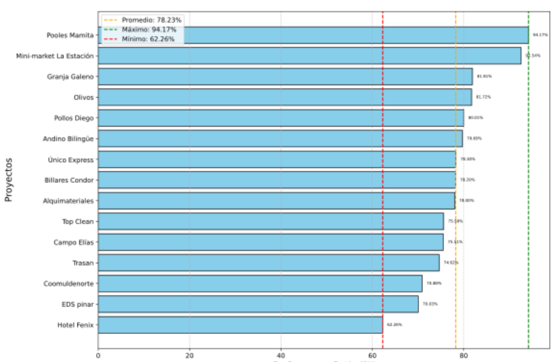

Figure 4. *Performance Ratio Analysis*

Energy Yield Analysis

Figure 5 compares Energy Yield values of the selected PV projects, ranging from 1109 kWh/kWp to 1460 kWh/kWp. This metric is useful to better understand the energy production performance regardless of system size, allowing a comparison between expected and actual production, which is key to evaluate operating efficiency and to detect possible deviations in system performance.

Energy yield is calculated as follows:

$$Energy\ Yield\ (EY) = \frac{Total\ energy\ output\ \ (kWh)}{Installed\ capacity\ (kWp)}$$

Economic Analysis

To calculate the cumulative savings for each project, we used the electric bills provided by the Grid Operator (CENS). For each month, we analyzed the cost of the electric bill of the customer, considering the items of the electric bill related to cost of electricity such as consumption, PV generation, and PV commercialization according to the Colombian regulations.

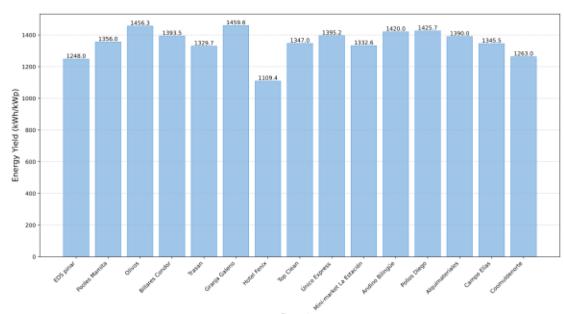

Figure 5. *Energy Yield Analysis*

The electricity bill without the PV system can be calculated as:

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$$\mathit{Electric\ bill\ (without\ PV\ system)} = \big(\mathit{total\ grid\ purchases}\ (kWh) + \mathit{self\ consumption}\ (kWh)\big) * \mathit{electricity\ tariff}\ (\$/kWh)$$

Total cumulative savings is obtained by adding up the difference between the electric bill without PV system and the actual electric bill value for all months since the PV project started operation. Figure 6 shows the cumulative savings and the total cost for each of the 15 selected projects.

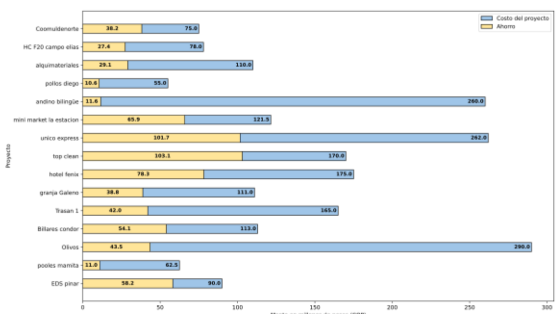

Figure 6. *Cumulative savings relative to total cost for each PV project*

CO_2 Emissions Analysis

The CO_2 Emission Factor for the National Interconnected System (nationwide electric grid), calculated by UPME and specified in their 2022 regulation, was updated in the Resolution 705 from August 30th, 2024. This update applies to emissions inventory and greenhouse emission gases mitigation projects. According to Article 1A, for wind and PV power plants, the Emission Factor is 0.493 tonCO2eq/MWh.

Up until September 2024, the total CO_2 reduction during the lifetime of all projects is approximately 614 metric tons using the Emission Factor from UPME. Figure 7 shows the total CO_2 emissions that have been avoided since the beginning of each PV project.

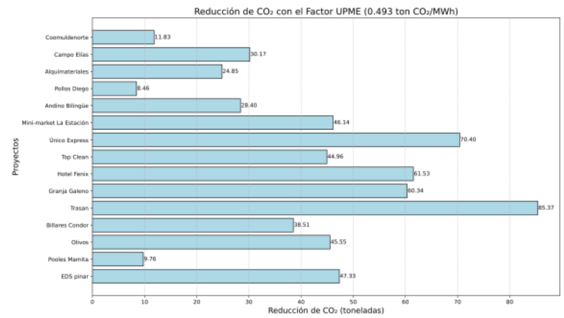

Figure 7. *CO_2 Reduction using the emission factor provided by UPME in selected PV projects until September 2024*

4. CONCLUSIONS

Regarding the PV projects installed by the local company, the average installed capacity is 21 kW, with a maximum of 350 kW and a minimum of 3.6 kW. The standard deviation of 33.14 kW indicates a significant variability among different projects. From the right skewed histogram, we can infer that most of the projects are residential PV systems, while a few industrial installations have been done in the Metropolitan Area of Cúcuta.

The average Performance Ratio (PR) of the 15 selected PV projects is 78.4%, which represents the general efficiency of the PV systems. PR values range from 62.3% to 94.2%, which imply potential areas of improvement for some of these systems. The standard deviation of 7.99% indicates some differences of energy production efficiencies among projects. These results highlight the importance of evaluating each system individually as well as collectively, to optimize energy production and overall procedures of the company.

The Payback Period for the projects are between 2.56 and 4.39 years, which are well aligned with initial estimations. This reasonable range suggest proper initial planning and analysis.

Energy Yield varies according to location and system design. It typically ranges from 1000 to 1600 kWh/kW/year. This parameter compares PV production performance regardless system size.

Regarding CO_2 emissions reduction, we could have used the emission factor of each regional electric generation source; however, the government agency (UPME) factor provides an official and accurate estimate which is commonly used in government reports. Since it is a national average, it might not reflect the regional conditions, however, by using it, we minimized the risk of over and underestimations in the emissions analysis.

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