Economic Analysis of Residential Photovoltaic Self-Consumption in Ecuador: Simulation Tool

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1 Introduction

1.1 Background

Grid-connected photovoltaic (PV) systems are designed to operate in parallel with the conventional electrical grid. These systems utilize solar panels, among other electronic components, to supply all or part of a building's electricity demand, a concept known as self-consumption. The electricity generated by these systems depends on solar irradiance, which means that it may not always provide the exact amount of energy required by a household. To ensure a continuous power supply, the PV system remains connected to the electrical grid. In instances where the system generates more electricity than is needed or consumed, the excess energy is fed back into the grid. These systems have the characteristic of providing some autonomy and potential economic savings in billing, depending on the tariff or incentive scheme applied [1].

Internationally, important policies have been implemented to incentivize and increase the use of energy from renewable sources [2], particularly in the use of PV in buildings [3–5]. The advantages that PV systems have over other renewable energy sources lie in the reduction of PV module prices (about 85% in recent years [6]) and the growth of research on increasing the efficiency of PV cells [7, 8]. At the

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same time, according to the International Energy Agency [9], the benefits of this type of system installed directly in buildings and connected in self-consumption mode are very varied, among which those related to the reduction of electricity costs (on the part of the consumer), those related to the repowering of the distribution grid, and the improvement in the security of electricity supply stand out. Likewise, the social and environmental benefits should also be highlighted insofar as economic profitability is improved with the reformulation of electricity market prices and energy efficiency is increased with less use of traditional energy sources.

In Ecuador, the existing legislation is relatively new. It officially started in 2018 through the regulation ARCONEL003/18, which establishes the technical, commercial, and legal conditions for users to implement PV generation facilities [10]. Three years later, an update was established with regulation ARCERNNR-001/2021 [11]. Despite the incentives presented in these regulations, the installation of grid-connected PV systems has a low number of registrations (around 100 installations across the country by 2021) [12]. This may be due to various factors, starting from administrative procedures, cost of the systems, and mode of compensation, among others.

According to [13], several schemes incentivize PV self-consumption. One of them is the Feed-in Tariff (FiT) model, where distributors pay a specific amount for the electricity the PV system generates and injects into the grid. Another compensation scheme is called Net Metering or Net Energy Metering (NEM), in which the electricity distribution company charges only the net value resulting from subtracting the energy consumed from the energy generated for self-consumption. Another incentive scheme is Net Billing, which, unlike the previous scheme, uses a bidirectional meter to record the energy demanded by the customer and the excess energy that is injected into the grid by the PV system, valuing them separately and at different prices [14]. In Ecuador, according to the regulations [11, 12], a Net Metering scheme is implemented, providing benefits to the "*prosumer*" (a combination of producer and consumer) since the reduction in consumed kWh directly reflects on the electricity bill. This scheme allows for the accumulation of surplus energy that can be consumed in subsequent billing periods, potentially resulting in positive energy balances.

In Ecuador, the greatest efforts have been made toward the rural electrification of remote areas without connection to the interconnected electricity system [15], which is why there are a greater number of publications describing experiences with off-grid systems compared to on-grid systems. Another interesting particularity regarding the connectivity of PV systems is the purpose given to this generation source in systems that interact with the electricity grid on the Ecuadorian mainland: mostly used to supply power supply stations for electric cars and electric passenger trams [16], lighting systems [17], a water desalination plant located on Floreana Island [18], and low-voltage grids in sensitive areas such as the Galapagos Islands [19, 20].

Similarly, small-scale PV applications (100 kW) have typically been restricted to the fields of telecommunications (powering repeaters, antennas) and rural electrification (mini-grids, tourist homes, etc.) [21]. On the other hand, since approximately

2014, research has been conducted on PV systems combined with control systems to efficiently manage the electricity demand of small- and medium-sized consumers [22, 23]. In addition to these experiences, an analysis of the research conducted in Ecuador regarding grid-connected PV systems concludes that this field of study is relatively new, with research conducted to determine their reliability, optimization, and cost-effectiveness. For example, Zambrano-Asanza et al. [24] conducted an estimation of PV potential in urban environments based on architectural conditions and building consumption. This study concludes that (in one case study), savings of up to 16 metric tons of liquefied petroleum gas can be achieved simply by using PV systems and proper demand-side management. On the other hand, specific applications of electricity consumption in buildings such as lighting and air-conditioning systems, which use electricity generation from PV systems, have been studied in Ecuador [17, 23, 25]. These studies conclude that this type of consumption can be supplied solely with solar PV energy available in the building itself, achieving savings in annual billing of up to 58%. In the same context, other studies [26–28] conclude that Ecuador has great potential for the installation of PV in buildings, mainly due to its geographical location with latitudes close to zero, which allows PV systems to easily adapt to the existing slope of buildings without affecting their production. Other studies have also focused on economic analyses and user incentives for the implementation of grid-connected PV systems [29]. For example, Benalcazar et al. [14] concluded that grid parity could not be achieved without some kind of incentive.

Among the Ecuadorian universities that have pioneered the installation of PV systems in their buildings, The Salesian Polytechnic University (UPS) can be mentioned (Cuenca campus) [30], as well as the Particular Technical University of Loja (UTPL) [31]. The UPS installed a PV system applied to electromobility in 2018. The system has an installed capacity of 13.2 kW_p in an area of 73.3 m^2 and serves for the self-consumption of buildings on its university campus and for recharging two motorbikes and two electric cars. On the other hand, in 2019, the UTPL installed one PV system composed of 68 panels of 275 watts that are connected to the electricity grid, which has allowed it to produce about 20% of the energy consumed in a building with the consequent economic savings in billing. Note that a few days ago, the UTPL installed the second stage of this system with an extension of 55 kW_p, which generated an average annual energy of 85 MWh. Finally, it is worth mentioning that Ecuador already has a regulation for micro-electricity generation [11]. This new regulation promotes PV generation for small *prosumers*, which will allow buildings to cover their electricity demand and deliver the surplus to the National Interconnected System. However, the use of this regulation is still limited in our country, especially due to a lack of knowledge and experimental studies that demonstrate or refute the technical and economic viability of grid-connected PV systems.

1.2 The Aim of the Investigation

Against this backdrop, the purpose of this chapter is to present the results obtained through a simulation tool created at the National University of Loja, which allows any user to determine the profitability of a PV system in their home by estimating potential savings on the electricity bill and the level of self-consumption. The tool utilizes databases from various sources [32–36] to assess the solar potential at a specific location.

The Perez model is then used to calculate the diffuse irradiance for tilted surfaces. Additionally, the characteristics of the PV system are entered as input variables (PV capacity, tilt, orientation, installation costs, among others), as well as the specific characteristics of the household (electricity consumption, location). The tool is programmed to automatically calculate detailed billing costs and, based on the PV self-consumption level, provide estimates of potential savings and return on investment. The results also include a sensitivity analysis to visually depict the outcomes of hundreds of simulations.

This simulation tool is based on a grid-connected PV system installed in a building at the *Universidad Nacional de Loja* (UNL) (see Fig. 1), and through measurements taken from this system, a decision support system has been developed to size and analyze the technical and economic feasibility of installing PV self-consumption systems in Ecuador.

2 Methodology

The methodology followed to assess the technical and economic viability of residential PV self-consumption in Ecuador is presented in the following flowchart (see Fig. 2).

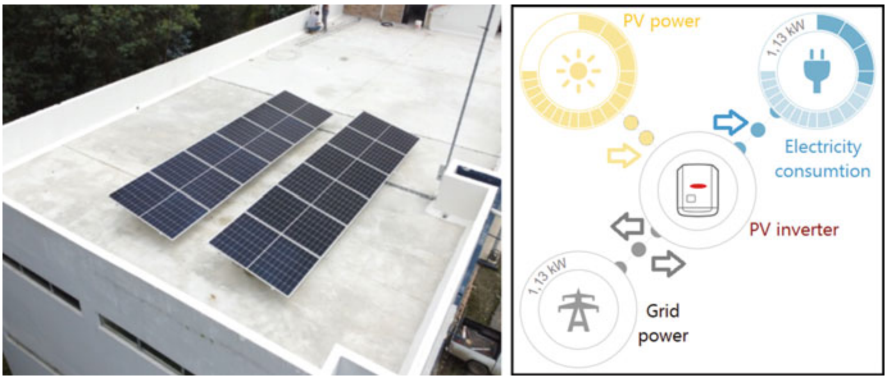

Fig. 1 Left: Aerial photograph of the 5 kW_p PV system at UNL. Right: Data diagram showing real-time monitoring

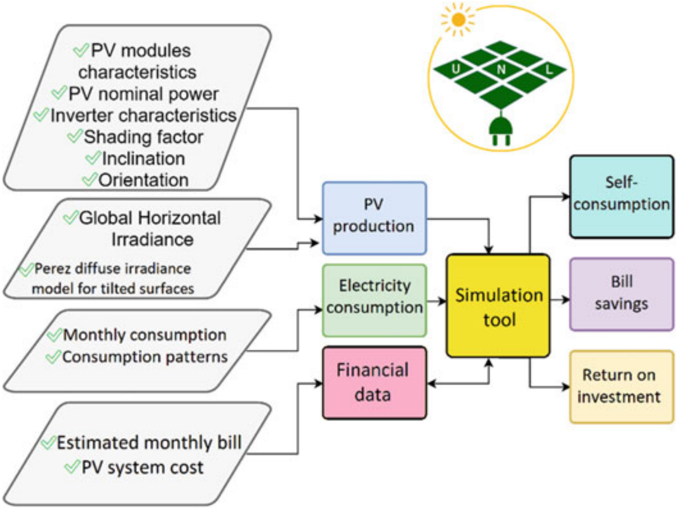

Fig. 2 The methodology used to calculate self-consumption, billing savings, and return on investment for grid-connected PV systems in Ecuador

2.1 Solar Potential

The solar potential in Ecuador has been published in the Solar Atlas of Ecuador [35] and more recently in the Solar Map of Ecuador [36]. In addition to this information, there are international sources with databases from which solar potential can be extracted for a specific location. For example, the National Aeronautics and Space Administration (NASA) [32], National Renewable Energy Laboratory (NREL) [33], and METEONORM [34]. From all these sources, the location (latitude) and solar potential (monthly average daily expressed in kWh/m^2) have been obtained for each parish in each canton of the provinces belonging to the Southern Region of Ecuador, which includes El Oro, Loja, and Zamora Chinchipe. These data are part of the simulation tool, but it is also possible to manually input data for any location in Ecuador, including specific data from meteorological stations if available.

All the data obtained from the sources above provide Global Horizontal Irradiance (GHI). However, to accurately assess how the PV system is influenced by panel tilt, the Perez model (A new simplified version of the Perez diffuse irradiance model for tilted surfaces) [37] has been utilized. This model, through extensive calculations, allows for the determination of monthly and annual irradiation on the tilted plane of the panels.

An example of how monthly irradiation varies on the horizontal plane and the tilted plane is shown in Fig. 3. These variations play a crucial role and directly influence the performance of the PV system.

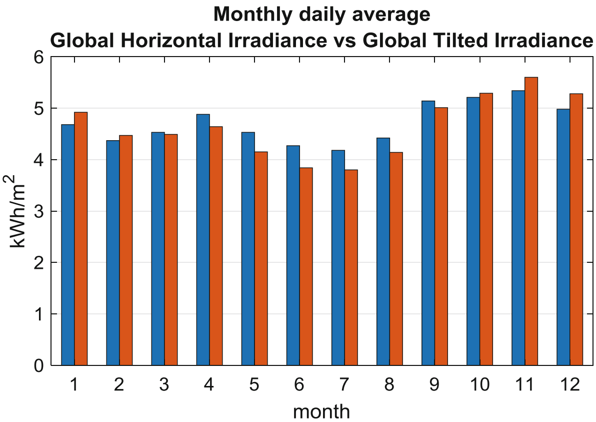

Fig. 3 Monthly irradiation on the horizontal plane (blue) versus monthly irradiation on the tilted plane (red). Example of use of the Perez model for the city of Loja using data from NREL

2.2 *PV System Characteristics*

As a first step, it is necessary to gather the general details of the PV system that will be installed. The input variables for the tool are as follows: nominal power of the PV generator (in kW_p), panel efficiency (in percentage), shading factor (ranging from 0 to 1, where 0 represents no shading and 1 represents complete shading), characteristic performance ratio (*PR*, with a value between 0.7 and 0.9. Losses correspond to DC-to-AC conversion, cell temperature, maximum power point tracking, etc.), and the cost of purchasing and installing the PV system, which will depend on the specific supplier and brand of the equipment (the approximate price in Ecuador ranges between 1000 and 1500 USD/ kW_p) [38].

The values of global irradiance on an inclined surface allow obtaining the generator's productivity (Y_R). With this value, the annual PV energy (E_{PV}) can be calculated using the following formula:

$$E_{PV} = P_{\mathrm{NOM},G} \times Y_R \times (1 - FS) \times PR \tag{1}$$

Where:

$P_{\mathrm{NOM},\,G}$ is the nominal power of the *PV* generator (in kW_p)
Y_R is the annual *PV* energy produced by the PV system (in kWh/m^2)
FS is the shadow factor (0–1)
PR is the system's efficiency percentage (%).

2.3 *Electricity Bill*

To determine the value that would be paid to the electricity company if a PV system is installed (compared to the amount paid previously without PV), it is necessary to

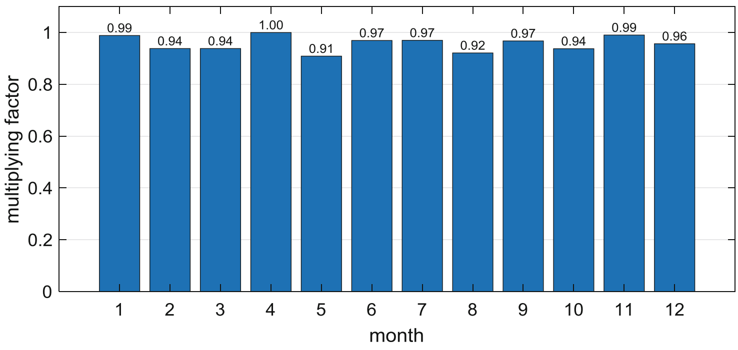

Fig. 4 Normalization of monthly average electricity consumption in the city of Loja

know the monthly consumption of the household, the type of contract (residential, commercial, etc.), and the cost per consumed kWh. For this purpose, this study has extensively utilized the Tariff Schedule of the public electricity service in Ecuador [39]. By knowing how much a user pays for monthly consumption, the amount that would be paid if the energy produced by the PV system is deducted for that month (applying the Net Metering scheme) and can be subtracted, ultimately determining the monthly savings.

Since the consumption varies each month, this tool allows for inferring the range of monthly energy consumption based on statistical data on electricity consumption (Fig. 4). These data are based on information provided to the research team of this chapter by the *Empresa Eléctrica Regional del Sur* (ERRSA) from over 60,000 residential meters in the city of Loja. However, users can also manually input homogeneous monthly consumption or, if available, the specific historical consumption data of the household for further analysis.

2.4 Sensitivity Analysis

Finally, by knowing the PV self-consumption and the savings in billing, it is possible to calculate the time it would take for the user to recover the investment in the purchase and installation of the PV system. From here, a sensitivity analysis has been conducted using the tool to determine how these parameters (self-consumption, savings in billing, and return on investment) vary within specific ranges. In the case presented in this chapter, a sensitivity analysis is shown by varying the installed PV power from 0.5 kW_p to 10 kW_p. At the same time, the monthly electricity consumption has varied from 0 kWh to 3000 kWh. In this way, the resulting graphs from the sensitivity analysis allow an understanding of the ranges in which the installation of these systems is economically profitable for the user.

3 Results

All formulations, models, input and output variables have been initially programmed in an Excel workbook (Fig. 5). The model is complex and occupies many sheets, but the main screen is responsible for displaying the main parameters. The screenshot shows a report with the key parameters that the installer must consider. It displays the annual solar PV energy produced by the system, the required panel area, the kWh/ kW_p ratio, the annual savings, the self-consumption percentage, the installation cost, and finally, the time it would take to recover the investment.

The specific example shown in Fig. 5 represents a particular case with fixed power and consumption. However, if the PV power increases or decreases and if household consumption increases or decreases, a sensitivity analysis graph (Fig. 6) is presented to determine immediately the variations. These graphs serve as a fingerprint of the specific installation considering the location, tilt angle, and solar potential of the site. The three graphs of self-consumption, savings in billing, and return on investment are shown as complements to each other. It is not recommended to decide based on a single graph. It is necessary to relate the three output parameters for a better analysis. For example, for monthly consumptions greater than 1000 kWh, the installation of any PV system would be profitable (return on investment in less than 10 years). However, not every PV system can cover the entire demand. The self-consumption graph shows that the PV generator power should be greater than 6 kW_p to achieve self-consumption percentages close to 100%. The investment recovery time represents only the time it would take for the user to recoup the investment made in the system purchase but does not guarantee that the system will cover the entire demand. On the other hand, the annual savings in billing is a parameter of interest to the user, as it is not always about recovering the investment, but rather knowing how much can be saved month by month to invest in other things.

Fig. 5 Screenshot of the simulation tool developed in Excel

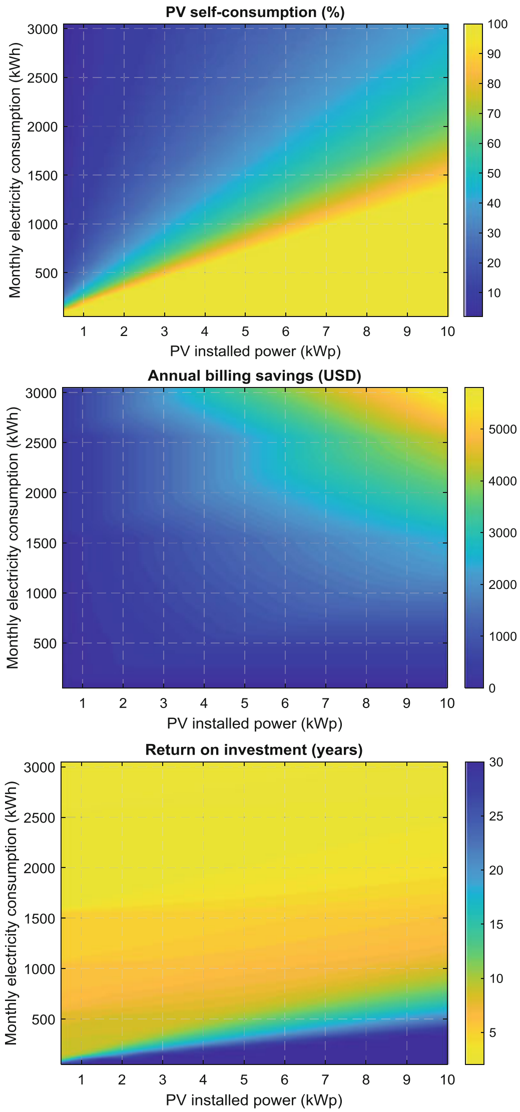

Fig. 6 Sensitivity analysis graphs for a residential PV system installed in the city of Loja

The efficiency and reliability of this simulation tool are based on its validation through the comparison and contrast with monitored PV systems installed in various cities across the country. As an example, three case studies can be mentioned (see Table 1) of different PV systems, whose analysis and results were presented in previous research [40]. Furthermore, these experimental results align with studies on the segmentation of residential customers for PV self-consumption purposes using profitability indices in Ecuador [41].

Table 1 Characteristics of the installed and monitored PV systems for case studies

Location	Avg. monthly consumption (kWh)	PV power (kW_p)	Actual Avg. monthly PV production	Actual Payback time (years)	Simulated Avg. monthly PV production	Simulated Payback time (years)
Manta	2153	8.25	1012	≈ 4	950	3.80
Quito	1926	5.23	640	≈ 3	670	3.45
Quito	4962	31.20	3065	≈ 2	4000	1.78

4 Conclusions

In Ecuador, the regulation of grid-connected PV systems for self-consumption is relatively new (around 5 years), and therefore, the implementation of these systems is not widely spread across the country, with only around 100 registered systems according to the latest report. Additionally, the low electricity prices make profitability a topic that users need to analyze beforehand, depending on their consumption and installation costs.

The simulation tool developed for grid-connected PV systems in self-consumption mode was designed to allow any residential user in Ecuador to input their data (such as consumption, location, and desired installed capacity), providing them with the potential savings in their electricity bills and the return on investment for purchasing a PV system.

The electricity billing structure in Ecuador is designed such that higher consumption results in higher bills, which directly affects profitability. Combined with the fact that Net Metering is applied in Ecuador, installations of PV systems for electricity consumption exceeding 1000 kWh/month can recover the investment in less than 10 years for almost any system size. For lower consumption levels, profitability depends on the installed power and the desired level of self-consumption. In this regard, the simulation tool provides additional value compared to other studies, as it allows users to input their data and perform multiple simulations to find the break-even point that helps them decide whether investing in a PV system is beneficial for them or not.

Up until the time of writing this chapter, the model and formulations have been developed in an Excel workbook. However, efforts are underway to create a web-based tool to make it accessible to all users. Furthermore, the simulations conducted by the current tool are being experimentally validated through a 5 kW_p PV system installed at the UNL, and the values of electricity consumption, billing, and return on investment have been compared with three residential PV systems installed in various locations in Ecuador, with the simulated values aligning with the experimental ones.

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