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A Novel Approach to Assessing the Cost Competitiveness of Self-Consumption Photovoltaic Systems

Fredy A. Sepulveda-Velez ¹, Diego L. Talavera ², Leonardo Micheli ³ and Gustavo Nofuentes ^{4,*}

¹ Department of Electronics and Automatic Engineering, University of Jaén, Campus Las Lagunillas, 23071 Jaén, Spain; fasv0001@red.ujaen.es

² Advances in Photovoltaic Technology (AdPVTech), Department of Electronics and Automatic Engineering, University of Jaén, Campus Las Lagunillas, 23071 Jaén, Spain; dlopez@ujaen.es

³ Department of Astronautical, Electrical and Energy Engineering (DIAEE), Sapienza University of Rome, 00184 Rome, Italy; leonardo.micheli@uniroma1.it

⁴ IDEA Research Group, Centre for Advanced Studies in Earth Science, Energy and Environment, University of Jaén, Campus Las Lagunillas, 23071 Jaén, Spain

* Correspondence: gnofuen@ujaen.es; Tel.: +34-953-212-434

Featured Application

The novel method presented here is a valuable tool that can inform institutions and potential owners/investors about the cost competitiveness of self-consumption PV systems. Its application will enable an assessment of how government policies, support mechanisms, technological advancements, and the economic landscape of a country can impact the cost competitiveness of self-consumption PV systems.

Abstract

Most existing studies on the cost competitiveness of self-consumption PV systems fail to jointly consider key technical, economic, and user-specific factors—such as the share of PV electricity self-consumed, energy exported or imported from the grid, and time-of-use electricity pricing—all of which significantly influence investment viability. To address these gaps, this study introduces a novel method based on a new model to calculate the unit cost of electricity consumption from the user's perspective (C_{EC} , in $\text{€}\cdot\text{kWh}^{-1}$). The array DC power rating is then optimally sized—assuming ideal orientation and tilt—to minimize C_{EC} . A self-consumption PV system is considered cost-competitive when the annualized minimized C_{EC} is lower than the applicable regulated electricity tariff. Colombia is selected as a case study to demonstrate the novel method due to the limited deployment and analysis of self-consumption PV systems in the country. The method is applied across residential, commercial, and industrial sectors in various locations. The resulting annualized minimized C_{EC} values (0.35–8.85 c€/kWh) are consistently below the corresponding regulated tariffs, demonstrating the economic viability of properly sized PV systems. The method's adaptability to international tariff frameworks makes it a valuable tool for global application and a useful resource for policymakers and stakeholders.

Keywords: photovoltaic; cost competitiveness; self-consumption; electricity demand



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1. Introduction

Photovoltaic (PV) solar energy has emerged as a highly cost-effective electricity source, with significant expansion potential through distributed generation (DG). In this context, self-consumption PV systems allow electricity to be used directly in homes or businesses,

reducing reliance on the conventional grid and increasing energy autonomy, while actively contributing to climate change mitigation.

Self-consumption PV systems are increasingly shaping the Latin American electricity mix, with countries like Brazil, Chile, and Mexico demonstrating significant progress and regional leadership [1–4]. Globally, this expansion is driven by renewable energy policies, including tax incentives, installation subsidies, and compensation schemes for surplus energy fed into the power grid. However, the cost competitiveness of these systems also depends on factors such as the availability of solar resources, installation and maintenance costs, as well as the regulatory framework and local electricity tariffs. There is abundant literature on the competitiveness of self-consumption PV systems in various countries, primarily focused on the Levelized Cost of Electricity (LCOE, in $\text{€} \cdot \text{kWh}^{-1}$) as the key criterion. This method estimates the break-even price a project needs to get paid per kWh generated in order to recoup its financing for a fixed rate of return [5]. In their work, Talavera et al. [6] proposed a pre-design decision tool for PV self-consumption systems that evaluates economic feasibility using standard financial metrics—Net Present Value (NPV, in €) and Internal Rate of Return (IRR, in %), among others—alongside cost competitiveness based on the LCOE. In their work, Liu et al. [7] conducted a techno-economic analysis of a PV system for a high-rise building in Hong Kong. Their analysis considered a comprehensive method for the calculation of LCOE, which comprises investment cost, maintenance cost, residual cost, transmission loss saving, network expansion saving and carbon reduction. In ref. [8], a techno-economic analysis was conducted to assess the feasibility of residential PV self-consumption in Peru. The analysis considered three key criteria: NPV, IRR and LCOE. This enabled an assessment of the cost competitiveness of the PV system in comparison to electricity tariffs. Wang et al. [9] presented a LCOE evaluation model of PV power generation—incorporating the impact of tradable green certificates (TGCs) on the economic viability of PV projects—in China applied to analyze the economic performance of PV power generation in various provinces of this country. The findings indicate that upon incorporating TGC schemes, the average LCOE of PV power generation decreases by 5.19%. Other studies rely on commercial simulation software to evaluate the LCOE of PV systems; for instance, Said et al. [10] utilized the Solar Advisor Model (SAM) to develop an improved financial framework, providing detailed LCOE modeling and analysis for PV power plants. Hirvonen et al. [11] analyzed self-consumption PV systems in single-family homes in Finland, also focusing on LCOE. Different heating technologies are compared, and thermal storage is considered as a strategy to improve self-consumption. The analysis shows that, with incentives and economies of scale, LCOE can compete with grid prices—especially in communities and in systems using electric heating. The profitability of PV systems for residential homes in Italy was evaluated in [12] by means of two indicators: NPV and LCOE, among others, which are applied to several studies that depend on three critical variables: plant size, solar irradiation levels and share of self-consumption. Several studies available in the literature [13,14] assess the competitiveness of systems with specific values of photovoltaic array DC power rating, yet they lack a clear rationale or established criteria for how those values were determined.

Accordingly, a growing body of literature examines the cost competitiveness of self-consumption PV systems. While LCOE remains a key parameter for evaluating utility-scale PV, it is widely acknowledged that LCOE alone is insufficient for assessing self-consumption competitiveness. Although some works, such as [15–21], include additional indicators such as NPV or IRR, these parameters are focused on evaluating the financial profitability of the investment and do not directly reflect cost competitiveness, which is the focus of this study. LCOE is a valuable tool for comparing the cost of generating electricity from PV with that of other technologies (wind, gas, coal, nuclear, etc.). At a first approximation, it suffices to

evaluate PV cost competitiveness at the grid level by comparing the wholesale electricity price with the LCOE of PV. In contrast, self-consumption PV lacks such a parameter, as its competitiveness depends on user-specific conditions such as the share of PV electricity self-consumed, the portion exported to the grid, the amount imported from the grid, and time-of-use (TOU) pricing. In other words, unlike utility-scale PV, self-consumption PV lacks a metric that can be directly compared with the retail electricity price to determine its competitiveness from the user's perspective. Therefore, this metric should express the cost per kWh of electricity consumed by the user over the system's lifetime. Moreover, it should be expressed in a manner that allows for a proper comparison with retail electricity prices throughout the system life cycle.

In view of the above shortcomings exhibited by previous approaches, a novel method has been developed to assess the competitiveness of self-consumption PV systems. This method is based on a new model to calculate the unit cost of electricity consumed in a building equipped with a self-consumption PV system without storage, from the user's point of view, by considering both technical parameters (e.g., load profile, array DC power rating, PV energy production, self-consumed and exported energy, energy drawn from the grid, PV system costs) and economic parameters (e.g., inflation, taxes, depreciation, electricity prices, cost of capital, and financing type). Next, the optimal array DC power rating of the system—assuming the orientation and tilt that maximize annual energy yield—is determined as the value of such array DC power rating that minimizes the aforementioned unit cost of electricity consumed in a building equipped with a PV self-consumption system without storage, from the user's perspective. Then, this minimized unit cost is annualized by means of the capital recovery factor. Finally, the comparison of this annualized minimized unit cost of electricity from the user's viewpoint with the final unit cost of electricity according to the regulated user determines the competitiveness of self-consumption PV systems. In such systems, the annualized minimized unit cost of electricity from the user's perspective can be compared with the retail electricity price in each year of the system's lifetime, since the former results from annualizing the minimized unit cost of electricity from the user's standpoint.

To gain a better understanding of the implementation of the method, Colombia has been selected as a case study to illustrate how the proposed approach is applied. Additionally, self-consumption PV systems have not yet been widely deployed in this country; therefore, the comprehensive analyses of their competitiveness remain scarce and should be welcomed. The proposed method will be applied under various scenarios, specifically in the residential, commercial, and industrial segments, and across different locations in Colombia. In this work, the method demonstration focuses on cases with a flat tariff, given the lack of smart metering in the aforementioned sectors in Colombia. However, under TOU (time-of-use) rate schemes, the average unit cost of electricity drawn from the grid over the PV system useful life should be calculated and compared with the annualized minimized unit cost of electricity discussed above.

This document is structured as follows. Following the literature review of the criteria used to assess the cost competitiveness of self-consumption PV systems, presented in the current section, Section 2 outlines the novel methodology developed for this purpose. To demonstrate its implementation, Section 2 presents the data employed, including a review of the regulatory framework for PV energy production in Colombia. In addition, the characterization of electricity consumption profiles for the residential, commercial, and industrial segments are examined in this study, as well as the definition of reference cases along with their technical and economic parameters. Section 3 presents and discusses the results obtained. Finally, Section 4 presents the conclusions of the study and the policy implications derived from this work.

2. Materials and Methods

2.1. Introduction to a Novel Method for Assessing the Cost Competitiveness of Self-Consumption PV Systems

Before introducing the novel method for analyzing the cost competitiveness of self-consumption PV systems proposed in this work, two of the most widely used indices for evaluating the match between PV production and load consumption are reviewed. Specifically, these are the self-consumption and self-sufficiency indices (*SCI* and *SSI*, respectively), which may be written as shown in Equations (1) and (2):

$$SCI = \frac{\int_{\tau} M(t)dt}{\int_{\tau} P(t)dt} = \frac{E_{PVcon,\tau}}{E_{PVgen,\tau}} \quad (1)$$

$$SSI = \frac{\int_{\tau} M(t)dt}{\int_{\tau} L(t)dt} = \frac{E_{PVcon,\tau}}{E_{L,\tau}} \quad (2)$$

where $P(t)$ is the output power (AC) of the PV system (kW) and $L(t)$ the load power consumption (kW). $M(t)$ represents the instantaneous overlapping between $P(t)$ and $L(t)$, τ is the reporting period (s, h or y) [22,23]. $E_{PVcon,\tau}$ is the self-consumed AC energy generated by a PV system—in which losses of power electronics have been taken into account—over τ (kWh); $E_{PVgen,\tau}$ is the AC energy generated by a PV system over τ (kWh) and $E_{L,\tau}$ corresponds to the load energy consumption over τ (kWh). Unless otherwise stated, *SCI* and *SSI* in the following discussion refer to the values of these parameters calculated over the full useful life of the PV system. The procedure to obtain the curves representing the *SCI* and *SSI* indices over the useful life of the PV system for PV self-consumption systems within a given range of array DC power rating values is shown in Figure 1. These curves can be used to assist in the optimal power sizing of PV self-consumption systems under certain premises of self-consumed energy and self-sufficiency, as shown hereafter. The calculation of the parameters E_L , E_{PVcon} and E_{PVgen} is carried out at hourly resolution—although other time intervals may be used, of course—which allows for a detailed and accurate analysis of the system behavior. $P_{0,ini}$ and $P_{0,fini}$ are the lower and upper bounds, respectively, of the array DC power rating range within which its optimal value is determined (kWp). $E_{PVcon,h}$, $E_{PVgen,h}$ and $E_{L,h}$ are the PV energy self-consumed (kWh), the AC energy generated by a PV system (kWh) and the load energy consumption (kWh), respectively, all estimated at 1-h intervals.

The novel method proposed to assess the cost competitiveness of self-consumption PV systems is structured in three steps:

1. Calculating the unit cost of electricity consumed in a building equipped with a PV self-consumption system, from the user's point of view by means of a new model.

This innovative model takes into account both technical (load profile, PV energy production, energy self-consumption and fed to the grid, energy from grid, costs of the PV system, etc.) and economic parameters (inflation, tax, depreciation, electricity price, cost of capital, funding sources, etc.) to obtain the unit cost of electricity consumed in a building equipped with a PV self-consumption system, from the user's point (C_{EC} , in $\text{€} \cdot \text{kWh}^{-1}$). The calculation of this parameter is given by Equation (3):

$$C_{EC} = \frac{PV_C + PW[PV_{OM}(N)] + PW[CE_{fromgrid}(N)] - PW[CE_{PVtogrid}(N)] - PW[CE_{PVcon}(N)] - PW[DEP(N_d)]}{E_L} \quad (3)$$

where PV_C represents the PV system cost (€), N is the life cycle of the system (y), $PW[PV_{OM}(N)]$ is the present worth of operation and maintenance cost over the system life cycle (€), $PW[CE_{fromgrid}(N)]$ represents the present worth of the cost of the energy

consumption from the grid over the system life cycle (€), $PW[CE_{PVtogrid}(N)]$ is the present worth of the revenues obtained from the PV energy fed into the grid over the system life cycle (€), $PW[CE_{PVcon}(N)]$ is the present worth of money savings due to PV energy self-consumed over the system life cycle (€), $PW[DEP(N_d)]$ represents the present worth of tax depreciation (€), N_d is the depreciation period and E_L is the load energy consumption of the building over the life cycle of the PV system (kWh).

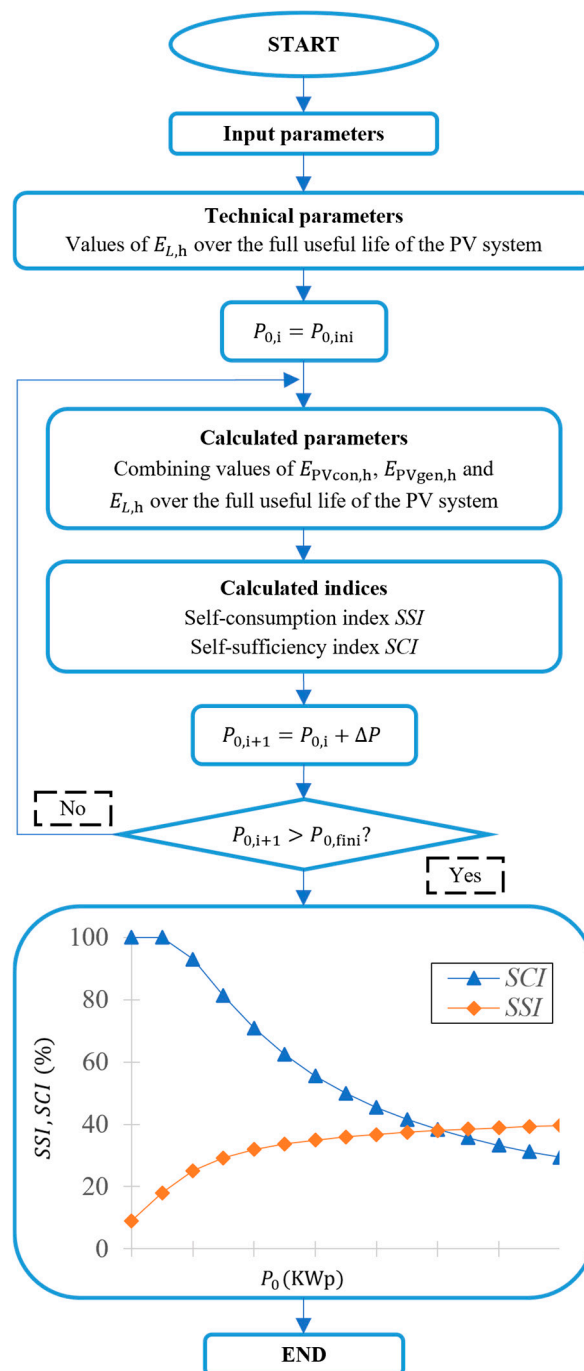


Figure 1. Flowchart of the procedure used to estimate SSI and SCI for PV self-consumption systems for a given array DC power range.

The term $PW[PV_{OM}(N)]$ of Equation (3) can be written as Equation (4) [24,25]:

$$PW[PV_{OM}(N)] = PV_{AOM}(1 - T) \cdot \sum_{n=1}^N \frac{(1 + r_{OM})^{n-1}}{(1 + d)^n} \quad (4)$$

where PV_{AOM} stands for the annual operation and maintenance expenditure (€) which is assumed to be constant over the life cycle of the system, this being yearly increased by the annual escalation rate of the operation and maintenance cost (r_{OM}), T is the income tax rate and d is the nominal discount rate.

$PW[CE_{fromgrid}(N)]$ may be written as Equation (5) [26–28]:

$$PW[CE_{fromgrid}(N)] = \left(\sum_{i=1}^{8760} p_{fromgrid_i} \cdot E_{fromgrid_i} \right) \cdot \sum_{n=1}^N \frac{(1 + r_{p_{fromgrid}})^{n-1}}{(1 + d)^n} \quad (5)$$

where $p_{fromgrid_i}$ is the unit electricity price from the grid in the i -th hour (€/kWh⁻¹); $E_{fromgrid_i}$ is the energy consumption from the grid in the i -th hour (kWh); 8760 is the number of hours in one year and $r_{p_{fromgrid}}$ stands for the annual escalation rate of the electricity price from the grid.

The term $PW[CE_{PVtograd}(N)]$ of Equation (5) is given by Equation (6) [26–28]:

$$PW[CE_{PVtograd}(N)] = \left(\sum_{i=1}^{8760} p_{PVtograd_i} \cdot E_{PVtograd_i} \right) \cdot (1 - T) \cdot \sum_{n=1}^N \frac{(1 + r_{p_{PVtograd}})^{n-1} \cdot (1 - PLR)^{n-1}}{(1 + d)^n} \quad (6)$$

where $p_{PVtograd_i}$ represents the price of the PV electricity fed into the grid (€/kWh⁻¹); $E_{PVtograd_i}$ is the PV energy generated that is fed to the grid in the i -th hour (kWh); $r_{p_{PVtograd}}$ stands for the annual escalation rate of the PV electricity price that is fed to the grid and PLR is the performance loss rate of the PV system.

$PW[CE_{PVcon}(N)]$ may be expressed as Equation (7) [26–28]:

$$PW[CE_{PVcon}(N)] = \left(\sum_{i=1}^{8760} p_{PVcon_i} \cdot E_{PVcon_i} \right) \cdot \sum_{n=1}^N \frac{(1 + r_{p_{PVcon}})^{n-1} \cdot (1 - PLR)^{n-1}}{(1 + d)^n} \quad (7)$$

where p_{PVcon_i} is the PV electricity price self-consumption in the i -th hour and E_{PVcon_i} represents the PV-generated energy that is used for self-consumption in the i -th hour (kWh).

The present worth of tax depreciation has been calculated using Equation (8) [24,25]:

$$PW[DEP(N_d)] = \sum_{n=1}^{N_d} \frac{D_n}{(1 + d)^n} \cdot T \quad (8)$$

where D_n is the annual depreciation for tax purposes (€), assumed linear and constant over the depreciation period (N_d). A maximum linear coefficient of 33.33% with $N_d = 3$ years [29,30] was assumed for the commercial and industrial sector. This means that the annual tax depreciation for the PV system (D_n) has been calculated as $D_n = \frac{PV_C}{N_d} = 33.33\% \cdot PV_C$.

Finally, the photovoltaic system cost is usually financed by means of debt or equity capital. In the case where the system cost PV_C is financed through a loan (PV_l)—debt—and the remainder by means of the issue of stocks (PV_s)—equity capital—then $PV_C = PV_l + PV_s$. According to the previous financing scheme, the photovoltaic system cost may be expressed as follows [22]:

$$PV_C = \left[PV_l \frac{i_l(1 - T)}{1 - (1 + i_l(1 - T))^{-N_l}} \cdot \frac{q(1 - q^{N_l})}{1 - q} \right] + \left[d_s \cdot PV_s \cdot \frac{q(1 - q^N)}{1 - q} + PV_s \cdot q^N \right] \quad (9)$$

The first term in square brackets of Equation (9) is related to the loan (PV_l), i.e., the amount of the system cost that is borrowed at an annual interest (i_l) to be repaid in N_l years. A possible tax rate (T) influence is also included and q is equal to $1/(1 + d)$.

The last term in square brackets in Equation (9) represents the equity share (PVs), with an annual return in the form of dividends (d_s) as compensation for the invested equity. This amount must be paid in full at the end of the system life cycle (N years).

The right-hand side of Equation (9) only equals its right-left side if the selected value of d is equal to the weight average cost of capital (WACC) of the investment, that is, the cost of the chosen financing.

In this study, the value of the nominal discount rate is assumed to be equal to the weighted average cost of capital (WACC), a widespread practice [22,31,32].

Once C_{EC} has been defined mathematically, its difference from LCOE is clearer. LCOE is often sufficient for utility-level comparisons. In that setting, PV cost competitiveness can be assessed by comparing LCOE with the wholesale electricity price. However, C_{EC} addresses a different question. It is tailored to the end user. Its calculation accounts for the share of PV electricity that is self-consumed, the portion exported to the grid, and the electricity imported from the grid. It also incorporates time-of-use (TOU) pricing and other user-specific consumption features over the PV system lifetime. This framework enables an annualized C_{EC} value (defined below). That value represents, in nominal monetary units, the cost per kWh of electricity actually consumed by the user. It can then be compared with the retail electricity price to assess PV self-consumption systems' competitiveness from the user's perspective, since both are expressed in nominal terms. Ultimately, this is what matters to the user.

2. Optimizing the array DC power rating sizing of the PV self-consumption system.

When sizing self-consumption PV systems, one of the most relevant decisions is to correctly attribute the optimal array DC power rating in view of the demand profile considered. In this work, the power will be based on the previously developed model for the calculation of the unit cost of electricity consumed of a PV self-consumption system from the user's perspective. Indeed, the array DC power rating sizing optimization criterion will be based on minimizing the unit cost of electricity consumed in a building equipped with a PV self-consumption system—assuming the orientation and tilt that maximize annual energy yield—from the user's point of view. To this end, the following parameters will be computed for a given array DC power rating range: (a) the value of C_{EC} across the specified array DC power rating range, (b) the optimal array DC power rating ($P_{0,opt}$, in kW), which corresponds to the maximum power at standard test conditions (STC) of the PV generator that minimizes C_{EC} ($C_{EC,min}$, in $\text{€}\cdot\text{kWh}^{-1}$). This procedure is illustrated in Figure 2. In this regard, the annualized value of $C_{EC,min}$ ($C_{EC,min,annualized}$, in $\text{€}\cdot\text{kWh}^{-1}$) will, for convenience, be referred to as the 'user-minimized annualized unit cost of electricity' from this point forward, and is expressed by Equation (10) [31]:

$$C_{EC,min,annualized} = \frac{C_{EC,min} \cdot E_L \cdot \frac{d(1+d)^N}{(1+d)^N - 1}}{E_{L,annual}} \quad (10)$$

where $E_{L,annual}$ is the annual load energy consumption of the building over the life cycle of the PV system (kWh) and is obtained by means of $E_{L,annual} = E_L/N$. To annualize a value, it must be multiplied by the capital recovery factor (CRF). The CRF is defined as follows:

$$CRF = \frac{d(1+d)^N}{(1+d)^N - 1} \quad (11)$$

Equation (10), the value to be annualized is $C_{EC,min} \cdot E_L$ and the result is then divided by $E_{L,annual}$ to obtain $C_{EC,min,annualized}$, in $\text{€}\cdot\text{kWh}^{-1}$.

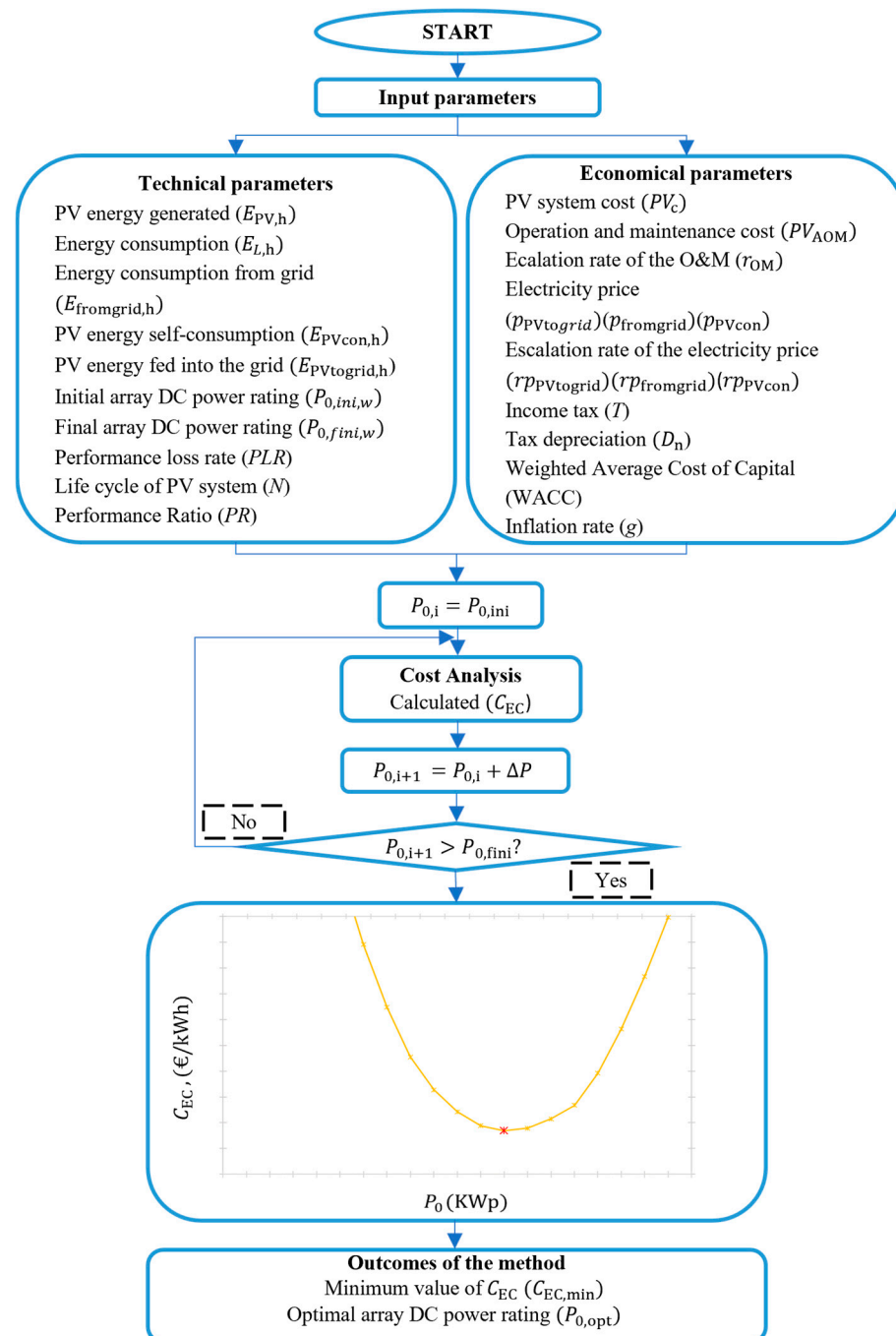


Figure 2. Flowchart of the procedure used to estimate $C_{EC,min}$ and $P_{0,opt}$ for buildings equipped with a PV self-consumption system for a given array DC power rating range. The symbol “*” denotes the optimal DC power rating, corresponding to the minimum value of C_{EC} .

3. Comparing the user-minimized annualized unit cost of electricity with the unit cost of the electricity tariff.

At this point, the only remaining step is to compare the user-minimized annualized unit cost of electricity obtained in Step 2 with the final unit cost of the electricity tariff according to the regulated user ($C_{unitFinal}$, in $\text{€} \cdot \text{kWh}^{-1}$). In this regard, if $C_{EC,min,annualized} < C_{unitFinal}$ the self-consumption PV system is considered cost-competitive. Conversely, if $C_{EC,min,annualized} > C_{unitFinal}$ it is not.

The calculation of most technical parameters shown in Figure 2 can be carried out using simulation tools such as SAM, PVsyst, or, more simply, PVGIS combined with a

spreadsheet—the latter being the option selected by the authors, as described in detail in the specific case study presented in Section 2.2. Regarding the system's life cycle, a duration of 25 or 30 years may be assumed. The performance loss rate of the system primarily depends on the PV technology used; however, a typical value of $0.5\% \cdot y^{-1}$ can be considered for state-of-the-art crystalline silicon PV systems. In the study by Louwen et al. [33], the initial and final array DC power ratings, in turn, depend on the specific self-consumption PV segment under investigation. The economic parameters presented in Figure 2 depend on the economic scenario in which the calculations are carried out.

The proposed method is readily applicable across countries due to the modular nature of the new model described above for calculating C_{EC} and its ability to accommodate a broad range of technical and economic conditions. In particular, Equation (3) accounts for energy-, system-, and taxation-related costs, while the use of hourly input data (e.g., PV generation, consumption profiles, and electricity prices) allows the framework to reflect diverse tariff designs and regulatory settings. Therefore, although the case study presented hereafter—by way of example of how to apply this method—considers a single country with flat tariffs and no storage, the method can be directly extended to other contexts by substituting the corresponding inputs, such as time-of-use or dynamic tariffs, different surplus export remuneration schemes (net billing, net metering, or other compensation mechanisms). Of course, battery operation strategies and their associated costs may be considered, in a way that in all cases, cross-country differences are captured through the input values and scenario definitions rather than changes to the new model structure, enabling consistent assessments of self-consumption PV cost competitiveness under varied economic and regulatory conditions.

It is worth noting that, although the *SCI* and *SSI* are not direct inputs in the calculation of either C_{EC} or $C_{EC,min}$, both constitute key output metrics that characterize the performance of the optimal configuration. In this economic analysis, both indices act as diagnostic and visualization tools, enabling users, policymakers, and other stakeholders to assess the influence the array DC power rating exerts on the system behavior. For instance, oversizing the array DC power rating may increase *SSI* (i.e., higher self-sufficiency) but simultaneously decrease *SCI*. This would lead to greater energy export to the grid and, consequently, a higher C_{EC} . The relationship between these parameters is illustrated in Section 3.

2.2. Demonstration of the Novel Method for Evaluating the Cost Competitiveness of Self-Consumption PV Systems: Case Study of Colombia

After presenting the novel approach to cost competitiveness of self-consumption PV systems in the previous section, Colombia is selected as a case study in which to apply it and demonstrate its practical implementation.

2.2.1. A Brief Overview of PV Self-Consumption in Colombia

Electricity demand has increased significantly in recent years in Colombia [34]. Laws 1715 of 2014 and 2099 of 2021 [29,35] regulate the integration of non-conventional renewable energy sources (RESs) into the National Interconnected System (NIS), including photovoltaic self-consumption, which operates under a net metering scheme defined in Law 1715. This scheme involves compensation offered by the grid operator to the owner of a self-consumption PV installation for injecting surplus energy into the grid. In this way, the user who engages in self-generation transforms from a consumer into a prosumer: an entity that actively participates in both the production and consumption of electricity [36–39].

In recent years, the Colombian electricity sector has been affected by a gradual increase in demand and a supply gap caused by extreme climatic events, such as the El Niño phenomenon. These conditions have had significant detrimental effects, particularly on hydropower, and are challenging the capacity of energy infrastructures to ensure a

continuous supply. In response, the Colombian government implemented Resolution 174 of 2021 [40], which integrates distributed generation (DG) into the National Interconnected System (NIS). Under this framework, 1 MW represents the maximum photovoltaic capacity permitted within the DG regime. This limit is further reduced for small-scale PV systems, also classified under the DG regime, which are defined as systems with a PV capacity of less than 0.1 MW.

To conduct the present study, different segments such as residential, commercial, and industrial were selected for analysis. Several scenarios for each segment were evaluated in different locations across Colombia. Subsequently, a description of the type of prosumer is provided, characterizing their consumption, the hourly price of energy purchased from the grid, and the surplus energy fed to the grid. The purchase and sale prices of electricity were obtained from various power grid operators. The remaining technical and economic parameters involved in the new model for obtaining the unit cost of electricity consumed in a building equipped with a PV self-consumption system from the user's perspective—as introduced in Section 2.1—are described below and estimated for the different scenarios considered in each sector under study.

2.2.2. PV Energy Production Estimation

The solar production profiles have been built with the PVGIS tool [41]. The PV energy production data used in this work consists of a value for every hour over a 1-year period. PV energy output is calculated from two sources, on the one hand, of the PV energy production data for each hour over a multi-year period, on the other hand, data from the typical meteorological year (TMY). All this data comes from the PVGIS tool, and the database used is shown in Table 1. The PVGIS-NSRDB dataset is provided by the National Renewable Energy Laboratory (NREL) and is part of the National Solar Radiation Database. For each specific month selected by PVGIS from the 2005–2015 period to generate the Typical Meteorological Year (TMY) for the site where the PV system will be installed, the corresponding month from the same period is utilized to determine the hourly AC output power values. These values are also derived using PVGIS, under the assumption that the output power remains constant throughout each hour. The calculations are based on a PV system with an array DC power rating of 1 kWp, resulting in 8760 hourly AC output power values. These values collectively represent a “typical yield year” (TYY₀), corresponding to year 0. In doing so, a 1-year dataset of values of hourly values of final system yield representative of every site is built.

Table 1. Solar radiation database used by the PVGIS tool for sites in Colombia.

Database	Type	Start Year	End Year	Spatial Res.	Comments
PVGIS- NSRDB	Satellite	2005	2015	0.038° × 0.038° (~4 km)	Default DB for the Americas (above 20S)

The tilt and orientation of simulated self-consumption PV systems is optimized, and monofacial crystalline silicon (c-Si) PV modules are used. The estimated system losses cause the power actually delivered to the electricity grid to be lower than the power produced by the PV modules. There are several causes for this fact, such as ohmic losses in cables, inverter efficiency, soiling on the modules, etc. A default value of 14% for the overall losses was set in the analysis—excluded those losses caused by the angle of incidence (AOI), spectral effects, temperature and low irradiance. Additionally, information about the local horizon to estimate the effects of shadows from nearby hills or mountains is used in the calculation of PV systems output in PVGIS. Performance ratio typically ranges from 0.70 to 0.80 for conventional PV systems in warm climates [41].

The PVGIS-NSRDB dataset, provided by the National Renewable Energy Laboratory (NREL), is part of the National Solar Radiation Database (NSRDB) [42], which provides meteorological data corresponding to sites with values of latitude and longitude within which Colombia is located. This database provides detailed information on solar radiation, mainly used for research and development of photovoltaic systems. A comparison with other climate databases, such as Meteonorm and the meteorological database of NASA—known as the NASA POWER (Prediction of Worldwide Energy Resources)—was performed and it was found that PVGIS and Meteonorm showed a smaller difference in year-to-year variability, averaging 4.16% for the locations to be studied in what follows. Finally, it was decided not to use Meteonorm and NASA POWER due to their lower accuracy, especially in mountainous areas such as Colombia, since these databases provide synthetic data, as opposed to high-resolution temporal and spatial data publicly available through PVGIS.

2.2.3. Demand Profiles

To define representative demand profiles, three categories have been created corresponding to the residential, commercial and industry segments. The residential segment was divided into six types of profiles according to socio-economic criteria (stratum 1, stratum 2, stratum 3, stratum 4, stratum 5 and stratum 6), the commercial segment encompasses different retail profiles (commercial 1 and commercial 2); finally, the industry segment is characterized by means of two different profiles (Industry 1, Industry 2). All the demand profiles considered were accessed from real data provided by [34,43–47].

Residential Segment

The technique employed to derive a representative residential consumption profile for each of the six socio-economic strata involved the use of characteristic algorithms, such as Multidimensional Scaling (MDS) analysis [48]. This statistical method enables the graphical representation of data similarities, facilitating the visualization of relationships within the dataset. The procedure was carried out through the following steps. It begins with the extraction of average electrical energy consumption from large datasets, where the most characteristic consumption patterns are identified. This is performed for a sample of users belonging to the same socio-economic stratum across the different localities analyzed. Additionally, the influence of geographical factors, such as the temperature of the localities and the users' activity calendar, has been examined. On the demographic side, the number of users comprising a family unit is also considered, with an average of 2.9 people per household, representing the typical size of a Colombian family [49].

As previously mentioned, six representative profiles were considered for the residential segment, categorized according to socioeconomic strata. The data were obtained from various sources [34,45,50–52]. Additionally, the allowance average hourly consumption profiles for a typical day for each stratum were provided by the Unified Information System of Public Utility Services of Colombia [53].

Due to the limited implementation of smart metering systems and advanced metering infrastructure (AMI) [54] among Colombian users, particularly in the residential segment, it is not possible to obtain hourly digitalized records of daily electricity consumption in kWh. Instead, only monthly consumption data collected through traditional meters—either electromechanical or electronic—are available. These monthly consumption records were randomly collected in groups of 30 users per socioeconomic stratum in each locality.

Using the MDS statistical method, the distribution that best reflected the behavior of 80% of the data was identified, allowing the necessary parameters to be obtained to construct a daily consumption curve. True, constructing hourly consumption profiles from monthly data, using MDS and representative patterns, entails inherent limitations. This approach tends

to smooth short-term fluctuations and underestimate potential peak demand events, which may introduce bias in estimating *SCI*, *SSI*, and in optimizing the array DC power rating. A sensitivity analysis using alternative profiles with higher peak-hour concentration would likely show that, although absolute indicator values may vary, the overall trends and key conclusions remain consistent, though this issue warrants further investigation. Access to higher time-resolution data, such as that provided by smart meters, would help mitigate these limitations and represents an important direction for future research.

The generated daily consumption curves were compared with consumption profiles from various electricity companies, validating that the data accurately capture the real consumption behavior for each socioeconomic stratum. Once the consumption profile was verified, the average monthly electricity consumption for each month was determined. Subsequently, the average of these monthly values over the course of a year was calculated to obtain a single value representing the annual average global consumption for this segment.

The (a) and (b) panels of Figure 3 illustrate the annual average hourly electricity consumption profiles in the residential segment for a typical working day and a holiday, respectively, derived from the monthly average electricity consumption values presented in Table 2. In its calculation, the variability in the length of the months has been considered, including those of 28, 30 and 31 days, in order to ensure an accurate representation of consumption behavior throughout the year. Stratum 1 represents the consumption profile of a working couple who are only at home during nighttime, with an average annual demand of 1177 kWh/year. Stratum 2 depicts the consumption profile of a working couple with three children, who are present at home in the late afternoon and evening, with an average annual demand of 1427 kWh/year. Stratum 3 represents the profile of a working couple with two children, who have greater home presence during nighttime, with an average annual demand of 1625 kWh/year. Stratum 4 corresponds to the profile of a retired couple who are at home all day and only leave for brief, specific activities, with an average annual demand of 1909 kWh/year. Stratum 5 depicts the profile of a working couple with three children, where activities are split with half-day work at home, having an average annual demand of 2254 kWh/year. Finally, Stratum 6 represents a working couple with two children who have greater home presence during nighttime, with daytime presence of service personnel, and an average annual demand of 3211 kWh/year.

Although some aspects have been detailed earlier—implicitly in certain cases—it is worth summarizing that residential load profiles were constructed considering three key factors: household activity patterns, local temperature, and the number of residents. Typical daily schedules of Colombian households were derived from national time-use studies, capturing morning and evening consumption peaks associated with work, school, and meal times. Since residential heating demand is negligible in Colombia, temperature effects were mainly linked to the use of fans and air conditioners in warm regions and water heaters in colder areas, with profiles adjusted accordingly. The number of residents per household, obtained from DANE data, was incorporated as a scaling factor that proportionally increases demand and modifies the curve shape, as larger households tend to exhibit more extended appliance use. Together, these factors determined the shape and magnitude of the hourly load curves, ensuring that the resulting profiles accurately represent the diversity of residential conditions across Colombia.

Table 2. Annual average monthly electricity consumption according to stratum for the residential segment in Colombia (data sourced from grid operators XM and DANE).

Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 5	Stratum 6
98 kWh	118 kWh	135 kWh	159 kWh	187 kWh	267 kWh

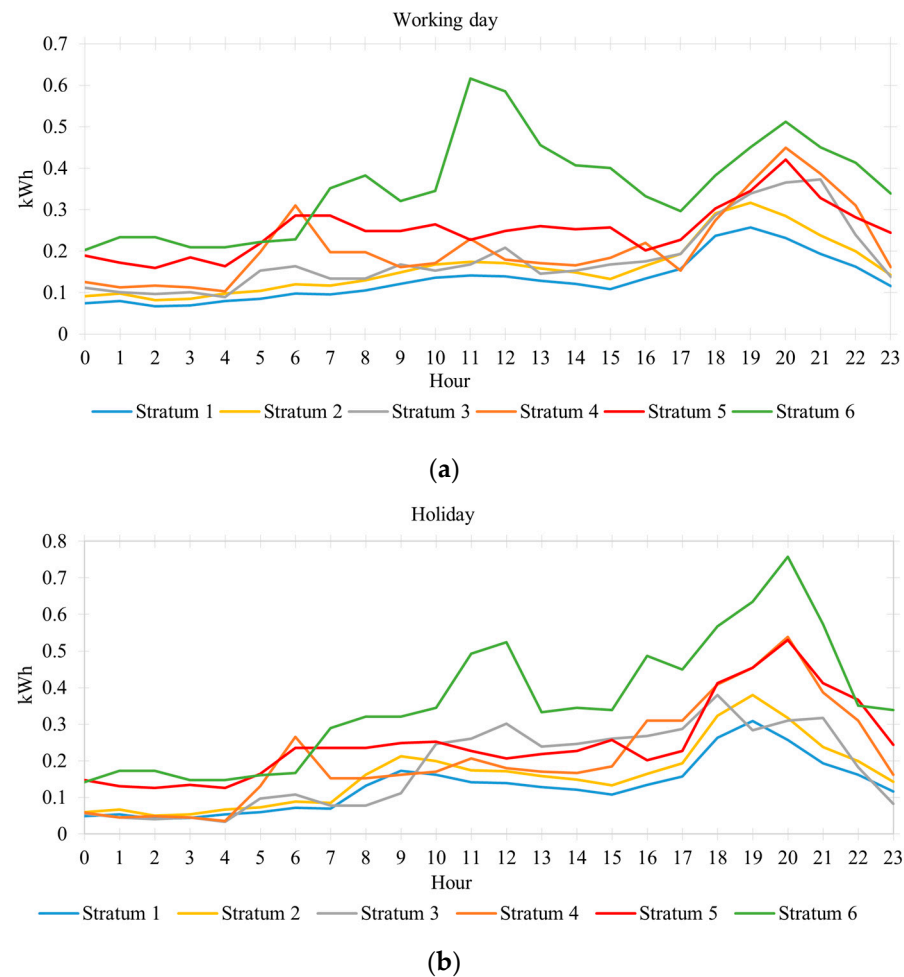


Figure 3. Annual average hourly consumption profiles of a typical working day in the Colombian residential segment (a). Annual average hourly consumption profiles of a typical holiday in the Colombian residential segment (b).

Commercial and Industrial Segment

In the commercial segment, various groupings are considered. Average monthly consumption records are obtained from databases or provided by either users or electricity distribution companies. As in the residential segment, the average monthly consumption was calculated by dividing representative samples of average annual consumption by 12. Subsequently, the annual average daily consumption values were determined, considering the variability in the length of months, including those of 28, 30 and 31 days. This approach ensures an accurate and detailed representation of consumption behavior throughout the year. This annual average daily consumption was then distributed across the hours of the day following an average hourly pattern, designed according to the specific characteristics of commercial and industrial activities in the country. Such hourly patterns are provided by electricity retail companies.

Commercial Profile 1 encompasses retail businesses, where electricity consumption is primarily concentrated during daytime working hours, while remaining at baseline levels during nights and weekends. In contrast, Commercial Profile 2 corresponds to the services sector, which exhibits a similar consumption pattern on weekdays but tends to register higher levels during weekends and holidays.

Figure 4a illustrates a typical weekday and holiday for Commercial Profile 1, which corresponds to retail businesses operating a 9-h daytime shift plus 4 additional overtime hours, with an annual electricity demand below 2160 kWh/year. Commercial Profile 2—Figure 4b—re-

presents restaurant chains located in shopping malls, operating for a 9-h daytime shift plus an additional 3 overtime hours, with an average annual demand of 8640 kWh/year.

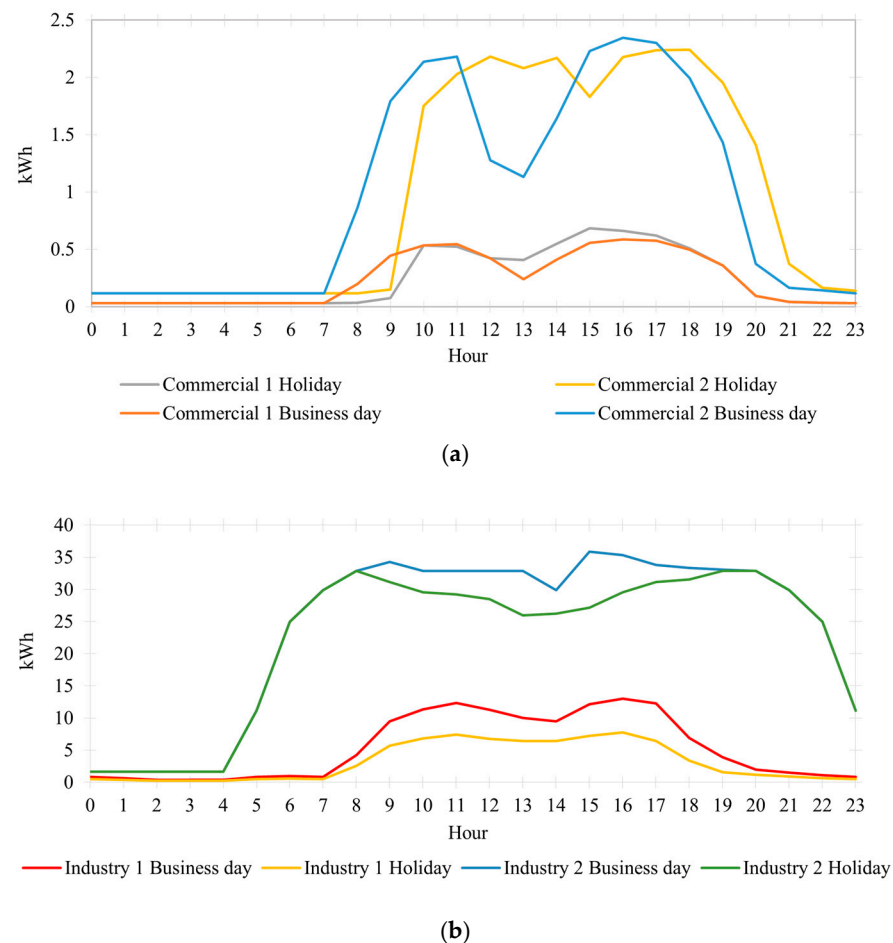


Figure 4. Annual average hourly consumption profiles of a typical business day and a typical holiday in the Colombian segment commercial (a) and industrial (b).

In the industrial sector, generating annual average hourly consumption profiles from annual monthly average consumption data is a more complex process due to the diversity inherent in this sector. Each industry exhibits unique characteristics in its production processes, operating schedules, and specific energy demands, which complicates the development of a standardized consumption profile. In this regard, for the classification of industries, various operational characteristics were considered. Regarding their size, two categories were assumed: small industries, with an assigned electrical capacity of 150 kVA in their transformation center, and medium-sized industries, with a capacity of 300 kVA. Concerning operating schedules, a distinction was made between those with a single work shift and those with rotating shifts, where productivity exhibits peak consumption during active hours and low or negligible levels outside this period. For this analysis, consumption profiles were divided into two categories: hourly profiles representing annual averages for weekdays and hourly profiles for annual averages on weekends and holidays, the latter reflecting lower electricity demand. These categories are represented by Industrial Profile 1 and Industrial Profile 2 showcasing variations in energy consumption according to economic activity.

Figure 4b, depicts the annual average hourly consumption profiles on working days and holidays within the industrial sector. The characterization of consumption in this sector is more complex due to the diversity of activities and operational patterns. In general

terms, industry maintains a stable consumption profile during working days, with regular usage, while during public holidays it tends to be slightly lower. These profiles result from a clustering process based on 30 consumption patterns provided by users engaged in different economic activities. The clustering was carried out in two stages. First, analysis of demand and consumption patterns, where profiles were classified according to maximum hourly demand (kWh) and similarities in daily patterns obtained from annual data. In the second stage, segmentation by industry size where small- and medium-sized industries were differentiated to establish a representative consumption profile. To obtain the annual average hourly consumption for a typical working day and public holiday, the monthly average consumption was first calculated by dividing the annual average consumption by 12. Subsequently, the annual average daily consumption values were determined, taking into account the variability in the length of the months (28, 30 and 31 days). Finally, the annual average daily consumption was distributed among the hours of the day following an average hourly pattern, designed according to the specific characteristics of the industrial sector. Within this classification, two groups were identified, Industry 1 and Industry 2, with an average annual demand of 43,560 kWh/year and 210,000 kWh/year, respectively.

The use of aggregated monthly data and average hourly profiles for the commercial and industrial sectors entails certain limitations, as these do not capture facility-specific variability or demand peaks. In Colombia, access to detailed hourly data at the establishment level is limited due to the scarcity of disaggregated measurements. Nevertheless, this approach enables the characterization of general consumption patterns and the development of representative segment profiles, suitable for energy planning and aggregated scenario modeling. The results are not intended to replace site-specific analyses, which require direct measurements to reflect operational variability and peak demand behavior. The obtained profiles describe the average performance of these segments in Colombia, providing valuable insight for macro-level demand analysis, while future work should aim to expand the database with higher-resolution data to improve accuracy in specific industrial and commercial contexts.

In summary, the residential, commercial, and industrial load profiles developed in this Section capture the representative consumption behavior of each sector in Colombia, integrating both behavioral and climatic factors. Although based on aggregated and averaged data, the adopted approach provides a consistent framework for cross-sectoral comparison and for assessing PV self-consumption performance and economic feasibility. These profiles therefore serve as the analytical foundation for this Section, which presents the main results and discusses how sectoral consumption patterns influence the results obtained.

2.2.4. Cost Model Parameters

This study considers self-consumption PV systems, in which their surplus electricity generated is fed into the grid ($E_{PV_{\text{tgrid}}}$) and the owner of the PV system receives compensation from the grid operator based on regulated prices ($p_{PV_{\text{tgrid}}}$). The self-consumed electricity ($E_{PV_{\text{con}}}$) is remunerated (saved) based on retail market prices $p_{PV_{\text{con}}}$.

Currently, the cost of PV systems per kWp continues to decrease due to economies of scale and the learning curve of the main components in PV systems [55,56]. In the case of Colombia in 2022, the average cost of a PV system is shown in Table 3 [57–59]. In this study, the conversion rates of Colombian pesos and US dollars to euros are as follows: 1 EUR = 4471.68 COP, and 1 EUR = 1.0530 USD (annual average for 2022) [60,61].

Electricity prices $p_{PV_{\text{tgrid}}}$, p_{fromgrid} and $p_{PV_{\text{con}}}$ depend on government regulations for self-consumption and the electricity market of each country. In Colombia, the electricity tariff composition is determined through a process regulated by the Energy and Gas Regulatory Commission (CREG, that stands for *Comisión de Regulación de Energía*

y Gas, in Spanish), which involves six independent components: generation cost (C_{Gen} , in $\text{€}\cdot\text{kWh}^{-1}$), transmission cost (C_{Tra} , in $\text{€}\cdot\text{kWh}^{-1}$), distribution cost (C_{Dis} , in $\text{€}\cdot\text{kWh}^{-1}$), commercialization cost (C_{Com} , in $\text{€}\cdot\text{kWh}^{-1}$), losses cost (C_{Loss} , in $\text{€}\cdot\text{kWh}^{-1}$) and restrictions cost (C_{Res} , in $\text{€}\cdot\text{kWh}^{-1}$). The CREG conducts periodic analyses to establish electricity tariffs by combining these six elements with other factors present in the national economy, such as Colombian market inflation, the source of electricity generation, or uncertainty due to environmental phenomena.

Table 3. Average cost of a self-consumption PV system in Colombia as a function of its array DC power rating.

Array DC Power Rating (kWp)	Unit Cost ($\text{€}\cdot\text{kWp}^{-1}$)
1–5	831
6–10	823
11–20	815
21–40	806
41–80	798
>81	790

As shown hereafter, C_{unit} is involved in the calculation of the price charged for each unit of electricity consumed. The composition of the unit cost of the electricity tariff (C_{unit} , in $\text{€}\cdot\text{kWh}^{-1}$) is derived from the weighted average of the six components mentioned above, and is given by Equation (12).

The C_{unit} is updated dynamically according to supply and demand, based on economic price indices and regulations. The Consumer Price Index (CPI) or other region-specific indices track variations in the prices of goods and services. These indices allow for periodic cost adjustments to reflect general economic changes [62].

$$C_{unit} = C_{Gen} \cdot 0.355 + C_{Tra} \cdot 0.063 + C_{Dis} \cdot 0.389 + C_{Com} \cdot 0.105 + C_{Loss} \cdot 0.0525 + C_{Res} \cdot 0.038 \quad (12)$$

In Colombia, the cost of the electricity bill includes subsidies and contributions that regulated users either receive or contribute, based on their final unit cost of the electricity tariff according to the regulated user ($C_{unitFinal}$, in $\text{€}\cdot\text{kWh}^{-1}$). This parameter is essential for calculating the total amount to be paid on an electricity bill, by multiplying the total consumption by $C_{unitFinal}$ [63]. The values of $C_{unitFinal}$ are determined in a stratified manner based on C_{unit} , as shown in Table 4 [64,65].

Table 4. Final unit cost of the electricity tariff according to the regulated user ($C_{unitFinal}$, in $\text{€}\cdot\text{kWh}^{-1}$).

Segment	Regulated User	$C_{unitFinal}$	Maximum Monthly Subsidized Consumption Limit for Strata 1, 2 and 3	
Residential	Stratum 1	$(C_{unit}) \cdot (1 - 0.60)$	130 kWh/month (*) for populations located above 1000 m.a.s.l. with a cold temperate climate.	173 kWh/month (*) for populations located below 1000 m.a.s.l. in a warm climate.
	Stratum 2	$(C_{unit}) \cdot (1 - 0.50)$		
	Stratum 3	$(C_{unit}) \cdot (1 - 0.15)$		
	Stratum 4	(C_{unit})		
	Strata 5 and 6	$(C_{unit}) \cdot (1 + 0.20)$		
Commercial Industry	Commercial	$(C_{unit}) \cdot (1 + 0.20)$		
	Industry	$(C_{unit}) \cdot (1 + 0.20)$		

(*) For consumption exceeding these values, the user is charged the unit cost (C_{unit}).

To estimate the electricity prices involved in this study, data from the main grid operators—representing 61.7% of users connected to the National Interconnected System (NIS)—were used. Parameter $C_{unitFinal}$ in Colombia can vary according to different contracting models, specifically depending on who owns the physical assets (transformer,

connection and meter). When the physical assets are owned by the grid operator, costs may be transferred to users in the form of a higher value of $C_{\text{unitFinal}}$. For this study, the least favorable scenario for $C_{\text{unitFinal}}$ (physical assets owned by the grid operator) was chosen. The electricity prices of p_{fromgrid} and p_{PVcon} for the different segments under study were based on the value established by the grid operator in $C_{\text{unitFinal}}$, as decreed by CREG Resolution 119 of 2007. The price for p_{PVtogrid} was determined based on market prices [66–70].

In the different segments PV electricity surpluses fed to the grid may be paid according to the concept called hourly spot price of the electricity (P_{Bol} , in $\text{€} \cdot \text{kWh}^{-1}$), which refers to the price at which energy is traded; the P_{Bol} considers a balance point between the supply and demand of energy for each hour of the day. The price can vary significantly depending on factors such as the availability of energy resources and associated demand. The value of P_{Bol} is set through a daily auction process known as the wholesale energy market (MEM, as the initials of *Mercado de Energía Mayorista* in Spanish) [71]. The average value for P_{Bol} during the period 2017–2022 was equivalent to 33.59% of C_{unit} [72]. Table 5 represents the process for the cases with and without energy surplus according to the array DC power rating, in order to establish the price of remuneration or payment for electricity, whether for self-consumption, surpluses or energy demand.

Table 5. Unit remuneration and payment of electricity for PV self-consumption systems in Colombia (Resolution 174 of 2021, CREG). *N.B:* $E_{\text{PVtogrid},m}$ and $E_{\text{fromgrid},m}$ are the monthly PV-generated electricity fed into the grid and the monthly electricity taken from the grid, respectively (kWh).

User	Array DC Power Rating	Case	Price of Remuneration of Electricity		Price of Payment of Electricity
			p_{PVcon}	p_{PVtogrid}	p_{fromgrid}
Group 1	[0, 100] kW	No energy fed into the grid		0	
		Energy fed into the grid without monthly energy surplus ($E_{\text{PVtogrid},m} < E_{\text{fromgrid},m}$)		$C_{\text{unit}} - C_{\text{com}}$	
		Energy fed into the grid with monthly energy surplus ($E_{\text{PVtogrid},m} > E_{\text{fromgrid},m}$)	$C_{\text{unitFinal}}$	Up to $E_{\text{fromgrid},m}$: $C_{\text{unit}} - C_{\text{com}}$ From $E_{\text{fromgrid},m}$: P_{Bol}	$C_{\text{unitFinal}}$
Group 2	[100, 1000] kW	No energy fed into the grid		0	
		Energy fed into the grid without monthly energy surplus ($E_{\text{PVtogrid},m} < E_{\text{fromgrid},m}$)		$C_{\text{unit}} - C_{\text{com}} - C_{\text{tra}} - C_{\text{dis}} - C_{\text{loss}} - C_{\text{res}}$	
		Energy fed into the grid with monthly energy surplus ($E_{\text{PVtogrid},m} > E_{\text{fromgrid},m}$)		P_{Bol}	

The percentage P_{Bol} [72] exhibits variations from year to year according to extreme meteorological phenomena such as the “La Niña” or “El Niño” phenomena, mainly due to Colombia’s energy matrix which is mostly based on hydroelectricity. The annual escalation rate of the electricity price from the grid (p_{fromgrid}) is linked to the evolution of the electricity markets and it is difficult to predict its value. Based on the evolution of electricity prices in Colombia’s regulated market, data from nine annual periods (2015–2023) were analyzed [73,74]. Considering these data series, an average year-on-year variation of 1.31% has been assumed for C_{unit} in all subsequent calculations.

In general, the cost of the PV system can present mixed financing, as outlined in the United Nations report [75]. This financing primarily consists of debt and equity capital. For the entire residential sector, the financing will be 100% of the investment cost (PV_C) with own resources. In commercial sectors and industrial sectors, long-term debt financing is referenced, composed of a loan (PV_1 , in €) with an average amount of 42.5% of the investment cost (PV_C) [76] for the period 2008–2023. The remaining 57.5% of the

investment cost is financed through equity capital (PVs , in €). In less stable economies like Colombia, banks tend to accept lower leverage, making property rights a crucial resource when granting loans—particularly in the commercial and industrial sectors. The guarantee of property rights serves as a key factor in ensuring protection and minimizing the risk of loss for the banking sector [77,78]. The loan interest rate (i_l) is set at 9.11% [79] with an amortization period (N_l , in years) of 10 years [80,81]. Regarding equity capital, the annual dividend of the equity capital (d_s) is set equal to 15.16% [82,83], which is the average value during the period 2000–2021 in the commercial and industrial sectors. For the residential sector, over the period 2017–2021, an average value of 4.81% is considered for d_s . This value is determined based on three key parameters, indicating the correlation or significant statistical measure between different economic indicators, such as the consumer price index (CPI), the deposit facility rate (DFT) and the time deposit certificates (TDCs) [84–87].

As previously discussed in this study, the nominal discount rate is assumed to be equivalent to the weighted average cost of capital (WACC) for calculating the cost of electricity consumed from the perspective of the user, generated in a building equipped with a PV self-consumption system.

This capital cost will vary depending on how the capital resources are chosen to finance the PV system cost. The income tax rate (T) for the organization or taxpayer varies depending on each country's regulations. Specifically, in Colombia, this tax showed an average value of 35.29% for the period 2003–2023 [88]. Typically, an annual performance loss rate of $0.5\% \cdot y^{-1}$ is assumed during the PV system useful life [89–91]. Indeed, this rate of performance decline is considered representative of crystalline-silicon-based PV systems, the technology that dominates the market—98% in 2024 [92]. However, if other PV materials were considered in the analysis presented in this work, the assumed PLR value should be adjusted accordingly. In this context, and by way of example, it is worth noting a recent and valuable study by Wu et al. [93] on commercializing perovskite solar cells as a promising and emerging PV technology. Nevertheless, further research is needed to estimate reliable PLR values for this PV material [93]. Regarding the annual inflation rate (g , in %), an average value of $g = 4.3\%$ has been considered for Colombia, based on data from the period 2008–2022 [94,95].

The annual operation and maintenance costs (PV_{AOM}) should be considered as the percentage of PV_C spent on operation and maintenance tasks on an annual basis. In this case, it has been considered 1.5% of PV_C [6]. Additionally, these costs will also be increased year-on-year by an annual escalation rate (r_{OM}). This latter parameter is set equal to the value of the inflation rate, so that $r_{OM} = 4.3\%$.

In this sense, the values assumed for every parameter that defines the proposed study cases (five Colombian cities) are gathered in Table 6. Parameters p_{PVcon} and $p_{fromgrid}$ are equal to $C_{unitFinal}$ and parameter $rp_{fromgrid}$ is set equal to $rp_{PVtogrid}$ and rp_{PVcon} .

Table 6. Assumed values of technical and economic parameters for the proposed cases of study.

Parameters	Stratum						Commercial		Industry		
	1	2	3	4	5	6	1	2	1	2	Units
Case PV_C	Values for the city of Medellín						823	806	790		€·kWp ^{−1}
$C_{unitFinal}$	5.85	7.58	11.73	13.80			16.56				¢€·kWh ^{−1}
Case PV_C	Values for the city of Bogotá						823	806	790		€·kWp ^{−1}
$C_{unitFinal}$	5.65	7.16	11.34	13.36			16.26				¢€·kWh ^{−1}
Case PV_C	Values for the city of Cúcuta						823	806	790		€·kWp ^{−1}
$C_{unitFinal}$	5.96	7.43	11.83	14.17			17.25				¢€·kWh ^{−1}

Table 6. Cont.

Parameters	Stratum						Commercial		Industry		
	1	2	3	4	5	6	1	2	1	2	Units
Case	Values for the city of Barranquilla										
PV_C				831			823	806		790	$\text{€} \cdot \text{kWp}^{-1}$
$C_{\text{unitFinal}}$	5.61	6.55	11.22	13.02			15.62				$\text{c€} \cdot \text{kWh}^{-1}$
Case	Values for the city of Cali										
PV_C				831			823	806		790	$\text{€} \cdot \text{kWp}^{-1}$
$C_{\text{unitFinal}}$	6.06	7.57	12.17	14.31			17.18				$\text{c€} \cdot \text{kWh}^{-1}$
PV_l				0				42.5			%
PV_s				100				57.5			%
P_{bol}						4.45					$\text{c€} \cdot \text{kWh}^{-1}$
PRL						0.5					%
$r_{\text{pfromgrid}}$						1.31					%
PV_{AOM}						1.5					%
r_{OM}						4.3					%
T				0				35.29			%
g						4.3					%
i_l				0				9.11			%
N_l				0				10			year
d_s				4.81				15.16			%
N						25					year
D_n				0			2.77	2.74	2.68	2.63	$\text{€} \cdot \text{kWp}^{-1}$
N_d				0				3			years

In Colombia, the residential and commercial segments do not operate under peak and off-peak hours but rather under a fixed electricity rate, as shown in Table 6. As discussed earlier, this is due to the absence of smart metering systems. TOU metering is applied only in the industrial segment, specifically for facilities with high energy demand and power ratings exceeding 55 kW, which are connected to the grid at medium voltage greater than 1 kV. The present study, however, focuses exclusively on companies operating at voltages up to 1 kV.

3. Results and Discussion

In this section, the novel method described in Section 2.1 is used to determine the optimal array DC power rating, by minimizing the unit cost of electricity consumed from the user's point of view ($C_{\text{EC,min}}$); then annualized, for each case of study in the residential, commercial, and industrial segments. Additionally, *SCI* and *SSI* are calculated according to Equations (1) and (2).

This investigation will be conducted in five locations in Colombia: Medellín, Bogotá, Cúcuta, Barranquilla, and Cali. For each location, 10 cases will be analyzed: 6 in the residential segment, 2 in the commercial segment, and 2 in the industrial segment. The values of the parameters involved in each case study of the mentioned segments are shown in Table 6, with the demand profiles described in Sections Residential Segment and Commercial and Industrial Segment.

Figure 5a graphically illustrates the procedure for the calculation of the optimal array DC power rating for self-consumption PV systems corresponding to the location of Medellín, in northwest Colombia, and the residential segment, stratum 3. This example serves to illustrate the procedure applied to all case studies across the five cities under investigation. In this specific case of study, the optimal array DC power rating was found to be equal to 1.9 kWp, which corresponds to the minimum C_{EC} value ($C_{\text{EC,min}}$) of $3.81 \text{ c€} \cdot \text{kWh}^{-1}$, which in turn corresponds to a value of $C_{\text{EC,min,annualized}}$ of $6.65 \text{ c€} \cdot \text{kWh}^{-1}$, according to Equation (9). Its *SCI* and *SSI* indices equal 24% and 41%, respectively. In this case, $C_{\text{EC,min,annualized}}$ is far lower than p_{fromgrid} ($C_{\text{unitFinal}}$), which equals $11.73 \text{ c€} \cdot \text{kWh}^{-1}$.

This makes the unit cost of electricity from the user's point of view utilizing a self-consumption PV system competitive in comparison to grid electricity prices.

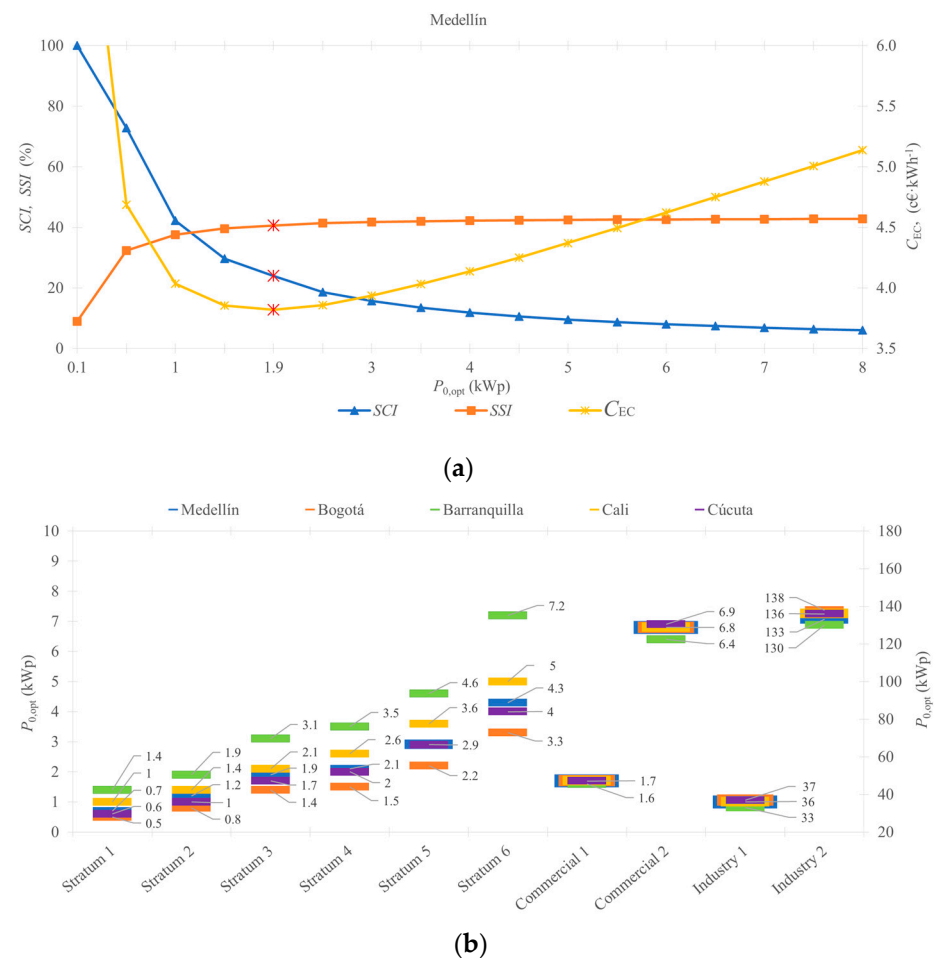


Figure 5. Values of SCI , SSI and $C_{EC,min}$ as a function of the DC array power rating for Medellín (northwest Colombia) in stratum 3 (residential segment). The red symbol “*” indicates the values of SCI , SSI and C_{EC} corresponding to the optimal array DC power rating (a). Values of optimal array DC power rating calculated for self-consumption PV systems across the groupings inside the segments studied for the five locations investigated (b).

The results presented in Figure 5b indicate that, for the six strata analyzed in the residential segment, the optimal array DC power rating values across the different locations, ranked from highest to lowest, correspond to Barranquilla, Cali, Medellín, Cúcuta, and Bogotá. This can be attributed primarily to the values of annual average horizontal irradiation (H_a (0), in kWh·m⁻²), combined with the absence of a cap on the amount of remunerated electricity fed into the grid. Such values of H_a (0) are 2024 kWh·m⁻² in Barranquilla, 1936 kWh·m⁻² in Cali, 1863 kWh·m⁻² in Medellín, 1802 kWh·m⁻² in Cúcuta, and 1655 kWh·m⁻² in Bogotá. Within the residential segment, a comparison across strata shows that the range of variation in the optimal array DC power rating is 0.9, 1.1, and 1.7 kWp for strata 1, 2, and 3, respectively, while in stratum 4, it increases to 2.0 kWp. In the upper strata 5 and 6, the optimal array DC power rating varies by 2.4 and 3.9 kWp, respectively. These differences are attributed to the underlying consumption profiles, with stratum 6 exhibiting the highest consumption and stratum 1 the lowest. Regarding the commercial segment, the consumption profiles peak coincides significantly with the higher electricity generation hours of the PV system. For commercial case 1, the values of $P_{0,opt}$ closely match for all the locations studied, varying by a maximum of 0.1 kWp between

them. For commercial case 2, which presents a higher consumption profile, the differences in $P_{0,opt}$ do not exceed 0.5 kWp between the locations under scrutiny with the lowest and highest values of this parameter corresponding to Barranquilla and Bogotá, respectively, which also represent the locations with the highest and lowest solar resource, respectively.

In the industrial segment, for case Industry 1, representing an industry with a single daytime shift, values found for $P_{0,opt}$ lie within 33 and 37 kWp for the locations studied. For industry case 2, which represents an industry with a workday distributed over two shifts, the matching between generation and consumption is less favorable compared to Industry Case 1. In this scenario, the largest difference in $P_{0,opt}$ values is observed between Barranquilla and Bogotá, amounting to 8 kWp. As observed in the industrial segment, the lowest and highest values of this parameter correspond to Barranquilla and Bogotá, respectively. This is again consistent with their solar resource levels—Barranquilla having the highest and Bogotá the lowest—and the absence of a cap on remunerated electricity fed into the grid in Colombia.

Figure 6 illustrates the *SCI* and *SSI* values obtained in this study for a building equipped with a self-consumption PV system—sized according to the optimal DC power rating shown in Figure 5b—within each grouping across the different segments. In Figure 6a strata 1 and 2 groupings in the residential sector display the highest values of *SCI*, whereas these strata exhibit low values of *SSI*, as shown in Figure 6b. This is due to their relatively low optimal array DC power rating, which ranges from 0.5 to 1.9 kWp. Strata 5 and 6 in the residential sector exhibit the lowest *SCI* values, while simultaneously showing the highest *SSI* percentages. This is primarily due to their higher optimal array DC power ratings, which range from 2.2 to 7.2 kWp—values that help offset their higher energy consumption profiles compared to those of the lower strata. In the commercial segment, commercial groupings 1 and 2 exhibit similar and higher *SCI* (54–56%) and *SSI* values (57–65%). This is due to the fact that a large part of their consumption is diurnal, coinciding with photovoltaic generation, and their $P_{0,opt}$ values do not vary by more than 0.5 kWp for each grouping. In the industrial segment, Industry 1 grouping exhibits higher *SSI* values compared to those of Industry 2. This discrepancy is largely attributed to the extended working hours in Industry 2, leading to a more pronounced mismatch between PV energy generation and the consumption profile.

Overall, the location of Bogotá shows the highest *SCI* values, while Barranquilla presents the lowest *SCI* values in almost all study cases. Regarding *SSI*, Barranquilla and Cali exhibit the highest values across all segments, ranging from 42% to 72%, with Cúcuta and Medellín positioned as the third location with the highest *SSI* values within the residential segment. Interestingly, Bogotá exhibits the lowest values of *SSI* across all segments.

Figure 7a shows the results obtained for the user-minimized annualized unit cost of electricity ($C_{EC,min,annualized}$) obtained by the method presented in this work. As discussed before, this parameter represents a constant value of $C_{EC,min}$ over the PV system's useful life. In the residential segment, across most socioeconomic strata, Bogotá shows the highest values of the former parameter, while Barranquilla presents the lowest, ranging from 3.66 to 8.28 c€/kWh^{−1} across the six strata investigated. Additionally, values of $C_{EC,min,annualized}$ are lower than those of the final unit cost of the electricity tariff according to the regulated user ($C_{unitFinal}$) across all strata, thus making self-consumption PV systems—sized with $P_{0,opt}$ —cost-competitive in the residential segment.

In the commercial 1 grouping, the following rank emerges when ordering the locations from highest to lowest values of $C_{EC,min,annualized}$: Bogotá, Medellín, Cúcuta, Barranquilla, and Cali, this parameter ranging from 4.49 to 8.85 c€/kWh^{−1}. In the commercial 2 grouping, the following rank emerges when ordering the locations from highest to lowest values

of $C_{EC,min,annualized}$: Bogotá, Cúcuta, Medellín, Barranquilla, and Cali, this parameter ranging from 3.22 to 7.48 $\text{c}\epsilon \cdot \text{kWh}^{-1}$. In the industrial segment, ordering the locations from highest to lowest $C_{EC,min,annualized}$ value, the following rank becomes apparent: Bogotá, Medellín, representing the highest values, while Cali in Industry 1 and Barranquilla in Industry 2 groupings exhibit the lowest values of 0.35 and 6.11 $\text{c}\epsilon \cdot \text{kWh}^{-1}$, respectively. The notably low values of $C_{EC,min,annualized}$ for both the commercial and industrial segments are mainly due to the relatively high values of SCI and SSI . This fact makes the present worth of money savings due to PV energy self-consumed ($PW[CE_{PVcon}]$) significantly contribute to reducing $C_{EC,min}$. Moreover, the inclusion of taxes (T) means that the value of tax depreciation also contributes to reducing $C_{EC,min}$. In both commercial and industrial segments, the $C_{EC,min,annualized}$ values are lower than those of final unit cost of the electricity tariff according to the regulated user ($C_{unitFinal}$) in the five groupings studied inside these segments, thus making self-consumption PV systems cost-competitive.

It should be noted again that the regulatory framework for self-consumption PV systems in Colombia does not limit the surplus energy ($E_{PVtogrid}$) that can be injected into the grid. Therefore, the term $PW[CE_{PVtogrid}(N)]$ can significantly affect the reduction in C_{EC} . This fact, along with those previously mentioned, contributes to the value of this parameter approaching zero, as observed in the case of Industry 1 in one of the five locations investigated, namely Cali.

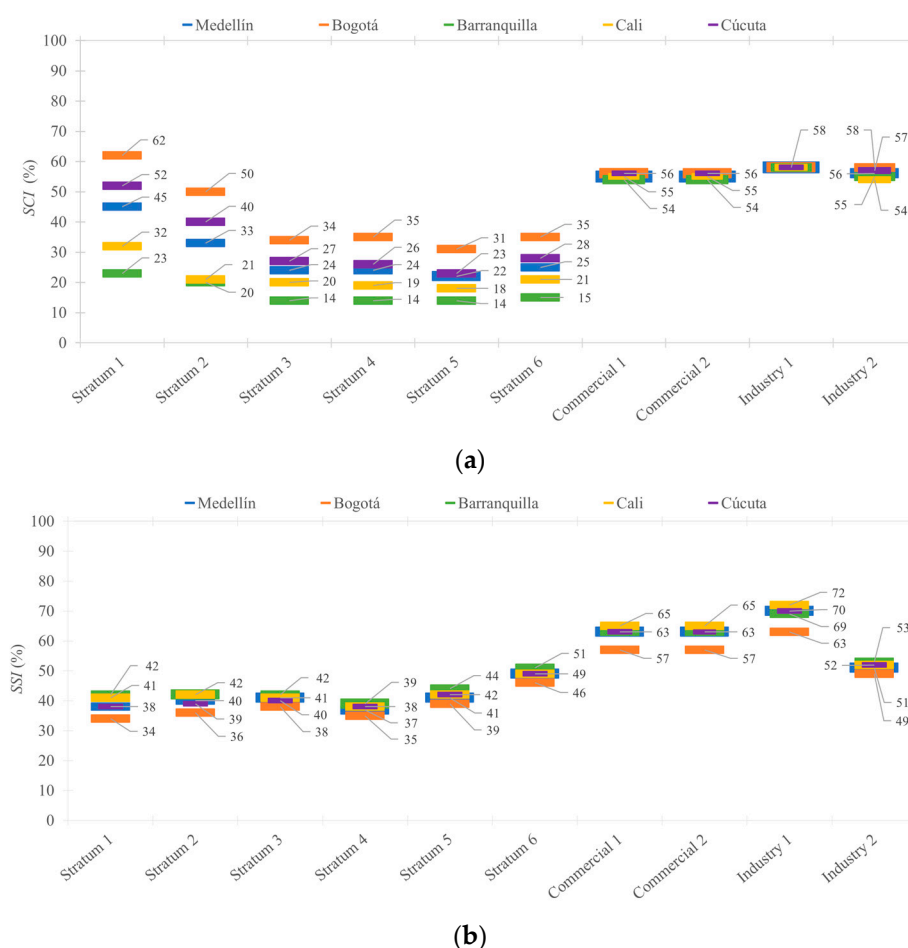


Figure 6. Values of SCI (a) and values of SSI (b), calculated for self-consumption PV systems—sized according to the optimal array DC power rating shown in Figure 5b—across the groupings inside the segments studied for the five locations investigated.

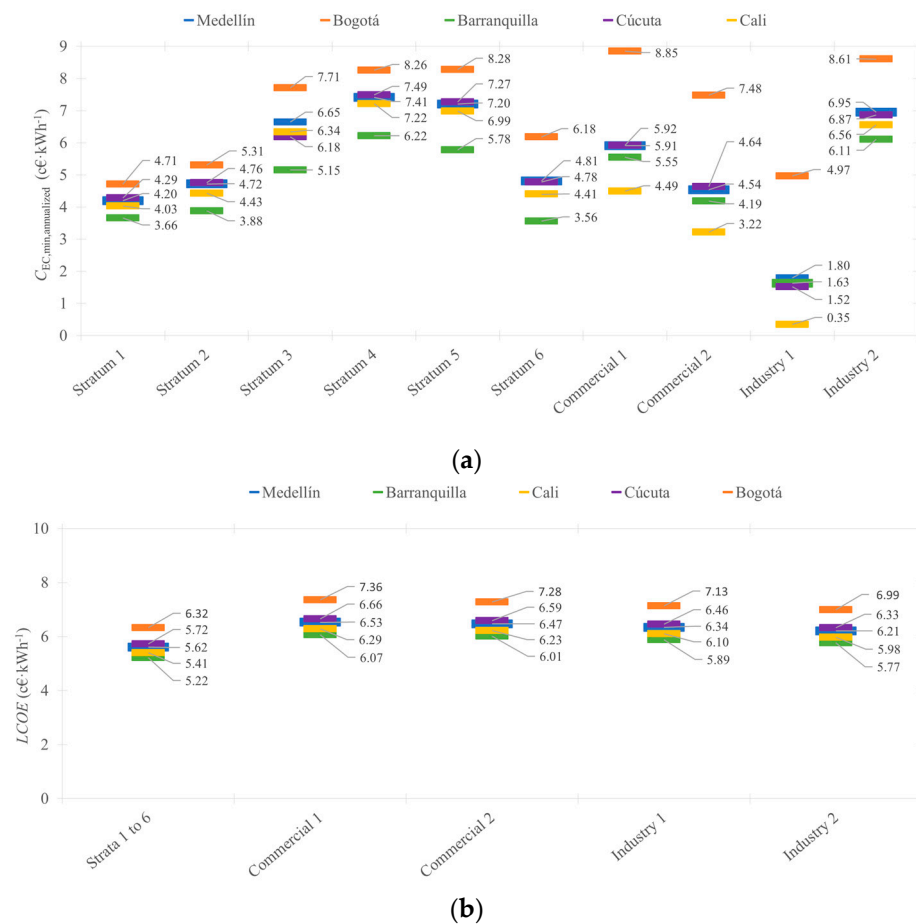


Figure 7. Values of $C_{EC,min,annualized}$ (a) and values of LCOE (b), calculated for buildings equipped with self-consumption PV systems—sized according to the optimal array DC power rating shown in Figure 5b—across the groupings inside the segments studied for the five locations investigated.

Figure 7b, depicts the values of LCOE in the case studies analyzed in this paper, following the methodology of previous works [96]. These values are presented for illustrative purposes only, to demonstrate that, in general, $C_{EC,min,annualized}$ is significantly lower than LCOE for strata 1, 2 and 6 of the residential segment, for Commercial 1 and 2 groupings of the commercial segment, as well as for the Industry 1 grouping of the industrial segment. In fact, it is lower across all groupings in the three aforementioned strata at the five locations under analysis.

It is important to note that the criterion of PV self-consumption competitiveness has been redefined in this study, excluding considerations related to the LCOE. Thus, according to the novel method presented in this work, a self-consumption PV system is considered competitive when the annualized minimized unit cost of electricity from the user's perspective is lower than the final unit cost according to the regulated user, i.e., $C_{EC,min,annualized} < p_{fromgrid} = C_{unitFinal}$. In this regard, a comparison between Table 6 and Figure 7a clearly shows that, according to the novel model proposed in this study, PV self-consumption systems are cost-competitive across all strata, as $C_{EC,min,annualized} < C_{unitFinal}$ consistently holds. For the commercial and industrial segments, both $C_{EC,min,annualized}$ —as discussed earlier—and LCOE values also remain below those of $C_{unitFinal}$. In summary, this study demonstrates that self-consumption PV systems are cost-competitive in all segments analyzed across the five studied locations in Colombia, even in socioeconomic strata 1, 2, and 3, where electricity prices are relatively low.

4. Conclusions

The assessment of the cost competitiveness of self-consumption PV systems is essential to foster the uptake of this decentralized approach to clean electricity generation. However, this assessment is significantly more complex than at the utility scale, where the levelized cost of electricity (LCOE) is widely used to evaluate grid parity and, by extension, competitiveness. In the context of self-consumption, LCOE alone is insufficient to capture the full economic performance of PV systems, as it does not account for user-specific dynamics. This study proposes a novel method to evaluate the cost competitiveness of self-consumption PV systems, addressing the limitations of traditional LCOE metrics. By integrating technical, environmental, and economic parameters, the proposed model identifies the optimal PV array size that minimizes the user-minimized annualized unit cost of electricity, enabling a direct and reliable comparison with regulated retail tariffs. In this regard, the user-minimized annualized unit cost of electricity represents the average cost—in nominal euros per kWh—of the electricity consumed over the system life cycle and can be directly compared with the average retail electricity cost for the same period, as both are expressed in nominal terms.

To demonstrate its applicability, the proposed method was applied to five representative locations in Colombia (Bogotá, Medellín, Cúcuta, Cali, and Barranquilla). The analysis evaluated ten distinct study cases per location, encompassing residential, commercial, and industrial profiles. Each case was individually analyzed based on its specific energy tariffs and consumption patterns, alongside the calculation of self-consumption and self-sufficiency indexes. The results confirm that self-consumption PV systems, when sized according to the proposed method, are cost-competitive across all studied cases, as the user-minimized annualized unit cost of electricity consistently falls below the regulated retail tariff. Furthermore, the commercial and industrial segments exhibit the most favorable economic outcomes, primarily driven by their high self-consumption and self-sufficiency indexes, applicable tax depreciation benefits, and favorable regulations permitting unrestricted surplus energy sales to the grid.

Due to its modular structure, the proposed method is highly transferable across countries, requiring only local input data—such as tariffs and compensation schemes—to adapt to diverse regulatory and economic conditions. This universal applicability provides a robust framework for policymakers, investors, and end users to evaluate how specific support mechanisms, technological advancements, and market landscapes impact the cost competitiveness of self-consumption PV systems, ultimately fostering broader engagement in the clean energy transition.

Future research should expand the proposed model to incorporate economic profitability analyses, including metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and discounted payback period (DPBT). Providing these highly sought-after financial indicators to potential investors will further accelerate the deployment of self-consumption PV systems, particularly in regions where adoption remains low.

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Abbreviations

The following abbreviations are used in this manuscript:

AMI	Advanced Metering Infrastructure.
AOI	Angle of incidence (°).
C_{EC}	Unit cost of electricity consumed from the user's point of view (€·kWh ⁻¹).
$C_{EC,min}$	Minimized unit cost of electricity consumed from the user's point of view (€·kWh ⁻¹).
$C_{EC,min,annualized}$	Annualized minimized unit cost of electricity consumed from the user's viewpoint, termed 'user- minimized annualized unit cost of electricity', for convenience (€·kWh ⁻¹).
C_{Com}	Commercialization cost (€·kWh ⁻¹).
C_{Dis}	Distribution cost (€·kWh ⁻¹).
C_{Gen}	Generation cost (€·kWh ⁻¹).
C_{Loss}	Losses cost (€·kWh ⁻¹).
C_{Res}	Restriction's cost (€·kWh ⁻¹).
C_{Tra}	Transmission cost (€·kWh ⁻¹).
C_{unit}	Unit cost of the electricity tariff (€·kWh ⁻¹).
$C_{unitFinal}$	Final unit cost of the electricity tariff according to the regulated user (€·kWh ⁻¹).
CPI	Consumer price index.
d	Nominal discount rate (%).
DFT	Deposit facility rate.
DG	Distributed Generation.
D_n	Annual depreciation for tax purposes (€).
d_s	Annual dividend of the equity capital/return on equity (%).
$E_{fromgrid}$	Energy consumption from the grid (kWh).
$E_{fromgrid,m}$	Monthly photovoltaic electricity taken from the grid (kWh).
E_L	Load energy consumption of the building over the life cycle of the PV system (kWh).
$E_{L,annual}$	Annual load energy consumption of the building over the life cycle of the PV system (kWh).
$E_{L,\tau}$	Load energy consumption over τ (kWh).
$E_{PVcon,\tau}$	Self-consumed AC energy generated by a PV system over τ (kWh.) (kWh).
$E_{PVgen,\tau}$	AC energy generated by a PV system over τ (kWh).
$E_{PVtogrid}$	Photovoltaic electricity fed into the grid (kWh).
$E_{PVtogrid,m}$	Monthly photovoltaic electricity fed into the grid (kWh).
g	Annual inflation rate (%).
i_l	Annual loan interest (%).
$L(t)$	Load power consumption (kW).
LCOE	Levelized Cost of Electricity (€·kWh ⁻¹).
$M(t)$	Photovoltaic power consumed (kW).

NIS	National Interconnected System.
N	Life cycle of the PV system (years).
N_d	Depreciation period (years).
N_l	Amortization of loan (years).
NO	Network Operator.
P_0	Array DC power rating (kWp).
$P_{0,ini}$	Lower bound of the array DC power rating range within which its optimal value is determined (kWp).
$P_{0,fini}$	Upper bound of the array DC power rating range within which its optimal value is determined (kWp).
$P_{0,i}$	i -th value of the array DC power rating within the range from $P_{0,ini}$ and $P_{0,fini}$.
$P_{0,i+1}$	$i + 1$ -th value of the array DC power rating within the range from $P_{0,ini}$ and $P_{0,fini}$.
$P_{0,opt}$	Optimal array DC power rating (kWp).
P_{bol}	Hourly spot price of the electricity tariff ($\text{€} \cdot \text{kWh}^{-1}$).
$P(t)$	AC output power (kW).
$p_{fromgrid}$	Price of electricity from the grid ($\text{€} \cdot \text{kWh}^{-1}$).
p_{PVcon}	Price of electricity self-consumed ($\text{€} \cdot \text{kWh}^{-1}$).
$p_{PVtograd}$	Price of electricity fed into the grid ($\text{€} \cdot \text{kWh}^{-1}$).
PLR	Performance loss rate ($\% \cdot \text{y}^{-1}$).
PR	Performance ratio (%).
PV	Photovoltaic(s).
PV_{AOM}	Annual operation and maintenance cost of a PV system (€).
PV_C	Photovoltaic system cost (€).
PV_l	Amount equal to the portion of the PV system cost financed with a loan (€).
PV_s	Amount equal to the portion of the PV system cost financed with equity capital (€).
$PW[CE_{fromgrid}(N)]$	Present worth of the energy cost consumption from the grid (€).
$PW[CE_{PVcon}(N)]$	Present worth of the savings due to photovoltaic energy that is self-consumed (€).
$PW[CE_{PVtograd}(N)]$	Present worth of revenues generated from photovoltaic energy fed into the grid (€).
$PW[DEP(N_d)]$	Present worth of the tax depreciation (€).
$PW[PV_{OM}(N)]$	Present worth of the PV system operation and maintenance cost (€).
r_{OM}	Annual escalation rate of the operation and maintenance cost of a PV system (%).
$rp_{fromgrid}$	Annual escalation rate of the electricity price from the grid (%).
rp_{PVcon}	Annual escalation rate of self-consumed electricity price (%).
$rp_{PVtograd}$	Annual escalation rate of the price of electricity fed into the grid (%).
SCI	Self-consumption index (%).
SSI	Self-sufficiency index (%).
T	Income tax rate (%).
TDC	Time deposit certificate.
WACC	Weighted average cost of capital (%).
ΔP	Array DC power rating increase (kWp).
τ	Reporting period (day, month, year).

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