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Technical and Financial Analysis for the Implementation of Small-scale Self-generation Projects, based on Grid-Tied Photovoltaic Solar Energy, for Residential Users under Colombian Regulations

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ABSTRACT

The study focuses on integrating non-conventional renewable energy sources into Colombia's power system. The regulatory framework allows small prosumers to trade energy surpluses with grid operators. The research analyzes the financial feasibility of implementing photovoltaic systems for residential users. Technical aspects governing energy production and implementation costs are examined. Colombian residential users, divided into six socioeconomic strata, undergo individual analysis based on their energy rates and consumption patterns. The study area is Bucaramanga, known for intermediate solar potential. Precise cost estimates for implementing photovoltaic systems that meet user energy requirements are provided. Financial viability indicators (NPV, IRR, Payback Time) are evaluated for three scenarios: existing energy prices, 50% government financing, and a 10% tariff reduction due to government intervention. Results show financial viability for strata 4, 5, and 6, but not for strata 1, 2, and 3. Government intervention can make strata 2 and 3 feasible. Lowering the kWh price adversely impacts the project's financial feasibility for all strata, particularly the lower-income ones. The study is valuable for potential investors and policymakers seeking to promote photovoltaic systems in the residential sector. It provides insights into economic viability and helps develop effective policies for Colombia's sustainable energy transition.

Keywords: Regulations, Photovoltaic, Grid-Tied, Residential
JEL Classifications: Q42, P48

1. INTRODUCTION

In the context of growing concern over the depletion of non-renewable resources and the urgent need to reduce greenhouse gas emissions (Ahmed et al., 2022; Smaisim et al., 2023), small-scale auto generation projects (AGPE, as defined in Colombia's resolution CREG 30 of 2018) based on grid-tied solar photovoltaic energy emerge as a proposition to address Colombia's energy and environmental challenges (Muñoz et al., 2021; Chien et al., 2022). As energy demand continues to rise, the pursuit of sustainable and environmentally friendly solutions becomes a global priority (Zhao et al., 2023).

Various research studies have highlighted the technological maturity and reliability of photovoltaic systems, demonstrating their ability to locally generate clean and renewable electricity (Ellabban et al., 2014; Muñoz et al., 2014; Khan and Arsalan, 2016; Lai et al., 2017; Lupangu and Bansal, 2017; Peña-Gallardo et al., 2020; Shafiullah et al., 2022; Østergaard et al., 2022). Furthermore, there is a progressive focus on assessing the economic viability of these projects, with careful evaluation of potential savings in the electricity bill and the environmental benefits associated with the adoption of this technology (Peña-Gallardo et al., 2019; Ospino-Castro et al., 2020; Duman and Güler, 2020; Muñoz et al., 2021; Wang et al., 2022; Kim et al., 2023; Bórawski et al., 2023;

Tarigan, 2023). Such analyses have reinforced the emphasis on a more sustainable energy matrix and have sparked increasing interest in the implementation of grid-tied solar photovoltaic AGPE for residential users in the country.

Within this context, the present study aims to comprehensively analyze the technical and financial aspects related to the implementation of small-scale grid-tied solar photovoltaic AGPE for residential users in Colombia. Photovoltaic solar technology, by directly converting solar energy into electricity, provides an inexhaustible source of clean and renewable energy (Tang et al., 2023; Awan et al., 2023). Its adoption in the residential sector not only has the potential to provide greater energy independence to households but also significantly contributes to the reduction of harmful gas emissions (Zhang et al., 2023; Wang et al., 2023).

In addition to the technical focus, this research will delve into the analysis of consumers' socioeconomic behavior, considering their consumption patterns. Several factors will be examined, such as generation capacity, implementation costs, potential electric bill savings, and return on investment time. Special attention will also be given to the study and implementation of Resolution CREG 174 of 2021, a crucial regulatory framework guiding the implementation of self-generating systems in Colombia (García-García et al., 2023). Although the relevance of this resolution is undeniable, its limited consideration in the scientific literature highlights the need for more comprehensive research in this area.

Ultimately, this article seeks to contribute to knowledge in the field of renewable energies and provide information to drive informed decision-making, both in the realm of public policies and for users interested in adopting clean and efficient technologies in their homes. The transition towards a more sustainable and environmentally conscious energy matrix is a global challenge that demands effective implementation of solutions such as grid-tied solar photovoltaic AGPE. This analysis serves as a tool to advance on the path towards a more responsible and sustainable energy future in Colombia.

The methodology employed for this purpose consists of four main phases: Firstly, the determination of energy production potential based on solar radiation and performance ratio at the study site. Secondly, the assessment of energy demand and the value of energy for residential consumers in each stratum defined by national regulations. Thirdly, defining the photovoltaic system to supply the average residential user's energy needs for each sector and its associated costs. Finally, the fourth phase involves an analysis of financial viability indicators, considering, in addition to the base scenario, two more scenarios: one involving 50% of the investment financed by the government, and another with a 10% reduction in the electricity tariff.

2. ELECTRICITY TARIFF IN COLOMBIA

In Colombia, electric power is provided to its inhabitants through Public Utility Services, which are incorporated into the 1991 Political Constitution. Article 365 establishes that public services are inherent to the State's purpose, obligating it to ensure efficient provision to all inhabitants of the national territory (Colombian Political Constitution of 1991). Thus, through Law 142 of 1994 on Public Utility Services, the government exercised regulation, control, and oversight (Garces et al., 2023).

To bill for electric power, a tariff system was created under Law 142 of 1994 on Public Utility Services. Subsequently, in 2007, the Energy and Gas Regulatory Commission (CREG) established the unit cost of service provision through Resolution 119. The cost consists of a variable component based on consumption level, expressed in COP/kWh (Colombian Pesos per kilowatt-hour), and a fixed component, expressed in COP/invoice, following the equation 1 (Perez et al., 2022):

$$CUv = G+T+D+Cv+PR+R+CUf \tag{1}$$

The components referenced in the mentioned resolution are: (G) Generation, (T) Transmission, (D) Distribution cost, (Cv) Commercialization cost, (PR) Cost of purchase, transportation, and loss reduction, (R) Restriction cost, and (CUf) Fixed unit cost (Resolution CREG No. 119, 2007).

2.1. Socioeconomic Strata

Once the tariff formula was established, the Colombian National Government, through Law 142 of 1994, classified the residential sector into six socioeconomic strata, reflecting different economic capacities within each residential area: (1) Very Low, (2) Low, (3) Lower-Middle, (4) Middle, (5) Upper-Middle, and (6) High (Law 142, 1994).

2.2. Subsidies and Contributions

The socioeconomic classification was intended to determine the allocation of subsidies and the collection of contributions. Thus, for stratum 1, 60% of the energy cost is subsidized, for stratum 2, it is 50%, and for stratum 3, it is 15%. On the other hand, strata 5 and 6, as well as commercial and industrial sectors, are subject to a contribution equivalent to 20% of the tariff value. Stratum 4 is considered neutral as it neither receives subsidies nor pays contributions (Law 142, 1994).

2.3. Subsistence Consumption

Law 142 of 1994 stipulates that subsidies will not exceed the value of basic or subsistence consumption. The Mineral-Energy Planning Unit (UPME), through Resolution 355 of 2004, established the subsistence consumption at 173 kWh/month for altitudes below 1000 m above sea level and 130 kWh/month for altitudes equal to or above 1000 m above sea level (Resolution UPME 355, 2004).

2.4. Public Lighting Tax

The Tax Reform Law 1819 of 2016, Article 349, granted municipalities and districts the authority to adopt a public lighting tax as compensation for providing this service. The tax is applied to each kWh consumed by electricity service users. Municipalities can set a surcharge, which cannot exceed 1 per thousand of the property value, the basis for calculating property taxes (Congreso de Colombia, 2016).

2.5. Recognition of Excess Photovoltaic Solar Energy Delivered to the National Interconnected System (SIN)

Self-generation is an activity carried out by natural or legal persons who produce electric power, primarily to meet their own needs. They may use distribution and/or transmission assets to deliver excess energy and to back up their grid use (Luna-Delrisco et al., 2018; Bohórquez and Durán-Tovar, 2018).

According to Resolution UPME 281 of 2015, a Small-Scale Self-Generator (AGPE) is one whose maximum installed capacity does not exceed 1 MW, a condition met by photovoltaic installations in households.

Considering that Law 1715 of 2014 created a legal framework for renewable energy use and that the Ministry of Mines and Energy must regulate distributed generation from solar energy, the CREG issued Resolution 030 of 2018, updated in 2021 as Resolution CREG 174. These resolutions regulated operational and commercial aspects to allow the integration of electricity generation from NCREs, especially photovoltaics, into the National Interconnected System (SIN) and established guidelines for economically recognizing this energy as excess (Hernández et al., 2019).

Article 25 of Resolution CREG 174 of 2021 establishes that for AGPE with an installed or nominal capacity of up to 100 kW, accumulated excess energy exported, which is equal to or less than their imported electricity from the grid, will be exchanged on a one-to-one basis during the billing period (Muñoz-Arango and Mora-Flórez, 2022; Hernandez et al., 2022).

For the exchanged accumulated excess energy, the electricity service provider will charge the AGPE the commercialization cost for each kWh, corresponding to the (Cv) component of the tariff formula. In cases where exported energy exceeds imported energy from the grid during a billing period, these kWh will be settled at the corresponding hourly energy market price of the same billing period (Cárdenas-Rangel et al., 2023).

3. FRAMEWORK FOR THE DEVELOPMENT OF PHOTOVOLTAIC ENERGY IN THE COLOMBIA'S RESIDENTIAL SECTOR

Colombia, due to its proximity to the equatorial region, enjoys favorable conditions for photovoltaic generation as it does not experience significant variations in climatic conditions, lacking the phenomenon of seasons (UPME, 2015). Available solar resource information indicates that the country has an average solar irradiation of 4.5 kWh/m²/day (Gelves et al., 2020), surpassing the global average of 3.9 kWh/m²/day and far exceeding the average received in Germany (3.0 kWh/m²/day), a country known for its significant use of PV solar energy, boasting approximately 36 GW of installed capacity as of 2013 (UPME, 2015).

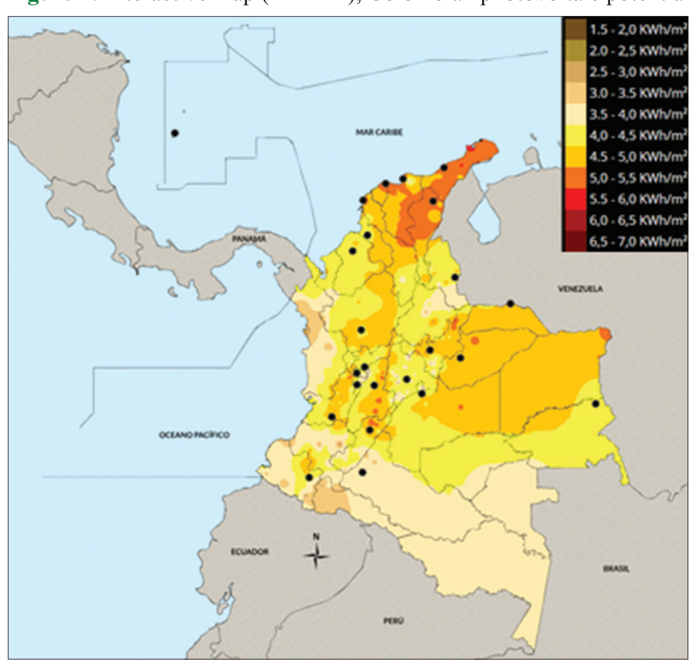
In the interactive solar radiation map provided by the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) (Figure 1), the Caribbean and central regions exhibit average insolation of 5 kWh/m²/day (Taba et al., 2017). In contrast, the southern region, including departments like Nariño, though below this average, still shows acceptable solar generation levels ranging from 3.5 to 4 kWh/m²/day.

Regarding photovoltaic solar energy generation in Colombia, statistics from the Mineral-Energy Planning Unit (UPME) as of December 31, 2022, indicate that out of the 16,532 newly registered generation projects in 2022, 7269 correspond to photovoltaic solar energy generation, reflecting a remarkable increase of 693.60% compared to the previous year, underscoring the burgeoning trend of this technology in the country (UPME, 2022). This highlights the importance of analyzing the implementation conditions of this technology in the country.

In 2014, the Colombian government achieved a milestone in renewable energy regulation by enacting Law 1715 of 2014, aimed at establishing a legal framework and instruments to promote the utilization of non-conventional renewable energy sources (NCREs), as well as to encourage investment, research, and development of clean energy technologies. Article 19 of the same law designates solar energy as an NCRE and calls for the study and analysis of its inherent characteristics for technical regulation by the CREG (Comisión de Regulación de Energía y Gas) (UPME, 2014).

This law also states that the National Government, through the Ministries of Mines and Energy, Housing, Environment, and Sustainable Development, will promote the use of solar resources in municipal or district urbanization projects. Additionally, the Ministry of Mines and Energy will regulate the conditions for solar energy's participation as a distributed generation source, establishing technical and quality regulations that installations using solar energy must adhere to, as well as specifying connection requirements, surplus delivery mechanisms, and safety standards for connections (UPME, 2014).

Figure 1: Interactive map (IDEAM), Colombian photovoltaic potential



Of particular relevance to photovoltaic solar energy, numeral 4 of Article 19 in Law 1715 of 2014 establishes that the National Government will consider the viability of developing solar energy as a self-generation source for low-income strata 1, 2, and 3 as an alternative to existing subsidies for electricity consumption by these users (UPME, 2014).This numeral is pivotal to the development of this research, serving as a legal foundation to assess the viability of photovoltaic projects in the aforementioned strata, given the focus of this investigation on Colombia's residential sector, in line with the intent of Law 1715 of 2014.

Subsequently, the Colombian Congress issued Law 2099 of 2021, which modified and supplemented Law 1715 of 2014, aiming to invigorate the energy market through the development and promotion of NCREs and the country's economic reactivation (Corzo Neira, 2021; Congreso de Colombia, 2021).

4. TECHNICAL ANALYSIS FOR THE INSTALLATION OF A GRID-TIED PHOTOVOLTAIC SYSTEM IN A HOUSEHOLD IN COLOMBIA

The analyzed case corresponds to net metering, where the energy generated by each system matches the demand of each household within each stratum. It involves a two-way exchange of electrical energy with the grid: injection when the produced energy exceeds the demand and consumption from the grid when the photovoltaic system's energy output is insufficient.

For the implementation of a solar photovoltaic system as a AGPE in a household, it was necessary to determine the average monthly electricity consumption in kWh and then calculate the annual consumption. This data was obtained from the official entity's website, the UPME (UPME, 2015). Through a study of electricity and gas subsistence consumption, UPME provided the monthly electricity consumption in kWh for each stratum based on the climate of the households' locations. Table 1 shows the variation in monthly kWh consumption for warm climates across strata 1-5, with stratum 5 having the highest consumption. Conversely, for moderate and cold climates, there is little variation in consumption across each stratum, with an average of 150 kWh per month.

After obtaining the monthly kWh consumption of each household, the peak solar hours (HSP) available in the location where this analysis was conducted were consulted. The study is centered in the municipality of Bucaramanga, Santander Department, Colombia, with a latitude of N 7° 7' 31.4" and a longitude of W 73° 7' 11.28". Given that this municipality is situated at an altitude of 974 meters above sea level, the subsistence consumption is 173 kWh.

Consulting the database of the official entity IDEAM, the average monthly sunshine hours for all regions in the country (hours of sunlight per day) showed an average of 4.5 daily h of sunshine at this location (IDEAM, 2018).

The photovoltaic modules used for the system are monocrystalline with a power rating of 490 Watts (W), with dimensions of 2080 mm × 1030 mm × 35 mm and a weight of 27.4 kg, readily available in the Colombian market. Other technical data is described in Table 2.

The efficiency of the photovoltaic system is 80.81% (Muñoz et al., 2021), as reported in the article "Technical and Financial Evaluation of Photovoltaic Solar Systems for Residential Complexes according to Colombian Regulation," a study conducted in the metropolitan area of Bucaramanga.

Using the data described in Table 1 and applying the performance ratio defined for the zone, the power (W) of each photovoltaic installation is calculated. This power results from dividing the daily consumption expressed in Wh/day by the peak solar hours, multiplied by the system's efficiency (Jutglar, 2004) through the following formula (Equation 2):

$$hotovoltaic\ Power = \frac{Daily\ Consumption(\frac{Wh}{day})}{Peak\ solar\ hours\ (HSP) * system\ efficiency} \quad (2)$$

Next, the number of panels to be installed is determined by dividing the system's power by the photovoltaic module's power, as follows (Equation 3):

$$Number\ of\ solar\ panels = \frac{Photovoltaic\ Power\ (W)}{Photovoltaic\ Module\ power\ (W)} \quad (3)$$

To find the required area (m^2) for the installation, the number of photovoltaic panels is multiplied by the dimension of each photovoltaic panel (Equation 4).

Requerided Area = Number of solar Panels × Panel area (4)

The weight of each photovoltaic installation is then established by multiplying the number of solar panels by the weight of each panel (Equation 5).

Table 1: Monthly kWh consumption by stratum and climate

Stratum	Warm climate (kWh-month)	Average climate (kWh-month)	Cold climate (kWh-month)
1	181,64	125,33	163,85
2	217,37	126,59	159,55
3	259,85	155,77	181,62
4	425,89	168,01	177,69
5	693,00	141,00	166,00

Table 2: Photovoltaic panel technical data

Technical data	Solar pannel 490W
Power [W]	490
Area [m^2]	2.3
Efficiency [%]	21
V mppt [V]	38.02
V oc [V]	45.65
I mppt [A]	12.89

PV Weight = Number of solar Panels × PV Weight (5)

To calculate the installed peak power (kWp) of each photovoltaic installation, the number of panels is multiplied by the power (W) of each solar panel, and the result is divided by 1000 (Equation 6).

$$kWp = \frac{Number\ of\ solar\ panels \times panel\ power\left(w\right)}{1.000} \quad (6)$$

For the calculation of the Performance Ratio (PR), the annual Photovoltaic production (kWh) is divided by the annual solar radiation (kWh/m_2), and the result is divided by the pick plant power, then multiplied by 100 (Kumar, 2022) (Equation 7).

$$Performace\ Ratio = \frac{Annual\ Photovoltaic\ Production\ (kWh)}{Annual\ solar\ radiation\left(\frac{kWh}{m2}\right)/\ kWP} \quad (7)$$

The established Performance Ratio for each photovoltaic installation is 78%.

To determine the annual kWh generated by each photovoltaic plant, the following equation was formulated (Equation 8).

Annual power (kWh)=Installed peak Powe (kWp) × PR × HSP (8)

Table 3 summarizes each technical consideration for each photovoltaic plant.

General Information and Study Restrictions:
- Houses from all strata located in the Santander Department, Colombia
- The construction must have an available area of 8–30 m^2 for the size of the photovoltaic system and must also support the weight, ranging from 94 to 358 kg.

5. FINANCIAL EVALUATION OF GRID-TIED SOLAR PHOTOVOLTAIC SYSTEMS IN EACH HOUSEHOLD AND STRATUM

Once the solar photovoltaic system was technically dimensioned for households in each stratum, a financial evaluation was conducted to determine the economic viability of these projects, considering three scenarios:

a. Financial evaluation of each photovoltaic installation with the kWh price as of December 2022, and projection up to 2047, considering the current regulations
b. Financial evaluation of each photovoltaic installation when the National Government contributes 50% of the capital cost for strata 1, 2, and 3
c. Financial evaluation of each photovoltaic installation when the kWh price decreases by 10% as mandated by the National Government.

The following considerations were considered for the evaluation:
- The USD price of electricity in Colombia in 2022, its trend since 2011, and projection for 25 years
- The amount of electricity (kWh) consumed by households according to the stratum and location in relation to the climate
- The subsidies granted to strata 1, 2, and 3, as well as the contributions charged to strata 5 and 6
- The USD price of the photovoltaic system to supply energy to each household
- Projection of generated electricity considering system degradation
- Annual maintenance cost of each photovoltaic system, equivalent to 1% of the capital cost (Ospino-Castro et al., 2020)
- Consumer Price Index (IPC) in 2022, the installation project date, published by the National Department of Statistics (DANE, 2022)
- Evaluate the project over 25 years, considering the useful life of the panels.

Taking into account the mentioned considerations, the kWh price in December 2022 applied by the Public Utility Company was 0.1979 USD. Regarding the price of the formula components, the following values were found: (G) 0.0632 USD; (T) 0.0126 USD; (D) 0.0769 USD; (CV) 0.0186 USD; (PR) 0.0148 USD; (R) 0.0094 USD (Electrificadora de Santander S.A. E.S.P, 2022).

At the same Public Utility Company, the kWh price was consulted from 2011 to 2022, with an annual increase of 5%. This data was considered to project the kWh price until 2047, the system's useful life, resulting in a price of 0.801 USD (Electrificadora de Santander S.A. E.S.P, 2022).

To determine the price of each photovoltaic system, values offered by local suppliers were considered, including the installation of the system with all components, design, certification of the Technical Regulation of Electrical Installations (RETIE), the process of being linked as AGPE with the electricity service provider and as a shared generator with UPME. The cost of each system is described in Table 4.

The Consumer Price Index (IPC) published by the National Department of Statistics (DANE) in December 2022 was 13.12%

Table 3: Technical data of each photovoltaic plant

Stratum	Wh/day	Photovoltaic power (W)	Number of panels - 490 (W)	kWp to be installed	kWh generated by year	Required area m^2	PV weight kg
1	6055	1682	3	1.68	2210	7.89	94.05
2	7246	2013	4	2.01	2645	9.45	112.55
3	8662	2406	5	2.41	3162	11.29	134.54
4	14196	3943	8	3.94	5182	18.51	220.51
5-6	23100	6417	13	6.42	8432	30.12	358.81

(DANE, 2022). Likewise, the capture rate published for the week of December 12-18, 2022, by the Central Bank of Colombia, the country's monetary authority, was 13.09% annual effective rate. This same rate was chosen as the discount rate to evaluate the project (Banco de la Republica, 2022).

To financially evaluate the project, a cash flow was established using the Monte Carlo method, which reflects the inflows and outflows of USD money. In the inflows, annual energy bill savings were considered until 2047, the useful life of the solar panels, as well as the sale of excess energy at the USD energy exchange price.

As for the outflows, the annual maintenance cost of the photovoltaic installation was reflected, corresponding to 1% of the system's capital cost, with a 5% increase each year.

Once the cash flow was calculated, the criteria for financial goodness were used: Internal Rate of Return (IRR), Net Present Value (NPV), and Payback Time (Aguer and Pérez Gorostegui, 1997; Sommerfeldt and Madani, 2017).

The IRR can be calculated by making NPV=0 in the following equation (Equation 9):

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{F_T}{(1+IRR)^t} = -I_0 + \frac{F_1}{(1+IRR)} + \frac{F_2}{(1+IRR)^2} + \ldots + \frac{F_n}{(1+IRR)^n} \quad (9)$$

Where:
Ft = Cash flows in each period t.
I_0 = Initial Investment.
IRR = Internal Rate of Return.

The Net Present Value is determined by the following equation (Equation 10):

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{F_T}{(1+k)^t} = -I_0 + \frac{F_1}{(1+k)} + \frac{F_2}{(1+k)^2} + \ldots + \frac{F_n}{(1+k)^n} \quad (10)$$

Where:
Ft = Cash flows in each period t.
Io = Initial Investment.
k = Opportunity/Discount Rate.

The Payback Time is defined by the following equation (Equation 11):

$$Payback\ time = a + \left[\frac{b-c}{d}\right] \quad (11)$$

Where:
a = Immediate previous year in which the investment is recovered.
b = Initial Investment.
c = Accumulated cash flow from the previous year in which the investment is recovered.
d = Cash flow of the year in which the investment is recovered.

6. RESULTS

Figure 2 presents the most relevant data for each photovoltaic system in each stratum, such as the number of installed photovoltaic panels, the installed peak power (kWp), and the electric energy generated by each photovoltaic system compared to the energy demanded.

The systems produce the energy demanded by the users in each stratum, although they exceed the production by a margin of 2%. As a result, the sale of excess energy at the exchange price is minimal and will only occur during the first three years, considering the system's degradation rate of 0.7% annually (Ospino-Castro et al., 2020). Figure 2 shows the annual energy generation compared to the demand over the same period.

In Figure 3, the price of the energy bill for one year is compared to the price of the bill when a photovoltaic system with grid-tied

Table 4: Photovoltaic system price according to each stratum

Strata 1	Strata 2	Strata 3	Strata 4	Strata 5-6
4.000 USD	4.411 USD	4.664 USD	6.731 USD	9.223 USD

Figure 2: Comparison between kWh generated and demanded by year

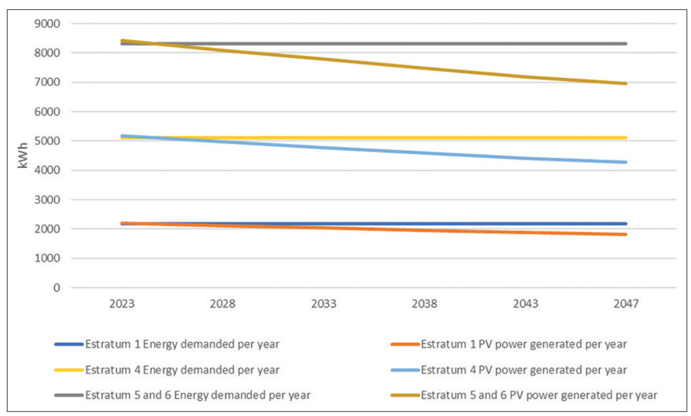
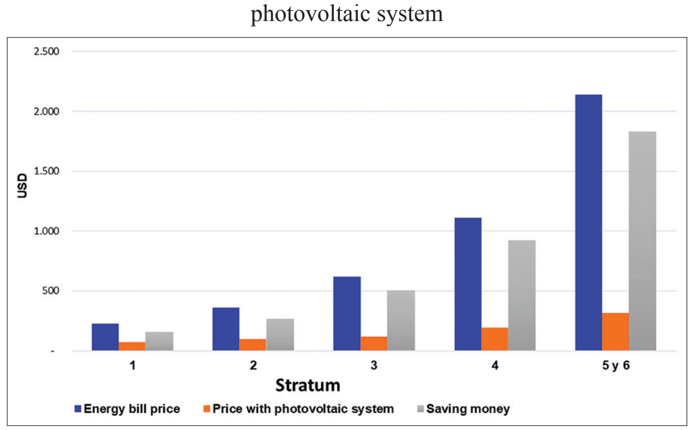


Figure 3: Billing price comparison. With and without photovoltaic system



capability is installed. Although the data from Figure 2 shows that the energy generated exceeds the demand in the first two years, the bill is not reduced to zero. This is due to the charge of the component (Cv) for each kWh exported to the grid and the charge for public lighting for each kWh consumed.

After performing the financial analysis using the criteria of financial goodness, such as the Internal Rate of Return (IRR), Net Present Value (NPV), and Payback Time, the results are described in Table 5.

In the previous table, it can be observed that the photovoltaic project is not financially viable in strata 1, 2, and 3. The NPV is negative, the IRR is below the 13.09% discount rate used, and the Payback Time exceeds 9 years, reaching 20 years in stratum 1. Conversely, financial viability is achieved in strata 4, 5, and 6, making the energy transition possible.

6.1. Government Provides 50% of the Photovoltaic System's Cost

Considering the results shown in Table 5, where there is no financial viability in strata 1, 2, and 3, it is essential to consider that Law 1715 of 2014, numeral 4, Article 19, states that the National Government will consider the feasibility of developing solar energy as a self-generation source for strata 1, 2, and 3 as an alternative to subsidies. Therefore, a scenario was analyzed where the Colombian State provides 50% of the photovoltaic system's installation cost to comply with the law and to offer compensation to households, as they will no longer receive subsidies from that point on.

Under this scenario, when applying the three financial indicators, the project becomes viable in strata 2 and 3. However, it remains unfeasible for stratum 1, as shown in Table 6.

6.2. 10% decrease in the kilowatt-hour price

One of the Government's policies is to decrease energy prices, considering that they are very high in the country, hindering wealth generation. One of the strategies announced is to take on the functions of the CREG to decrease the electricity value. Although specific guidelines and criteria for this decrease have not been provided, a 10% reduction in the kWh price was simulated for this scenario (Hoyos Rengifo, 2023).

Under this scenario, the three financial indicators were applied again, and the result is that the Payback Time would increase, making the project even more unfeasible for strata 1, 2, and 3, as shown in Table 7.

6.3. Results Comparison

Comparing the financial indicators used to evaluate the project in its three scenarios – photovoltaic system installation with the kWh price in December 2022 and projection to 2047 considering current regulations; Government providing 50% of the capital for strata 1, 2, and 3; photovoltaic system installation with a 10% decrease in the kWh price ordered by the National Government. Figure 4 shows that compared to the initial project; the Payback Time decreases by 5 years in strata 1-3 when the Government subsidizes 50% of the photovoltaic system installation. This is due to the lower initial investment. Conversely, when the tariff decreases by 10%, the Payback Time increases in all strata, especially in strata 1 and 2.

In Figure 5, it is evident that the Internal Rate of Return is positively impacted when the Government contributes 50% of the project for implementing photovoltaic systems. However, for stratum 1, it remains lower than the 13.09% discount rate. When the kWh value decreases by 10%, the project's profitability decreases in all strata.

Figure 6 shows that the Net Present Value is lower when the kWh value decreases by 10%, especially for strata 3-5. When the government subsidizes 50% of the installation, it is also not profitable for stratum 1.

Table 5: Financial Indicators analysis

Stratum	Payback times years	Internal rate of return (IRR) %	Net present value (NPV) USD
1	19.71	3.05	−2.729
2	13.02	8.30	−1.711
3	9.53	12.45	−258
4	6.61	18.21	3.328
5-6	4.74	24.83	11.137

Table 6: Financial Indicators for stratums 1, 2 and 3 with 50% subsidized by the government

Strata	Payback times years	Internal rate of return (IRR) %	Net present value (NPV). USD
1	12,69	8,51	-729
2	8,95	15,44	494
3	6,03	19,98	1.546

Table 7: Financial Indicators analysis with 10% decrease on the kWh price

Strata	Payback times. Years	Internal rate of return (IRR) %	Net Present Value (NPV). USD
1	21.726	1.81	−2.942
2	15.359	7.06	−2.084
3	11.661	9.71	−1.290
4	7.344	16.46	2.143
5-6	5.263	22.57	8.822

Figure 4: Payback time comparison

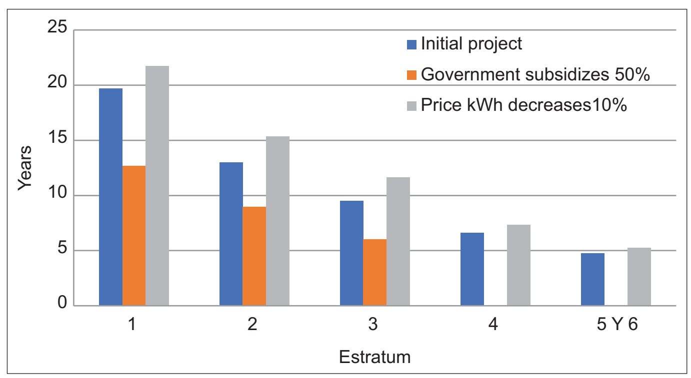


Figure 5: Internal rate of return comparison

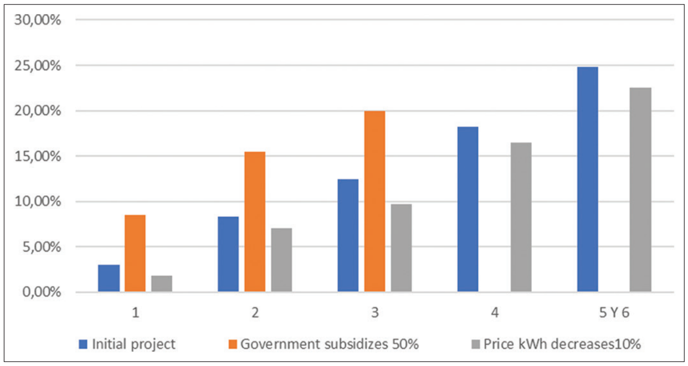
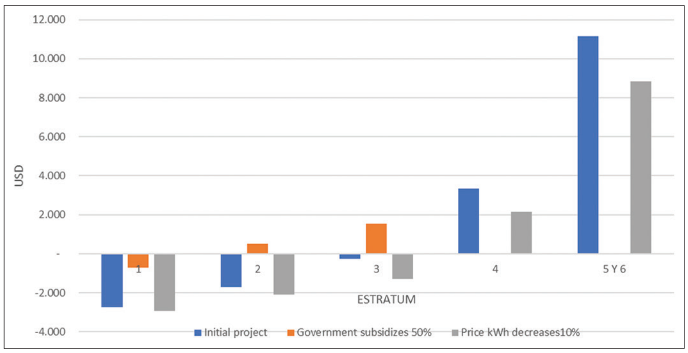


Figure 6: Net present value comparison



7. CONCLUSIONS

A comprehensive analysis of technical and financial aspects related to the implementation of small-scale self-generation projects based on grid-tied photovoltaic solar energy for residential users in Colombia, has been carried out. In this country, it was found that the electricity tariff is differentiated from 1 to 6, according to socioeconomic strata. In accordance with the current government's objectives, it was determined to be important to consider three scenarios: a reference scenario with current conditions, a scenario with a 50% government subsidy and a scenario with a 10% reduction in the energy tariff.

The results indicate that the implementation of grid-tied photovoltaic systems is financially viable in strata 4, 5, and 6, while it is not feasible in strata 1, 2, and 3. However, with the Government's intervention and support, financial viability can be achieved for strata 2 and 3. Furthermore, a decrease in the kWh price could negatively impact the project's financial feasibility in all strata, making it even more challenging for the lower-income strata.

These comparisons and findings are crucial for decision-makers and policymakers to design effective policies and incentives that promote the adoption of renewable energy sources, such as solar power, while ensuring energy affordability and sustainability for all segments of the population. A balanced approach that combines financial support and regulation is necessary to foster a successful energy transition towards a greener and more sustainable future for Colombia.

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