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Photovoltaic System Connected to the Residential Electrical Network: Case Study in the City of Dibulla, Colombia

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Abstract

This article presents a technical-economical simulation for a solar photovoltaic system connected to a residential grid of users in the municipality of Dibulla, Colombia. The study was performed by detailing the demographical characteristics of the region, as well as the energetic potential coming from the implementation of renewable energy sources. Afterwards, a simulation was carried out with the RETScreen software for a user with an installed load of 1 kWp. The result was an approximation of the energetic model and cost analysis as well as the financial details that show the internal return rate on the investment and the cost-benefit relationship in the implementation of energetic projects in non-interconnected areas of the Colombian territory.

Keywords: communication, control, PV system, research projects, smart grids

1. Introduction

Primary energy networks consist of a complex network of generation plants, transformers, substations, and distribution and transmission lines that provide for the cities, mainly to residential, commercial and industrial users. However, apart from conventional electrical networks there are independent electrical networks with a lower generation scale, commonly known as microgrids or micronetworks. In some cases, they are isolated from the urban interconnection system.

The rural areas of remote operation have limited access or no access to primary energy which is why the supply is generally given by diesel generators and backup systems for fossil combustibles. This undoubtedly seeks to the growth of the environmental impact for the dependency of conventional energy sources. Therefore, a great challenge for the technological infrastructure of the micronetworks lies in the integration of non-conventional energy sources (also named alternative energies) with the centralized or distributed electrical network systems. The objective is to guarantee that the fluctuations in the demand do not affect the system's continuous operation and that the electrical energy must be governed under equality, quality and continuity. [1].

There is no doubt that electrical energy is essential for the domestic and industrial processes of the human being. The constant dependency has led to the evolution of the criteria and regulation policies in a similar way than the control and operation of electrical systems have evolved. Different investigations have established the scenarios from the regulatory framework, offering a viewpoint from the public and private sectors and, last but not least, with the participation of the client with the producer-consumer duality.

With the increase of the energy demand, most of the electrical and electronic processes of domestic and industrial use have led to the need of a service governed under the principles of quality and reliability. Hence, renewable energy resources are an energetic technology that takes progressively more protagonism in the needs of the human being. Adding to that, energetic resources from renewable sources have had a positive impact on the market. The big pillar is: "Diminishing the dependency on combustible fossils".

The photovoltaic (PV) energy generation system connected to the network has the advantage of a more efficient use of the generated energy [2]; most of the current investigation is focused in the autonomous PV system. There seem to be some studies about the PV system connected to the network in residential energy systems [3]. In spite of the analysis of the PV systems for residential users [4], few studies have been presented with quantitative information on the optimized design of PV systems connected to a network for residential applications in the urban and tropical climate such as the municipality of Dibulla. The limited information has seriously blocked the implementation of these types of solar technologies for the residents of the rural areas of the city, specifically for the inhabitants that are not connected to the local distribution system.

In this way, computational tools have reached the necessary spotlight to obtain energetic conclusions moreover on non-interconnected areas of the Colombian territory. Some simulation techniques are commonly used to demonstrate and analyze the performance and viability for different components of a PV system [5]. All of this must be done while keeping in mind that such simulations must be performed before the installation of PV in a conventional network as an estimate or forecast with the purpose of reducing the costs of materials and installation [6] [7]. This article presents a technical-economical simulation of the design of PV systems connected to the network, specifically for the residential sector of Dibulla, Colombia. Consequently, it is expected that the present study helps to demonstrate the advantages and challenges of the installation of a PV system connected to the residential network of this city.

2. Simulation of the photovoltaic system

The present investigation focuses on the technical-economical assessment of the design of a photovoltaic system for the city of Dibulla, located in the West of the Department of Guajira. This town was chosen as a study case since its geographical extension has a tropical climate where solar energy is available throughout the entire year. Under these weather conditions, photovoltaic systems should be converted into a favorable energy source.

2.1 Population analysis

The Dibulla town is located in the West of the department of Guajira with a geographical extension of 1744 km. The current total population in 2015 was reaching 32963 inhabitants with 5388 of them in the urban area, i.e., more than three quarters of the community live in rural areas [8].

Nowadays, the energetic supply is offered by the company GECELCA S.A. E.S.P that is directly in charge of the operation and maintenance of unities 1 and 2 of the Termoguajira Central with an effective capacity of 151 MW each located in the jurisdiction of the Mingueo town, Dibulla municipality, Guajira department. These unities operate on natural gas and also operate with carbon [9].

It is estimated that total number of houses without electricity ascends to 1659 in areas of local distribution, whereas 622 houses do not have the service in non-interconnected areas [10]. This is the main reason why the Institute of Planning and Promotion of Energetic Solutions for Non-interconnected areas (IPSE in Spanish) has focused its statistics on showing to the Mining and Energy Planning Unit (UPME in Spanish) the big goal of guaranteeing that the next years there is a plan that allows the electrification for 173000 new users.

2.2 Analysis methods

In the study formulated in [8], it was informed that only 67% of the population has access to electrical energy. The study also indicates that 97% of the houses are of the indigenous type, 3.9% are apartments and 5.4% are rooms. However, the number of people per home is about 4.7.

It is important to know the previous indicators to have an estimate value of the consumed power for each home. According to the DANE (National Administration Department of Statistics), one person consumes 38 kWh per month which implies that for a 4-person family, the monthly consumption must be 152 kWh of energy.

Based on the previous affirmation, in terms of the installed capacity for the distribution network, the houses of Dibulla are fed by 2 to 8 kW of power (120 V monophasic two-wire). Hence, the present analysis will take as reference point this type of consumption for the inhabitants where the basic energetic needs for a typical home will be in the 3.2 kWh/day and some additional energy could be considered. The simulation of this study was carried out for 1 kWp, capacity of the PV system connected to the network. A simple diagram for a PV system connected to the network is shown in Figure 1.

According to the RETScreen's excellent results in comparison to other computational tolls [11], the system simulation was carried out in terms of: energetic model, cost analysis, greenhouse effect analysis and financial analysis. The financial analysis and simulation are performed for two hypothesis or suppositions:

(i) System connected to the network without any incentives (where the price of PV energy sent to the network is the same price as the network's electricity)
(ii) Condition with supply fee of COP$500 / kWh.

RETScreen is a software tool that can analyze the viability for various renewable energy systems including the PV system connected to the network [12]. One of its main characteristics is the meteorological database of the National Aeronautics and Space Administration (NASA) [13]. The software offers tools that may be used to analyze configurations in PV systems with different precision including connected networks, isolated networks, isolated networks with internal load [5], i.e., the system can be simulated in a centralized and distributed network. Moreover, RETScreen allows the user to assess the simulation results with the purpose of identifying the best technical and economical solution, and, manage to closely compare the results of the different technological alternatives for any specific PV project.

The locations of the simulation data are the following:

- Geographical location: Dibulla city, Guajira department
- Country: Colombia
- Geographical coordinates: 11°16′21″N 73°18′32″O
- Altitude: 2 MASL

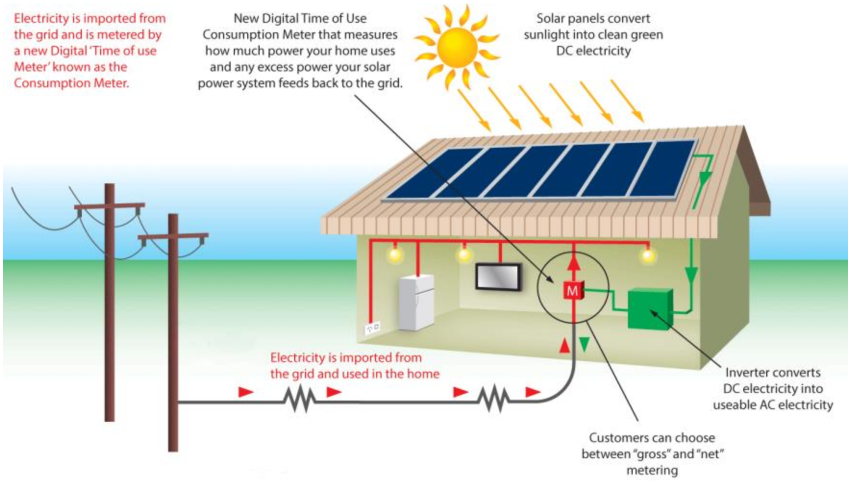

Figure 1. Distributed energy resource connected to the network
Source: Taken from [14]

The meteorological simulation data were taken from the RETScreen database. This information is consistent with the daily average of solar radiation, temperature and wind speed. The value for the Albedo effect (radiation percentage that any surface reflects based on the received incident radiation) for urban areas generally varies from 0.14 to 0.22; In this simulation, we used a 0.2 average [9].
During simulation, the project design tools were used starting from a system connected to the network. Hence, for its optimization, all other known and modifiable parameters were simulated such as: PV module types, module orientation, sizes of each unit, matrix structures and inverter sizes, among others. Unknown parameters were defined with default values. Table 1 shows the general parameters used during simulation.

Table 1. General simulation parameters

General parameters of the system	
Location	Dibulla, Guajira, Colombia
Technology	PV
Manufacturer	Sunpower
Capacity per unit	320 W
Number of units	80
Capacity	25600
Efficiency	19.6%
Structure area	1.62 m^2
Annual load	144 kW

3. Results

The technical simulation results for the PV system connected to the network with 1 kWp consist of a series of significant data, i.e. balances, meteorological data and incident energy, optical factors, system losses, inverter losses, used energy and normalized performance coefficients. The results can be determined on a daily, monthly or annual basis.
Los resultados de la simulación se pueden realizar sobre una base diaria, mensual o anual.

3.1 Financial analysis

The financial analysis of the project is presented focusing on the viability of implementing an electrical generation dynamical system through PV solar panels. The research's results will allow the areas of control, instrumentation, automation, protection coordination, energy quality and management to be concatenated as a management system in profiting from renewable energies and the efficient use of electrical energy.

Table 2 defines the guidelines for the project's study as main analysis focus points in the most accepted economical tendencies that determine the scaling level of the investment plans. One of the most important factors is: the duration of the project, the return on the investment and the net present value.

Table 2. General financial parameters

Financial parameters		
General		
Inflation rate	%	5%
Project lifespan	años	15
Finances		
Incentives y donations	COP	20,000,000
Debt relationship	%	30.0%
Capital	COP	93,279,368
Debt	COP	217,651,858
Interest rate on the debt	%	2.25%
Debt duration	años	15
Debt payments	COP/año	7,395,983

An approximation is now presented that generally details the investment costs of the project. Furthermore, it is necessary to break down the investment activities so that the project's baseline can be generated. This alternative is an anticipation on the income and expenses that will experiment the implementation of the energy management system. Table 3 describes the fees and participation percentages in terms of the investment activity.

Table 3. Project costs

Summary of costs/savings/income of the project			
Initial costs			
Viability study	3.2%	COP	10,000,000
Development	3.2%	COP	10,000,000
Engineering	5.8%	COP	18,000,000
Electrical power system	59.9%	COP	186,400,000
System balance and others	27.8%	COP	86,531,225
Total initial costs	**100.0%**	**COP**	**310,931,225**
Annual costs/debt payments			
Operation and Maintenance		COP	24,000,000
Fuel cost – as proposed		COP	0
Debt payments - 15 years		COP	7,395,983
Total annual costs		**COP**	**31,395,983**
Periodical costs (credits)			
Project end date – cost		COP	35,000,000
Total rent and annual savings		**COP**	**75,000,000**

3.2 Financial viability

Future performances in the implementation of the energy management system of the city have a positive impact. Hence, when measuring and comparing the investment profitability based on the internal opportunity rate (20%), the company or organization structure that decides to implement the project achieves an operational utility that covers the debt cost and pays the return on the investment.

This project has been assessed over a 15 year timespan. However, it is expected that the project produces income over the savings' representative value after the fourth year of operation. This is due to the favorability of the internal return rate which is greater than the internal opportunity rate established as an input parameter in the investment planning.

Assessing the net present value of the project, it is evidenced that the implementation of the energetic solution satisfies the basic financial goal of maximizing the acquisition and the cost-benefit relationship complies with the execution criteria. Table 4 summarizes the financial viability indicators.

Table 4. Financial viability

Financial viability		
IRR before taxes - capital	%	47.2%
IRR before taxes - assets	%	33.3%
IRR after taxes - capital	%	47.2%
IRR after taxes - assets	%	33.3%
Simple payment of capital return	year	3.0
Repayment - capital	year	2.2
Net present value (NPV)	COP	1,172,409,895
Annual savings during life cycle	COP/year	94,691,392
Benefit-cost relationship		2.24
Debt service covered		14.19
Energy production cost	COP/MWh	
Greenhouse reduction cost	COP/tCO2	(2,716,997)

3.3 Cash flow

Projecting the temporary horizon over a 15 year period, Table 5 shows the income and expenses volumes that generate the investment. This allows appreciating the growing relationship of the project that details the optimism in front of future investments. Consequently, the present values express a confidence index of the anticipation towards futures deficits and then search for financing sources opportunely.

Table 5. Income and expenses relationship

Annual cash flow			
Year	**Before taxes**	**After taxes**	**Accumulate**
#	**COP**	**COP**	**COP**
0	-217,651,858	-217,651,858	-217,651,858
1	97,535,556	97,535,556	-120,116,302
2	100,179,502	100,179,502	-19,936,800
3	102,877,566	102,877,566	82,940,766
4	105,630,113	105,630,113	188,570,879
5	108,437,453	108,437,453	297,008,331
6	111,299,841	111,299,841	408,308,172
7	114,217,469	114,217,469	522,525,641
8	117,190,465	117,190,465	639,716,106
9	120,218,880	120,218,880	759,934,986
10	123,302,688	123,302,688	883,237,674

Table 5. (Continued): Income and expenses relationship

11	126,441,779	126,441,779	1,009,679,452
12	129,635,949	129,635,949	1,139,315,401
13	132,884,896	132,884,896	1,272,200,297
14	136,188,210	136,188,210	1,408,388,507
15	66,782,883	66,782,883	1,475,171,390

Figure 2 corresponds to the economical diagram which serves a useful interpretation tool in the project's lifespan in terms of income and expenses. The behavior of money over time is thus described as well as the repayment (number of years that takes to recover the additional costs) in terms of annual savings can be observed.

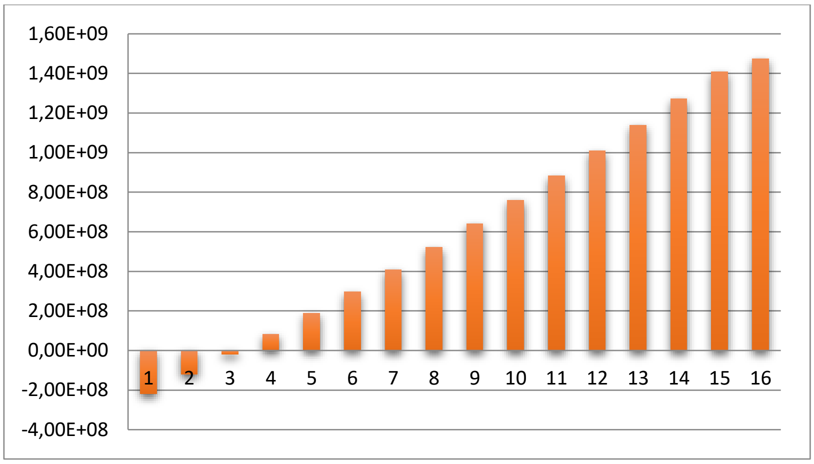

Figure 2. Income and expenses relationship for project temporality

3.4 Sensibility analysis

When generating a technological investment in an energy management system that visualizes profitability, it is necessary to establish a sensibility analysis which will be under the debt's interest rate scenario for the present project. Table 6 describes some sensibility parameters.

Table 6. Sensibility parameters

IRR analysis after taxes - capital	
Sensibility range	10%
Threshold	20%

With the sensibility analysis it is possible to identify the pessimistic, probable and optimistic scenarios. The present case study includes confidence intervals where the IRR is 47.2%. All of this takes into account the possible variations in the interest rate determined by the moneylender entity and is supervised by the Banco de la República (see Table 7).

Table 7. IRR sensibility in terms of the debt's interest rate

Interest rate of the debt		Initial costs (COP)				
		279,838,103	295,384,664	310,931,225	326,477,786	342,024,348
%	**Value**	-10%	-5%	0%	5%	10%
2.03%	-10%	52.7%	49.9%	47.3%	45.0%	42.8%
2.14%	-5%	52.7%	49.8%	47.3%	44.9%	42.8%
2.25%	0%	52.7%	49.8%	47.2%	44.9%	42.8%
2.36%	5%	52.6%	49.8%	47.2%	44.9%	42.7%
2.48%	10%	52.6%	49.8%	47.2%	44.8%	42.7%

3.5 Risk analysis

One of the most important aspects in determining the investment project is the risk analysis in front of the different uncertainties of the descriptor or financial parameters. Therefore, Table 8 presents the maximum and minimum ranges that describe the confidence intervals in decision-taking for the energy project through solar PV panels for the city of Dibulla.

Table 8. Risk analysis

Risk analysis					
Parameter	**Unit**	**Value**	**Range (+/-)**	**Minimum**	**Maximum**
Initial costs	COP	310,931,225	30%	217,651,858	404,210,593
Operation and maintenance	COP	24,000,000	30%	16,800,000	31,200,000
Consumption cost – electrical network	COP	126,341,300		126,341,300	126,341,300
Debt relationship	%	30%	30%	21%	39%
Interest rate on debt	%	2.25%	5%	2.14%	2.36%
Debt duration	Year	15	21%	11.85	**18.15**

Figure 3 represents a tornado chart that shows the parameters with the most influence and how they affect the internal rate of return after taxes, the net present value, the project's positive cash flows, among other indicators. The chart expresses what could be interpreted as a measure of the uncertainty which is why the central tendency of the investment is not enough. Consequently, the chart proposes a vision which is more in line with reality at the moment of taking implementation decisions of the energy supply system.

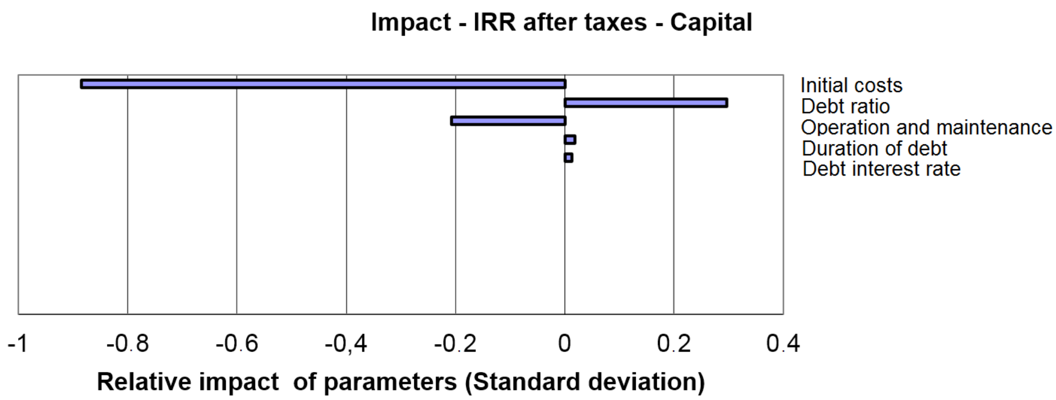

Figure 3. Standard parameter deviation

A more detailed risk analysis can be determined through Monte Carlo simulations where it is possible to establish the frequency distributions for the study indicators such as internal return rate, net present value, cost-benefit relationship, equilibrium point, among others. To get a more representative idea of how trustworthy would the internal return rate be, the RETScreen tool was used [9]. This software facilitated the system analysis focusing on the project's viability in terms of energetic efficiency, renewable energy and operational energetic performance.

The histogram shown in Figure 4 was obtained through 500 pre-established iterations or combinations. Once the level of risk is established, the software can determine the confidence intervals as seen in Table 9.

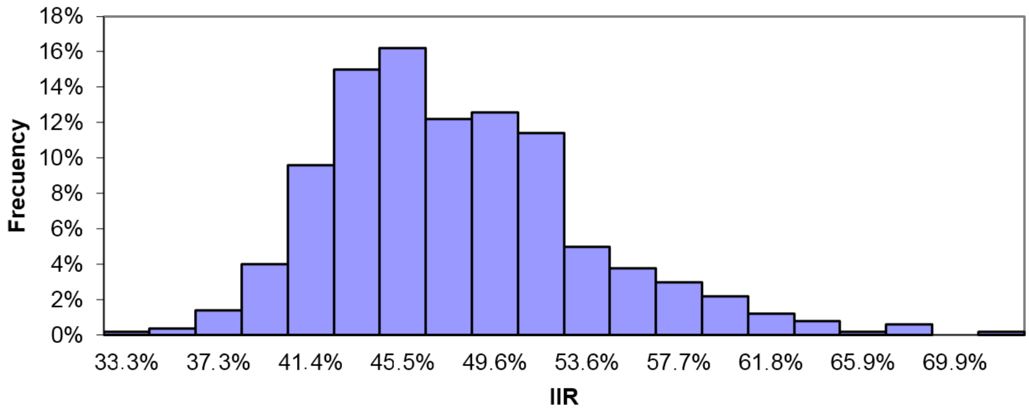

Figure 4. Distribution histogram for the IIR

Figure 4 shows that the interval with the highest frequency has an IRR of 45.5% in which case the IRR is within the 45.5% ± 0.89% in 16% of the times (the uncertainty value was found through the maximum absolute confidence value that Figure 3 expresses).

Table 9. Risk indicators

Median	**46,9%**
Risk level	10%
Minimum confidence level	46.9%
Maximum confidence level	46.9%

4. Conclusions

The average daily global radiation in Dibulla was 5.17 kWh/ m^2d or approximately 1,887 kWh/m^2 per year based on a 365-day year. The highest insolation level registered a 1,005 W/m^2. Based on this solar energy potential, the PV system connected to the network of 1 kWp could send electricity with a 1.3 MWh/year average; so technically, it would comply with the basic electricity demands of a 500-inhabitant population.

Given the results of the energetic study of Dibulla, it is concluded that the implementation of an alternative clean energy system is an excellent option at almost the installed nominal capacities for the production plant. Hence, the geographical location of such city is an important resource for the energetic profiting of the region.

Starting from the financial analysis, it is beneficial for the municipality to invest in technological solutions such as solar PV panels and an energy management system. The return on the investment would be visualized around the fifth year within the established range in the project lifetime (15 years). Additionally, the NPV of COP$ 1,172,409,895 as well as the cost-benefit relationship (2,24), would corroborate the viability of the implementation of non-conventional clean energies in this zone of the Colombian territory.

Electrical energy is essential for the activities of an organization and may represent economic impacts for it due to an inadequate energy management. For this reason, the present document concludes that organizations cannot control the energy prices but can improve the management of energy consumption. In that case, the municipality of Dibulla has a great viability in implementing technological strategies that contribute to cost minimization, penalizations, etc. and, most importantly, to the improvement of the environment and therefore the society.

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