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A Technical and Economical Study of a Photovoltaic System Installed on the Rooftop of a Public Building

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Abstract. The rooftops of industry, business and public buildings have been good options for the installation of photovoltaic systems. These systems can contribute to the reduction of energy consumption and energy losses in the buildings, as well as to relieve the transmission circuits. This research work presents a technical and economical study of a photovoltaic system installed on the rooftop of a government building. The analysis methodology applied to this specific case is also presented. Calculations were made to obtain the system's potential for photovoltaic power generation, as well as the economic feasibility indicators based on the project's lifetime, in order to inform investment decisions.

Key words

Photovoltaic energy, shading studies, solar irradiation, PV arrays, economic feasibility study.

1. Introduction

At the location where this study was conducted (the city of Goiânia, in the state of Goiás, Brazil) electric systems are found to be saturated in the loading of the circuits, transformers and energy substations, thus demanding large investments. As result, in periods of high consumption, as in the summer months, energy breakdowns are constant, due to the system's overload. The production of energy in a decentralized manner can be an option to mitigate the problem.

This research work presents a case study that analyzed technical and economical aspects of installing a grid connected photovoltaic system on the rooftop of a public building in Goiânia.

Initially, an analysis was conducted on the potential of photovoltaic power generation, given the available installation area and the solar irradiation data. By using an estimated amount of photovoltaic energy an economic analysis was conducted, considering the savings obtained in the building's energy bill and the investment costs.

2. Analysis of the Potential of Photovoltaic Power Generation

The evaluation of the estimated amount of photovoltaic power generation for the proposed system was made by considering the characteristics of the installation site, conducting a study of its shading, testing the allocation of panels and using solar radiation data. A simulation was used to model the real operational conditions of the photovoltaic system [1].

A. Characteristics of the Installation Site

The researches visited the public government building in order to recognize the area, do a photographic register, measure the rooftop's tilt angle and get drawings of the rooftop made in *Autocad*.

The rooftop has a heliport in its centre. Two side areas have roof tiles, each with a footbridge in the centre. The roof tiles have a 6-degree tilt angle relatively to the horizontal plane. Figure 1 presents a photo of the rooftop.

Fig. 1. Rooftop photo

B. Shading Study

According to reference [2], partial shading limits the electrical current of a single module and of the entire assembly mounted in the series. Therefore, it is necessary to consider the shading area of the rooftop throughout the year. The installation of modules is not recommended for this area.

The shading analysis was conducted between 9am and 3pm, as this is the period in which solar irradiation is higher [3]. The sun declination angle reaches two extremes throughout the year, on June 21 (winter solstice in the southern hemisphere) and on December 21 (summer solstice in the southern hemisphere) [2]. Shading simulations for these two dates inform shading patterns for the entire year [3].

On-site observations showed that there are not adjacent structures to the building that are capable of projecting shade on its coverage. Yet, there are internal structures which are capable of causing shading on the rooftop, such as access stairs, the heliport and the central footbridge.

A three-dimensional model of the building's rooftop was made with both *Autocad* and a 3-D modelling software called *SketchUp*, as shown in Figure 2.

SketchUp was used to define the geographic north and geolocation. Geographic coordinates for the studied building are latitude 16°40'54.7"S and longitude 49°15'21.6"W.

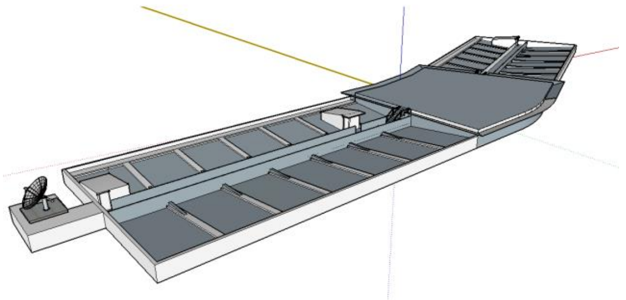

Fig. 2. Rooftop modelling with *Sketchup* software

Four areas of the rooftop were defined as Rooftops 1, 2, 3 and 4, with the same geographic orientation. Figure 3 shows the geographic north and the azimuth angle of these four areas. Table I presents the parameters for each area.

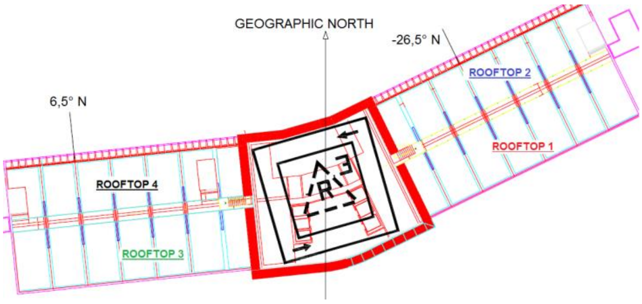

Fig. 3. Rooftop areas and azimuth angle

Table I. - Parameters for Rooftop Areas

	Rooftop 1	Rooftop 2	Rooftop 3	Rooftop 4
Azimuth Angle	-26.5° N	153.5° N	-6.5° N	173.5° N
Tilt Angle	6°	6°	6°	6°
Available Area	341.22 m²	273.33 m²	341.24 m²	257.12 m²

As the modelling was defined, *SketchUp's* shadow simulation tool was used to simulate the incidence of sunrays upon the model throughout the year, at any time of day. Shading amplitude was calculated between 9am and 3pm, considering the winter and summer solstices.

Such calculations informed the shading area where the solar modules should not be installed, as it can be observed in the red-colored areas shown in Figure 4.

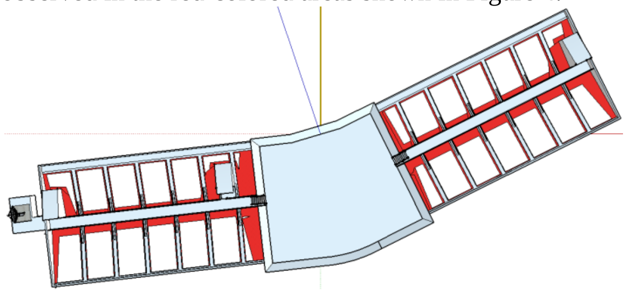

Fig. 4. Maximum shading area of rooftop (9am – 3pm)

C. Selection of photovoltaic module

As the available area was calculated, the next step was choosing a module for this study. The CS6P-250P module made by *Canadian Solar* was used. The most relevant parameters for this module are presented in Table II.

Table II. – Parameters for the CS6P-250P module

PARAMETERS	DATA
Module Efficiency - Ef_{STC}	15.54%
Nominal Maximum Power - Pmax	250 Wp
Dimensions	1638 x 982 x 40 mm
Nominal Operating Cell Temperature	45±2 ºC
Short Circuit Current - Isc	8.87 A
Open Circuit Voltage - Voc	37.2 V
Temperature Coefficient (Isc) - K_{Isc}	0.065 %/ºC
Temperature Coefficient (Voc) - K_{Voc}	-0.34 %/ºC
Temperature Coefficient (Pmax) - K_{Pmax}	-0.43 %/ºC
Cell Type	Poly-crystalline
Warranty	25 years

The data in Table II relate to STC (Standard Test Conditions). As such, when the module is submitted to a radiation of 1,000 W/m², cell temperature reaches 25 °C and air mass (AM) = 1.5.

The solar modules rarely work at standard conditions and its functions are affected by incident irradiation and cell operating temperature, NOCT (Nominal Operating Cell Temperature). Thus, it was necessary to recalculate the module efficiency according to its temperature coefficients and estimated operation temperature. The equation below was used for these calculations [4]:

$$Ef_{NOCT} = Ef_{STC} \times \left[\frac{100-(|K_{Pmax}| \times \Delta T)}{100}\right] \quad (1)$$

Where,
Ef_{NOCT}: module efficiency at operating temperature.
Ef_{STC}: module efficiency at STC conditions.
K_{Pmax}: temperature coefficient to module power.

ΔT: difference between operating temperature (NOCT) and STC temperature.

According to information on Table II, STC temperature is 25°C, and the operating temperature is 45°C. By applying equation (1), the module efficiency at NOCT condition, $Ef_{NOCT,}$ was equal to 14.2%.

D. PV array

In order to calculate the best PV array, two alternatives of solar panel installation were tested. In the first alternative, the modules were installed according to the rooftop's tilt. In the second alternative, panels were adjusted to a 16° tilt in the north direction. For each configuration, the modules were installed in both horizontal and then vertical positions, in order to calculate the best use of the available area.

D.1 Alternative 1: with no angle correction

A gap of 2 centimetres was determined between adjacent panels to set the supporting structures. A gap of 20 to 60cm was determined between rows of modules, according to the available area in each rooftop, in order to leave room for maintenance. The vertical installation allowed for 350 modules to be installed. The horizontal installation allowed the installation of 311 modules. Thus, the vertical installation proved to offer the best use for the area. Figure 5 shows the PV array with panels vertically installed over Rooftops 3 and 4.

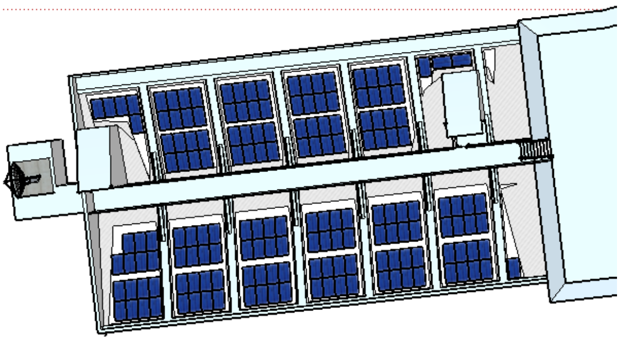

Fig. 5. Panels vertically installed with no angle correction

D.2 Alternative 2: with angle correction

It is recommended that the tilt angle of the PV array equals local latitude where the system is installed, in order to achieve maximum energy generation throughout the year [2]. By following this recommendation, the tilt angle for the modules was regulated to 16° in the north direction. The azimuth angle was kept according to the rooftop.

A minimum clearance between rows was calculated, so that the inclined panels would not cause shading to one other. Figure 6 shows a diagram with parameters to determine the minimum distance between rows. The definition of distance is given according to equations (2), (3) and (4) [1].

$$sen\,\beta = senL\; sen\delta_s + \cos L \cos\delta_s \cos hs \qquad (2)$$

Where,
β: solar altitude angle.
δ_s: solar declination.
L: local latitude.
hs: solar hour angle.

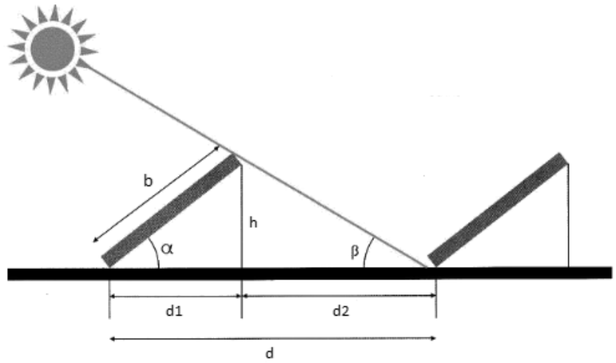

Fig. 6. Distance between rows for inclined panels [1]

$$hs = 15° \times (ts - 12) \qquad (3)$$

Where ts is the local solar hour, ranging between 0 and 24 hours.

$$d = b \times \left(cos\alpha + \frac{sen\alpha}{tan\beta}\right) \qquad (4)$$

Where,
d: minimum distance between rows.
b: module length.
α: module tilt relative to the base.

The minimum distance, d, must be calculated for the minimum height solar angle (β), which is the day of the year when the sun reaches its lowest height (δ_s) to the local latitude. This day is the winter solstice in the southern hemisphere (June 21st), with a solar declination of -23.45° at local solar hour (ts) at 12 o'clock [1].

Equation (3) shows that the solar hour angle, hs, is zero at ts = 12 o'clock. By using equation (2), where L = 16.7°, δ_s = -23.45° and hs = 0, the minimum height solar angle, β = 49.85°.

To reach 16º north, the module tilt angle to the rooftop (α) was 10° for Rooftops 1 and 3, and it was 22° for Rooftops 2 and 4. With these data and the module dimensions shown in Table II, we applied equation (4) to calculate the minimum distance between rows, d, which is shown in Table III to both horizontal and vertical assemblies.

Table III. – Minimum distance to inclined assembly

	Minimum distance (d)
Vertical Assembly	
Rooftop - 1 and 3	1.85 m
Rooftop - 2 and 4	2.04 m
Horizontal Assembly	
Rooftop - 1 and 3	1.10 m
Rooftop - 2 and 4	1.22 m

The vertical installation allowed for 312 modules to be installed. The horizontal installation allowed for the installation of 270 modules. Thus, the vertical installation offered the best use for the area. Figure 7 shows panels vertically installed with an angle correction over Rooftop 4.

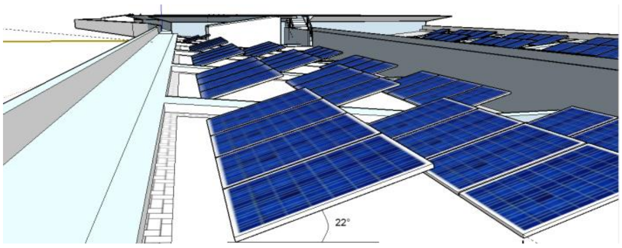

Fig. 7. Panels vertically installed with angle correction

E. Solar irradiation data

According to the procedure adopted by references [3] and [4], the indicators for solar radiation were collected using the *Radiasol 2* software developed by the Solar Energy Laboratory at the Federal University of Rio Grande do Sul, in Brazil. Radiasol 2 uses data from the SWERA project (Solar and Wind Energy Resource Assessment) and it simulates monthly average solar radiation on the plane of the module's inclined surfaces.

By feeding Radiasol 2 with the positioning data of the modules in Alternatives1 and 2, we could obtain the solar radiation indicators for each PV array. Table IV shows the annual average daily solar irradiation for each rooftop.

Table IV. – Average irradiation data obtained from *Radiasol 2*

	Alternative 1			
	Rooftop 1	Rooftop 2	Rooftop 3	Rooftop 4
Annual average irradiation (kWh/m²/day)	5.1000	4.8508	5.11	4.835
	Alternative 2			
	Rooftop 1	Rooftop 2	Roof 3	Roof 4
Annual average irradiation (kWh/m²/day)	5.2167	5.2167	5.2442	5.2442

Data analysis shows that the irradiation gain is small with the angle correction. This conclusion is in agreement with reference [2] which states that irradiation does not change considerably with azimuth and tilt deviation at low latitudes, such as in the tropic regions.

F. Estimating energy production

The energy produced for alternatives 1 and 2 was estimated by studying the average solar radiation data, the module area and the conversion efficiency, as it was calculated with equation (5):

$$E_P = E_S \times A_M \times \eta_M \times \eta_I \qquad (5)$$

Where,
E_P: daily produced energy by module (Wh).
E_S: daily irradiation (Wh/m²/day).
A_M: module area (m²).
η_M: module efficiency (%).
η_I: inverter efficiency (%).

Equation (5) calculates the energy produced by one module during one day. The total energy produced by a photovoltaic system can be obtained by multiplying equation (5) by the total number of modules.

The inverter used in this study is the M Plus 3600E made by *Santerno*, with a stated efficiency of 94.5%. The module efficiency at NOCT conditions had previously been calculated as 14.2%. The dimensions of the CS6P-250P are shown in Table II. The calculations for the energy produced in Alternatives 1 and 2 is shown in Tables V and VI.

As it can be observed, Alternative 2 produces more energy by panel than Alternative 1. However, the clearance between panels reduces the number of panels. Thereby, the total energy produced by Alternative 1 is higher than the one produced by Alternative 2.

Table V. – Calculations of energy produced by Alternative 1

	Alternative 1			
	Rooftop 1	Rooftop 2	Rooftop 3	Rooftop 4
Number of Modules	96	86	96	72
Daily production by panel (kWh)	1.0949	1.0413	1.0971	1.038
Total daily production by roof (kWh)	105.119	89.553	105.3251	74.7427
Total annual production by system (kWh)	136,780.12			
Maximum Power (kW)	87.5			

Table VI. – Calculations of energy produced by Alternative 2

	Alternative 2			
	Rooftop 1	Rooftop 2	Rooftop 3	Rooftop 4
Number of Modules	96	65	95	56
Daily production by panel (kWh)	1.12	1.12	1.1259	1.1259
Total daily production by roof (kWh)	107.5244	72.803	106.9653	63.0532
Total annual production by system (kWh)	127,876.29			
Maximum Power (kW)	78			

3. Economic Viability Analysis

An economic viability analysis was conducted for Alternative 1. Alternative 2 was rejected because it would produce less energy than Alternative 1.

A. Building electric power consumption

Monthly electric power consumption (in kWh), and respective energy costs for the studied public building were obtained for the period between March 2013 and

March 2014. Average monthly consumption during this period was 300,877.20 kWh, as shown in Figure 8. The monthly average energy bill was R$ 74,388.86.

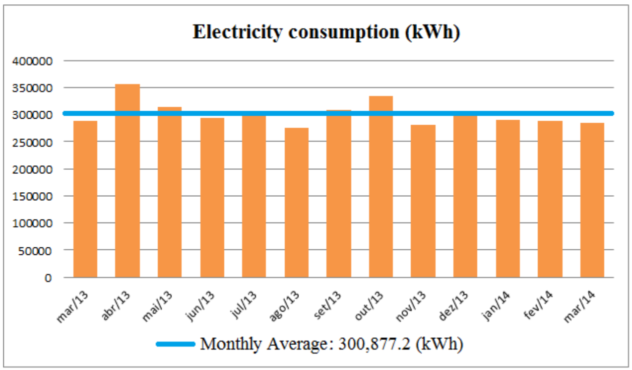

Fig. 8. Monthly electric power consumption [kWh]

The end consumer price is formed by various items, such as the contracted demand, the consumption level, Government taxes and exceeded consumption fee. Thus, a different price is charged for every month. In order to simplify this study, an average price was calculated based on a kilowatt-hour unit for a period of thirteen months. The calculated price was 0.247 R$/kWh per month.

This study showed that the energy produced by the PV is not sufficient to supply the building's energy demand. As such, selling the photovoltaic energy is not recommended, but is use can reduce the amount of energy purchased from the energy provider.

B. *Investment costs*

A survey of market prices was conducted for this specific study by consulting specialized companies. Survey results showed that the total initial cost for the PV system in Alternative 1 is R$ 639,760.00, this resulting in a unit cost of 7.31 R$/kWp. This amount includes the acquisition of modules and inverters, installing structures, hiring manpower, etc.

C. *Economical viability indicators*

The following parameters were used to calculate the economical feasibility analysis, as indicated in reference [2]:

- Unit cost of PV system: 7.31 R$/kWp.
- Maintenance and operation costs: 1% of investment costs per year.
- Project lifetime: 25 years.
- Minimum Acceptable Rate of Return (MARR): 7.5% per year.
- Residual value: zero.
- Efficiency loss of modules: - 0.75% per year.
- Average monthly tariff : 0.247 R$/kWh per month
- Revenue: annual savings in energy bill with the PV System = R$ 33,846.79.
- Replacement of inverters: once every 10 years.

Table VII shows the contribution of photovoltaic power generation to reduce the purchasing of energy in one year.

Table VII. – Annual average savings

Annual average consumption of building (kWh)	3,610,526.00
Annual average cost of consumption (R$)	892,666.30
PV's annual production (kWh)	136,780.12
Annual savings (R$)	33,846.79

The economic indicators used to assess this project were:

- Net Present Value (NPV).
- Modified Internal Rate of Return (MIRR).
- Payback.

Table VIII presents the investment indicators calculated for this case study.

Table VIII. – Economic indicators to PV system

Economic Indicator	
NPV	- 421,584.89
MIRR	5.09%
Payback	Up to 25 years

The economic indicators used in this analysis show negative results. As such the proposed investments are not recommended. Nevertheless, the project variables are in constant change, which indicates that the PV system may be feasible in the following years, as it is shown in the sensitivity analysis below.

D. *Sensitivity analysis*

This analysis considered that there are annual energy rate adjustments in Brazil, PV costs are in constant reduction and BNDES, the Brazilian Government investment bank, uses a rate of 5% for similar investments.

According to reference [3], PV costs will reduce about 5% per year and rate adjustments for conventional energy will be between 4 and 7% per year. Based on such data, some simulation scenarios were created, in which the project variables were changed one at a time, while the other variables were kept the same.

D.1 Sensitivity analysis: energy tariff

In the 1st scenario the energy price was adjusted to a 7% annual rate. Figure 9 shows the impact of price changes in the NPV. As it can be observed, prices above 0.5417 R$/kWh make the PV system feasible by NPV indicator. The same was observed for MIRR and Payback.

By proving the trend considered in this scenario, at the date of this article was written, there was a price adjustment by the local energy provider, thus increasing the energy average costs by 24.97%, as of September 2014.

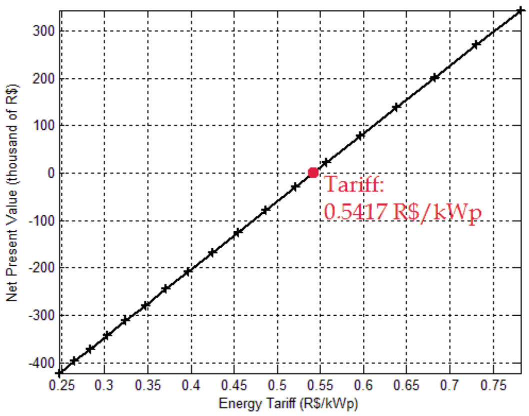

Fig. 9. NPV with changing prices

D.2 Sensitivity analysis: initial cost

In the 2nd scenario it was considered that there will be a reduction of initial costs of PV systems in the following years at a rate of 5% per year. Figure 10 shows how the initial cost affects the MIRR indicator. An initial cost around 4.6178 R$/kWp makes the MIRR higher than the MARR, thus making the project economically attractive. For NPV and Payback the system will be feasible to the initial cost above 3.34 R$/kWp.

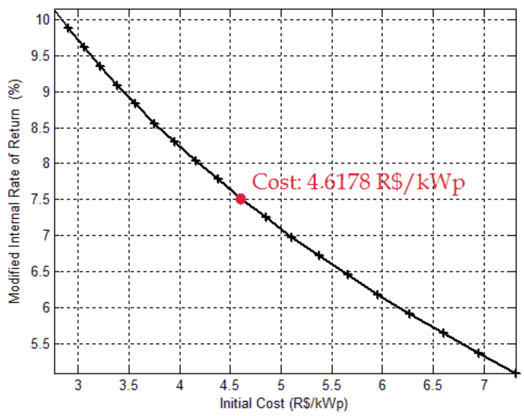

Fig. 10. MIRR with initial cost reduction

D.2 Sensitivity analysis: MARR

In the 3rd scenario a reduction of 7.5 to 5% in the Minimum Acceptable Rate of Return was assumed. Figure 11 shows that the NPV is affected positively. Payback is affected positively too, but MIRR is affected negatively.

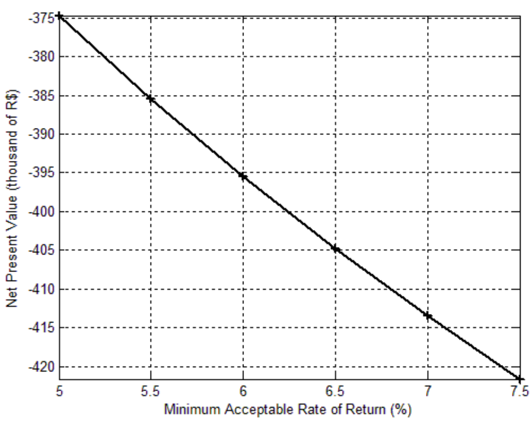

Fig. 11. NPV with MARR reduction

D.2 Sensitivity analysis: the most likely scenario

Finally, the most likely scenario for the following years was simulated. A reduction of 30% in the initial cost of the PV system was established, with a tariff of 0.425 R$/kWh and a MARR of 5%. Table IX shows that in this scenario the PV system is economically feasible according to the economic indicators.

Table IX. – Economic indicators to PV system

Economic Indicator	
NPV	190,414.00
MIRR	9.71%
Payback	13.15 years

4. Conclusion

The study carried out in this paper evaluated the technical and economic aspects of a photovoltaic system installation on the rooftop of a public building in the city of Goiânia, Brazil. Under current conditions, the project is feasible from a technical point of view, but it presented negative economical indicators.

Nevertheless, the sensitivity analysis showed that that the changes in project variables can make photovoltaic technology economically feasible in Brazil in the near future.

For the insertion of PV system in the national energetic matrix, the experience of developing countries shows that government investment is essential for its implementation. Strong government intervention will be necessary to change the photovoltaic system variables indicated in this research work, thus making it economically feasible in Brazil. This can be achieved through the adoption of efficient public policies that promote the nationalization of the production chain, reduce taxes, create special conditions for investment rates, encourage research, disseminate solar photovoltaic culture in society and implement adequate regulations.

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