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TECHNICAL, ECONOMICAL AND COMPUTATIONAL ANALYSIS OF A PV SYSTEM ON A BRAZILIAN UNIVERSITY: A CASE STUDY

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Abstract. *PV solar has been showing to be an excellent option for electricity generation. This is also a renewable, non-pollutant source of energy. Despite not being any novelty, the growth of this type of energy in Brazil has increased particularly in the last three years due to governmental incentives for small-scale distributed generation. This study aims to evaluate, from a technical and economic point of view, the viability of installing a PV system for supplying the electrical demand of professors' offices at a building in a Brazilian public university. For that, the system was projected through theoretical methodology and further compared to the results from computational software PVSyst^{TM}. The economic analysis was based on Monte Carlo method using software Crystal Ball^{TM} trough statistical analysis of payback and Net Present Value for various scenarios. Results have shown the investment in such systems becomes more attractive as financing grows. This research allowed to confirm the applicability of PV technology for this particular case study, both technically and economically. The investment on PV panels has been proved to be a suitable option for Brazilian universities to reduce expenses on electricity and to redirect cash for projects and researches.*

Keywords: *PV solar energy, economic analysis, PV system dimensioning, viability, computer simulation*

1. INTRODUCTION

Population growth and industrialization have been leading to an increase in energy consumption in Brazil and the world (EIA, 2017; EPE, 2017). From 2010 to 2016 only, world has registered significant increasing in energy consumption (9.1 %) (British Petroleum, 2017), population (7.4 %) (World Bank, 2018a) and carbon dioxides emissions (6.0 %) (British Petroleum, 2017). The current scenario, associated with environmental concerns, has encouraged researchers and case studies of options like geothermal, wind, hydro and solar energy (Hussain et al., 2017; IRENA, 2014).

Among these options, solar PV has been especially focused due to a recent and quick decrease in its costs, showing a generation cost 3 times less expensive than it was 9 years ago (IRENA, 2014).

The decrease of the prices, due mostly to the decrease in PV modules costs, has been accelerated by governmental incentives, making PV generation even more attractive (Strupeit, 2016). The growing viability of this type of energy explains the increase in its installed capacity in both residential and commercial sectors.

The Brazilian government has been creating incentives for the use of solar energy in the country (Fraga et al., 2018). Among these, taxes deduction for transmission and distribution, tax-free generation, facilitation of PV equipment imports and special financing options for distributed generation can be highlighted (MME, 2017).

Brazil geographic location between the tropics favors solar energy use. Almost 90 % of Brazilian territory receives an average solar radiation greater than 4 kWh/m².day. Despite that, Brazil counts with only 1.2 GW of installed capacity (ANEEL, 2018; World Bank, 2018b). For comparison purposes, Germany presents an installed capacity of 42 GW (IRENA, 2018), even though receiving much less solar radiation than it is registered in most of the Brazilian territory (World Bank, 2018b).

Up until 2012, Brazil had 2 MW of installed PV capacity (EPE, 2017; IRENA, 2018). From then on, with the normative resolution nº 482/2012 of ANEEL (Brazilian National Agency of Electrical Energy), it was created a compensation system that allows excess electricity to be injected into the grid, generation credits for the consumer that can be used in the future (ANEEL, 2014). This resolution has favored distributed generation and allowed solar PV energy

to grow in Brazil, jumping from 1784 micro and mini-generation plants in 2015 to approximately 29,000 in May of 2018 (ANEEL, 2018).

Although on-grid PV systems not necessarily increase grid's reliability, the decrease in the paid value by the consumer can offer an option for medium-term investment. This scenario is particularly attractive for institutes that need to conciliate monthly expenses among various activities, as it occurs in public universities.

Thus, this work evaluates the viability of installing PV panels for the supply of demand in a professor's office building at UNIFEI, located in Itajubá, state of Minas Gerais, Brazil. The evaluation was done through technical, economic and computer simulation analysis.

2. MATERIALS AND METHODS

The study was done for IEM's building, located in Itajubá, Minas Gerais, Brazil, with an altitude of 842 meters. The building has three floors and 73 rooms, divided into offices, meeting rooms and secretaries. The roof where the solar panels should be installed has 53.5 m x 12.8 m and an azimuthal angle of 37° from the North (Y=37). Figure 1 shows IEM's building and a view from the roof where the panels are to be installed, respectively.

Figure 1. Mechanical Engineering Institute's (IEM) building.

It has been proposed the use of PV panels as an option for electricity generation at lower prices than those observed by the local energy company. For that, it was done a project dimensioning followed by an economic analysis. Dimensioning is done by creating a theoretical model to be later validated using computational software PVSyst™.

2.1 System dimensioning

PV system dimensioning was based both on consumption data registered by an electrical measurement device installed in the building and on irradiation intensity for the place. Table 1 presents information related to electricity demand.

Table 1. Electricity consumption for the building in kWh.

Month	Off-peak electricity consumption (kWh)	Peak electricity consumption (kWh)	Total consumption (kWh)
Oct/2017	3820.1	381.2	4201.3
Nov/2017	3464.1	430.4	3894.5
Dec/2017	3034.6	330.6	3365.2
Jan/2018	2190.4	211.1	2401.5
Feb/2018	2938.8	388.3	3327.1
Mar/2018	4256.9	488.9	4745.8
Apr/2018	3885.7	425.8	4311.5
Mai/2018	2999.3	342.3	3582.5
Average	3325.6	374.2	3730.6

In this study, energy consumption will be considered as constant based on the month in which more energy is used (March/2018). Since IEM's building is not isolated (it belongs to the same consumer unit as the university), possible excesses in the generation can be used to reduce the consumption at UNIFEI.

PV panels considered for dimensioning and computer simulation are from model Canadian Solar CS6P-265, whose data are presented in Table 2.

Table 2. Technical information for PV panel CS6P-265.

Canadian Solar CS6P-265	STC	NOCT
Nominal maximum power (P_{max})	265 W	192 W
Optimal operating voltage (V_{mp})	30.6 V	27.9 V
Optimal operating current (I_{mp})	8.66 A	6.88 A
Open circuit voltage (V_{oc})	37.7 V	34.7 V
Short circuit current (Isc)	9.23 A	7.48 A
Module efficiency	16.47 %	11.94 %
Cell type	Polycrystalline	
Dimensions	1638 x 982 x 40 mm	
Temperature coefficient (P_{max})	-0.41 % / °C	

By using the information presented by tables 1 and 2, it is possible to calculate the amount of electricity generated per month by each panel by using the irradiation data of IEM's location, by using Eq. (1) and the necessary number of panels to supply electricity demand, by using Eq. (2).

$$E_{prod} = \frac{d \cdot E_{rad} \cdot A \cdot \eta}{1000} \qquad (1)$$

$$N_{panels} = \frac{E_{c,avg}}{E_{p,avg}} \qquad (2)$$

Where E_{prod} is the produced energy, d is the number of days in each given month, η is the module efficiency in STC, $E_{c,avg}$ is the average electricity consumption and $E_{p,avg}$ is the average electricity produced.

Incident radiation (E_{rad}) over a tilted surface with azimuthal deviation can be estimated based on solar radiation and geographic parameters as latitude and solar declination. Table 3 presents values for horizontal irradiation $E_{rad,hor}$ for Itajubá according to CRESESB database alongside the estimated radiation for a surface with 10° inclination and 37° azimuthal deviation based on the method proposed by Sukhera et al., 1984.

Table 3: Irradiation over horizontal and tilted surfaces (10°).

	CRESESB	SUKHERA et al.
Month	$E_{rad,hor}$ [kWh/m²day]	E_{rad} [kWh/m²day]
January	5.37	5.29
February	5.68	5.55
March	4.93	4.75
April	4.57	4.48
May	3.83	3.83
June	3.57	3.60
July	3.79	3.81
August	4.69	4.64
September	4.96	4.79
October	5.42	5.28
November	5.38	5.29
December	5.81	5.73

At the same time, by using the software PVSyst[TM] and data presented at tables 1 and 2 it was possible to calculate the number of panels, the produced energy and the energy injected to the grid, i.e., considering all expected losses.

After calculating the number of panels and its produced energy, the inverters should be dimensioned. Selection of the inverter must take into account maximum voltage and power of each string. The maximum voltage for an inverter ($V_{OC,inv}$) is calculated based on the number of panels in the string ($N_{PV,string}$) and the open circuit voltage of the panel (V_{OC}). It is known that the nominal voltage increases as temperature decreases (see Table 2). Thus, the coefficient of variation of voltage with temperature (ζ_v=0.41 %/°C) was considered for selecting the inverter. It was also adopted a safety factor (F=1.1). Calculation for inverter maximum voltage is according to equation (3). The maximum temperature variation (T_0-T_{min}) is considered to be 25 °C.

$$V_{OC,string} = F \cdot V_{OC} \cdot \left\{ 1 + \left[\zeta_V \cdot (T_0 - T_{min}) \right] \right\} \cdot N_{PV,string} \tag{3}$$

Since the power generated also has a coefficient of variation with temperature ζ_p, maximum power in the inverters $P_{max,inv}$ is calculated in the same way. In this case, however, the power of each inverter must be multiplied for the number of the strings ($N_{strings}$) connected to the inverter. The maximum power can be obtained from equation (4).

$$P_{max,inv} = P_{max} \cdot \left\{ 1 + \left[\zeta_P \cdot (T_0 - T_{min}) \right] \right\} \cdot N_{PV,string} \cdot N_{string,inv} \tag{4}$$

This way, maximum power and voltage to be operated by each inverter are calculated.

2.2 Economic analysis

According to normative resolution n°. 414 de 2010 by ANEEL, consumer units that operate 2.3 kV or higher are classified as high voltage consumers. In these cases, the distributor must supply a predefined power and the consumer unit must pay a referent value whether the energy is consumed or not.

Consumer units are divided into five groups. UNIFEI belongs to group A4 (voltage between 2.3 kV and 25 kV) and receives a supply of 13.8 kV. The taxes are composed by the contracted demand and by the value associated with the peak (17pm-22pm, Monday to Friday) and off-peak (remaining hours). The taxes for May 2018 was 0.36142 US$/kWh (peak) and 0.07925 US$/kWh (off-peak).

In this study it was considered that the energy is always generated in off-peak hours, so the reduction of the value paid for electricity is equal to the injected energy times the off-peak tax.

The economic analysis was made through simulations in Crystal Ball™ software by varying the rate of change of the taxes and the efficiency loss on the panels over time. Net present value method was used for different financing scenarios.

Following, the main concepts related to this economic analysis and the assumptions made are commented.

- Initial investment

The initial investment is estimated as a proportion that takes into account the costs of the panels and the inverters and its contribution to the total costs, herein assumed as approximately 80 % of total costs. The remaining costs are due to manpower, cables and other electric materials, according to Figure 2. These values were assumed based on real budgets.

Cost division in a regular PV system

- 68.6 % PV Panels
- 10.05 % Inverter
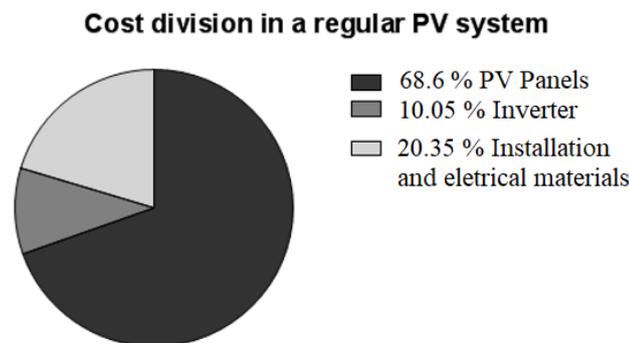- 20.35 % Installation and eletrical materials

Figure 2: cost distribution on a regular PV system.

- Minimum attractiveness rate

Once the proposed investment will be done with governmental funds, the minimum attractiveness rate will be adopted as equal to the SELIC interest of 6.5 % per year.

- Inflation and taxes

Inflation was not taken into account in this analysis since the floating of values in various sectors cannot be foreseen. Besides, inflation tends to increase the viability of the project, thus adopting a value of 0 % can be considered a pessimistic approach. If the project is proven to be suitable even then, it will be even more attractive in a real situation. Taxes are not applied since UNIFEI is a public institution and thus tax-free.

- Panels efficiency loss

PV panels tend to lose efficiency over its lifetime. According to NREL report "Photovoltaic Degradation Rates - an analytical review (Jordan and Kurtz, 2013), the decrease in the generation can vary from -0.2 % to 4.2 %, but the average value for polycrystalline panels installed after 2000 is 0.59 %. For this analysis, it was adopted a triangular distribution with the same range with 0.59 % as the more probable value.

● Financing and interest rate

Since UNIFEI is a governmental institution, it cannot make any type of investment. However, for this work it will be assumed a financing option up to 80 % provided at an interest rate of 6.0 % per year. This financing can be paid in up to 25 years. This choice was made based on BNDES financing options.

● Electricity tax increase rate

Based on historical data of local electricity taxes, it was estimated a yearly variation between -1 % and 15 %. This analysis considered that the more probable variation is 6 % and a triangular distribution was applied.

● Payback period

Payback period refers to the amount of time in which an initial cash outflow is expected to be recovered through cash inflows generated by the initial investment.

● Net present value (NPV)

NPV is a common method used in economic viability analysis. This method consists basically in the transfer of all the expected cash inflows and outflows, discounted to the minimum rate of attractiveness, to the current date. Eq. (3) presents the NPV calculation.

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+MARR)^t} \qquad (3)$$

At equation (3), C_0 represents the initial investment, MARR represents the minimum attractiveness rate and CF_t is the cash flow during the period of analysis.

By using software Crystal Ball[TM], simulations were carried out to estimate the expected NPV for different scenarios by varying the initial investment, minimum attractive rate, financing and interest rate of it, panel efficiency loss and energy tax increase rate. Payback period was also verified with Crystal Ball[TM].

3. RESULTS

3.1 Dimensioning results

Once the average irradiation and the nominal power of the panels are known, the number of panels needed to supply the electrical demand is directly calculated as presented in Table 4.

Table 4: calculation of the number of panels.

Average irradiation [kWh/m²dia]	Power per panel [kWp]	Monthly energy per panel (without losses) [kWh]	Monthly energy consumed [kWh]	Number of panels needed
4.75	0.265	37.76	4745.8	126

The procedure for selecting the inverters must take into account the panels arrangement and the number of strings to be connected to each inverter. For this project, it was proposed 6 strings with 21 panels each, totalizing 126. Since the maximum power expected is relatively high, the strings can be divided equally between two inverters Fronius Symo 12.5-3-M, which operate inputs up to 1000 V and 18.8 kWp. Table 5 presents the results of the inverters dimensioning.

Table 5: inverters dimensioning.

V_{OC} [V]	$N_{PV,string}$	$N_{string,inv}$	$V_{OC,inv}$ [V]	$P_{max,inv}$ [kWp]
37.7	21	6	938.4	36.8

The results shown in tables 4 and 5, were validated by using PVSyst[TM] software. As in occurred for the applied theoretical model, computer simulations have also obtained 126 PV panels, with 6 strings containing 21 modules each.

Table 6 shows the electricity production per month of the proposed PV system for both theoretical model and computer simulation. It is important to notice that the difference between $E_{prod.}$ (produced energy) and $E_{inj.}$ (energy injected to the grid) in the theoretical model is due to losses as mismatch, temperature and Ohmic wiring losses, herein adopted as 23 %.

Since the losses in the theoretical model were estimated and not calculated, some difference between the injected electricity in theoretical and computational models can be identified. By analyzing injected energy ($E_{inj.}$) over the years, the two models have presented a variation of approximately 8 %.

Table 6: calculation of the number of panels.

	Theoretical model [MWh]		PVSyst^{TM} simulation [MWh]	
	$E_{prod.}$[A]	$E_{inj.}$[B]	$E_{prod.}$[C]	$E_{inj.}$[D]
January	5.472	4.214	4.506	4.182
February	5.192	3.998	4.349	4.048
March	4.916	3.785	4.429	4.120
April	4.491	3.458	4.114	3.829
May	3.966	3.054	4.034	3.762
June	3.608	2.778	3.927	3.665
July	3.944	3.036	4.127	3.849
August	4.806	3.700	4.654	4.340
September	4.796	3.693	4.427	4.116
October	5.463	4.206	4.579	4.260
November	5.298	4.079	4.422	4.106
December	5.930	4.566	4.617	4.294
Monthly average	4.824	3.714	4.349	4.048
Year total	57.887	44.573	52.183	48.570

[A] Produced energy in the theoretical model (without loss)
[B] Energy injected into the grid (after 23 % loss)
[C] Produced energy in the computer simulation (considering temperature, mismatch and Ohmic wiring loss)
[D] Energy injected into the grid considering inverter losses

3.2 Economic analysis

Based on data for tilted irradiation from Table 3 and considering the number of panels calculated, it is possible to estimate the energy generated by the PV system each month. By using known values of electricity taxes, the monthly electricity costs can be calculated for scenarios with and without the PV system. Calculated values are shown in Table 7.

Table 7: estimated reduction on monthly electricity costs.

Month	E_{prod} [kWh/month]	Cost without PV	Cost with PV
January	4.214	USD 337.37	USD 3.40
February	3.998	USD 337.37	USD 20.50
March	3.785	USD 337.37	USD 37.33
April	3.458	USD 337.37	USD 63.25
May	3.054	USD 337.37	USD 95.30
June	2.778	USD 337.37	USD 117.14
July	3.036	USD 337.37	USD 96.68
August	3.700	USD 337.37	USD 44.08
September	3.693	USD 337.37	USD 44.69
October	4.206	USD 337.37	USD 3.96
November	4.079	USD 337.37	USD 14.05
December	4.566	USD 337.37	-USD 24.51
Total/average	44.573	USD 4,048.38	USD 515.87

Based on real prices and budgets, the costs for each panel and inverter was adopted as US$ 213.90 and US$ 3981.81, respectively. Thus, it is estimated a US$ 43644.36 initial investment.

Sensitivity analysis was made from the clash flow, aiming to verify NPV for different scenarios. Financing of 0 to 100 % was studied. Figure 3 presents paybacks for each one of the evaluated cases.

Figures 3 indicate an increase in viability as the financed value grows. This tendency is due to factors like the difference between the money applied in the future and its net present value. Despite the interest rates, financing makes the project more attractive from an economic point of view.
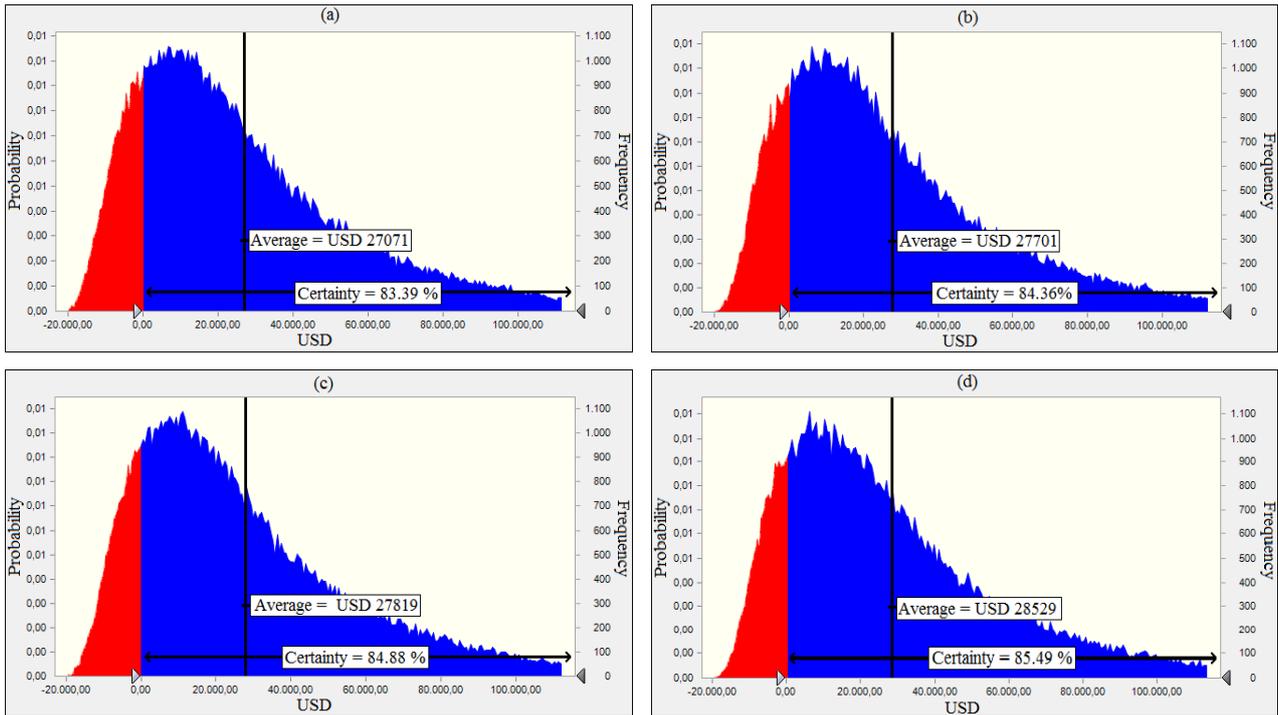
Figure 3: NPL for different financing scenarios – (a) 0 % financing, (b) 40 %, (c) 60 % and (d) 100 %.

Considering all of the variables together in only one analysis, varying discreetly parameters as financing value and financing time, the graph from Figure 4 is obtained. It indicated the high viability of the project, with chances of economic return of over 84 % and 83 % of probability of a Payback in less than 15 years.
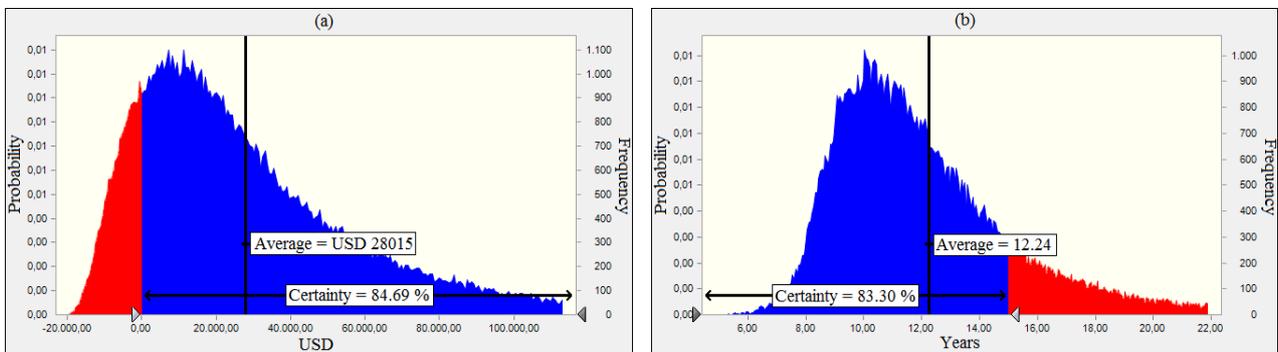

Figure 4: (a) NPV of the system, (b) Payback of the PV system.

Finally, a sensitivity analysis was done considering four parameters: electricity tax, panel price, interest rate and panel efficiency loss; and it is presented in Figure 5. As it can be seen, the increase of electricity tax is the one which has the most positive impact in the NPV of this project, while panel price is the one which prejudice the most.

4. CONCLUSIONS

The comparison between theoretical and computational models has indicated that the theoretical analysis was consistent and able to fully supply the average consumption of the studied building. Installation of 126 265 Wp PV panels and 2 inverters of 18.8 kWp in a 6 strings array was proposed. It is estimated that this PV system will be able to supply 44-48 MWh to the grid yearly.

NPV time for different financing scenarios shows high probability of this project being economically viable, in special with the increase in the amount of financing. A general case study, varying all parameters together presented a high probability of a positive NPV and an average Payback of 12 years.

Sensibility analysis shows that an increase in the electricity tax can greatly rise the NPV of the project, which is normal to occur. An increase in the interest rate and panel efficiency loss prejudices the viability of the project, but not as

much as the increase in panel price does, which indicates that governmental incentives by reducing module costs can rise the PV systems viability and make this energy production even more attractive.
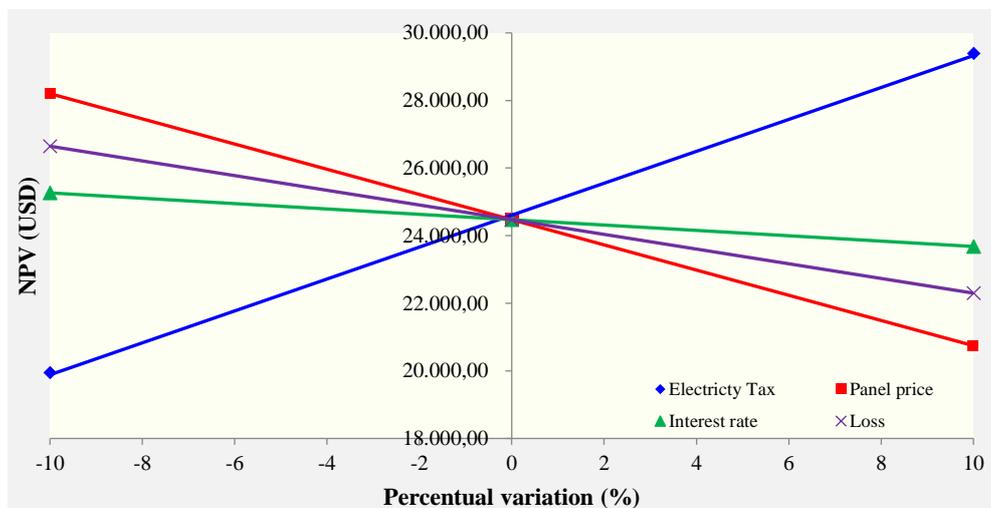

Figure 5: Sensitivity analysis.

Computer simulation has estimated a performance ratio of 80.4 %, putting the project as a high-efficiency system. Simulation has also shown that the panels are able to inject 3.99 kWh/kWp yearly. Thus, the option for PV systems in public universities has proved to be an excellent option for reducing electricity expenses, allowing the governmental funds to be applied to projects and research. In this particular case study, the system was able to save about US$ 3.532,51 yearly.

5. ACKNOWLEDGEMENTS

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