Techno-Economic Analysis of a PV (Photovoltaic) Plant for High Radiation Conditions from the Altiplanic of Bolivia

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Abstract

The altiplanic of Bolivia has one of the best solar resources in the world due to the high annual radiation that reaches these places that combined with its unique geography, climate and other aspects, make it an ideal place to implement different solar projects. In addition, the different mineral deposits such as tin, zinc, antimony, gold, copper, lithium and others, which are exploited in an unsustainable way with the environment. Currently through solar energy is intended to provide sustainable energy solutions to different mining processes, which are directly related to the economic cost of electricity, this due to different subsidies that the state of Bolivia makes to the price of electricity due to the production of fossil fuels, in addition this place is isolated from the country's national electricity system interconnected which outlines an opportunity for the development of solar power generation projects that can gradually cover the demand for energy. This publication presents a technical and economic analysis by obtaining the capacity factor, investment cost and the estimated Levelized Cost Of Energy of a 60 MW solar photovoltaic plant located in the Department of Potosí (20.59 S, 66.78 O), which can be compared with a real plant of the same capacity located in the municipality of Uyuni.

Keywords: Solar Photovoltaic, LCOE, Bolivia, High Radiation.

1. Introduction

The electricity sector is experiencing a period of rapid and unprecedented change in the scale and breadth of deployment of renewable energy generation technologies. Since 2012, they have accounted for more than half of the new additions of power generation capacity worldwide. New additions of renewable energy in 2016 reached 162 GW, with 36 GW of new hydropower capacity, 51 GW of wind power, 71 GW of solar photovoltaic (PV) power, 9 GW of bioenergy power generation capacity and a combination of 1 GW of Concentrating Solar Power (CSP), geothermal and marine power (International renewable energy Agency, 2018).

The global photovoltaic market has grown rapidly in the last decade from 2010 to 2016, net additions increased approximately 28 % per year on average and additions in the period represented approximately 94 % of the total capacity installed between 2006 and 2016 (International renewable energy Agency, 2018).

In Bolivia, since 2014, electricity generation has been registered for the first time through two renewable energy sources such as wind energy and solar energy (Ministerio de hidrocarburos y energia del estado plurinacional de Bolivia, 2015).

Energy production in 2017 was 8981.3 GWh; of which 2229.9 GWh corresponded to hydroelectric production, 6690.0 GWh to thermoelectric production, 60.4 GWh to wind production and 1.1 GWh to solar generation, equivalent to 24.83 %, 74.49 %, 0.67 % and 0.01 %, respectively (Comité Nacional de Despacho de Carga, Ministerio de Energías and Estado Plurinacional de Bolivia, 2017).

Bolivia currently has 91% national coverage of electric service, of which 99% in urban areas and 80% in rural areas, and it is expected to reach 100% national coverage by 2025 (Raul Dominguez, 2019). There is an enormous mining potential in Bolivia, which is found in the Andean Orogen (Western and Eastern Cordillera, Altiplano and Sub-Andean), which covers approximately 42 % of the national territory and hosts more than 2200 prospects and mines of silver, tin, wolfram, antimony, lead, zinc, copper, bismuth, gold, and so on. This important potential has allowed the mining sector to become one of the main economic activities of the country (Ministerio de hidrocarburo y energia,

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2014).

At the beginning of 2019 Bolivia had an energy supply of 2235 MW compared to an energy demand of 1511 MW. With a reserve in the system of 724 MW, the existing reserve allows domestic demand to be guaranteed and consolidates energy export projects to neighboring countries such as Argentina and the study of interconnection with Peru (Raul Dominguez, 2019).

The generation of electricity through renewable sources is very new in Bolivia currently have connected to the national interconnected system two photovoltaic plants of 60 MW located in the town of Uyuni in the department of Potosi and another photovoltaic plant of 5 MW of power located in the town of Yunchara in the department of Tarija, on the other hand the wind generation is concentrated in the town of Qollpana in the department of Cochabamba, which has a power of 27 MW. The first experience of generation with renewable sources was given in the municipality of Cobija city of Pando in which is installed the first hybrid photovoltaic diesel system with a power of 5MW, another hybrid photovoltaic plant called Sena in the Municipality Madre de Dios, city of Pando that has a power of 400 kW, being both plants isolated systems. Analyzing the information obtained from the CNDC (Comité Nacional de Despacho de Carga, 2019), the supply of energy through renewable sources has a percentage of approximately 2% of which 1.74% are generated through photovoltaic energy and 0.17% from wind energy.

2. Procedure

2.1. Modeling and simulation

Annual yield, capacity factor, investment cost, and leveled energy cost were evaluated using simulated models in Matlab software, simulation models, and the main assumptions for evaluating PV plant performance under particular site conditions are presented in the following sections.

2.2. Solar resource

The present study was carried out using meteorological data per hour of the meteorological year type (TMY) obtained through the National Solar Radiation Database, the data included are Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Horizontal Diffuse Irradiance (DHI), ambient temperature, relative humidity and wind speed. The place considered for the study is (20.59 S, 66.78 O). The western part of Bolivia is characterized by high daily solar radiation with an annual GHI of 7.4 kWh m^{-2} and an annual DNI of 9.5 kWh m^{-2}, which greatly influences the performance and profitability of the PV plant. Figure 1 and 2 show the solar radiation values throughout the year.

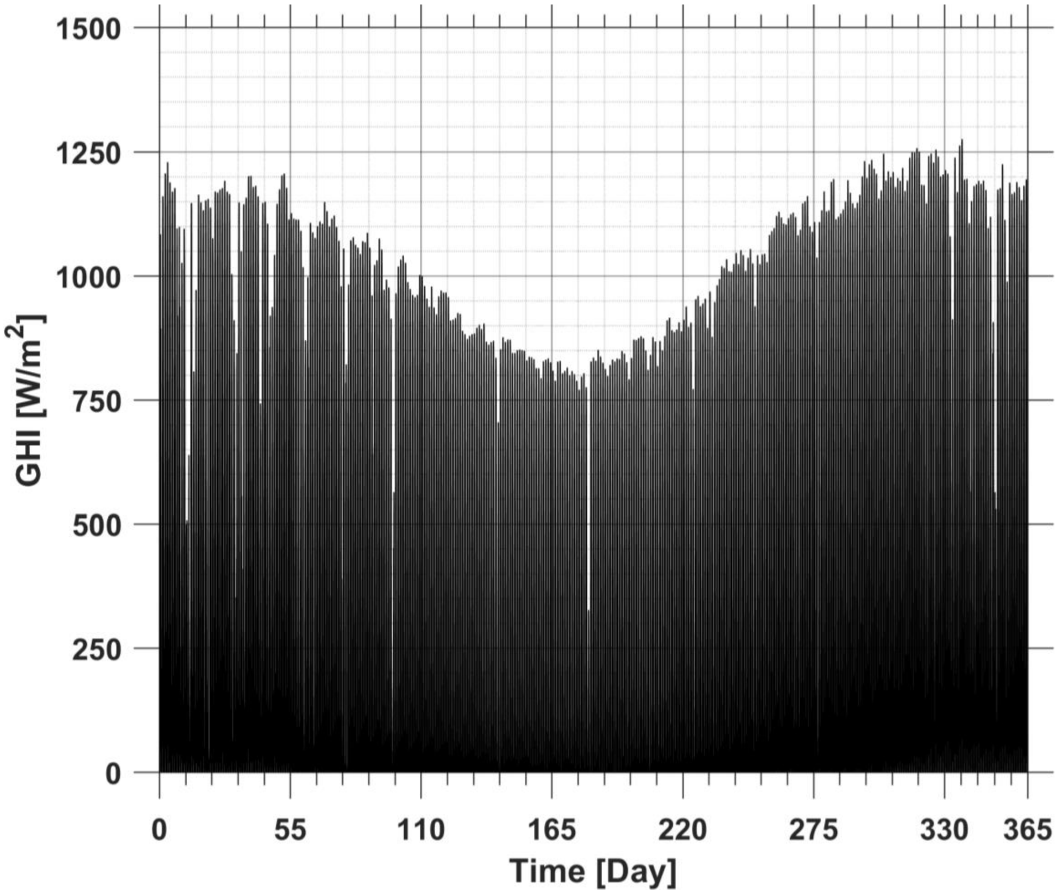

Fig. 1: Global solar radiation during one year.

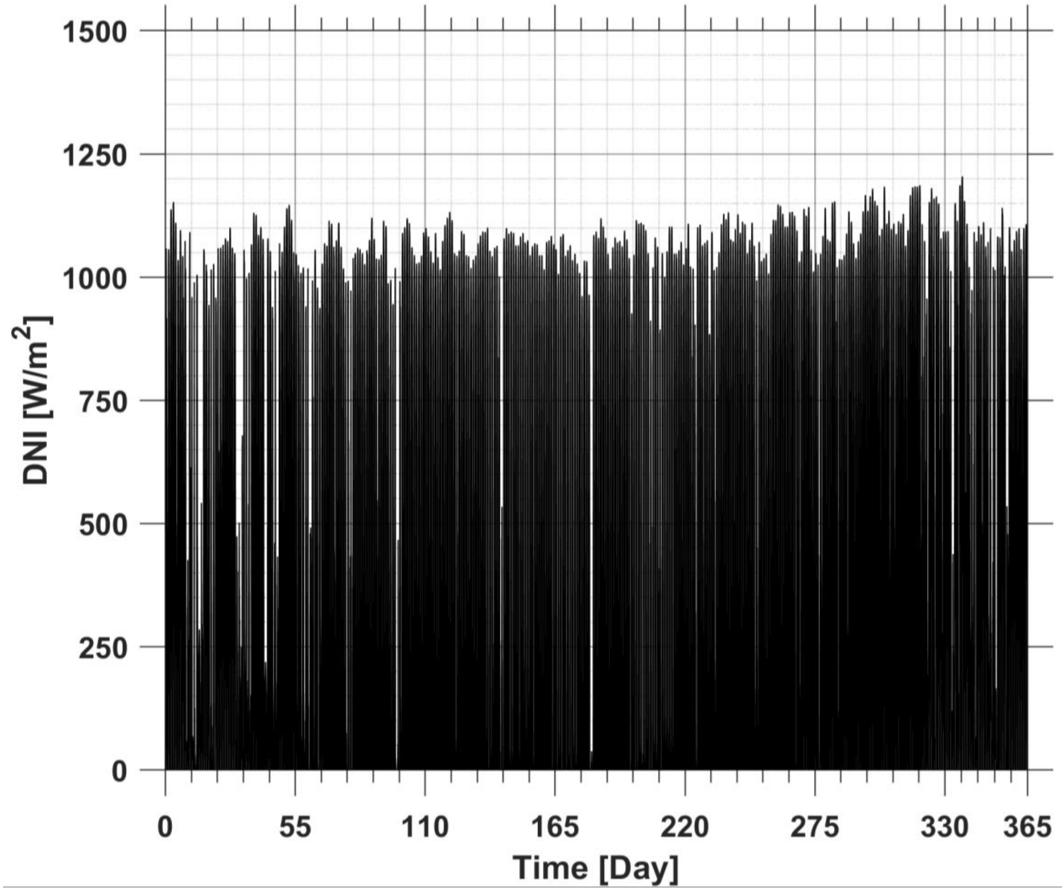

Fig. 2: Direct normal radiation within one year.

2.3. PV plant model

The PV plant was modeled for an output of 60 MW consisting of 187500 fixed-axis modules characterized by a nominal output of 320 W. The main characteristics of the photovoltaic module are shown in Table 1.

Tab 1: Parameters taken for the PV system (Etsolar, 2017) (Petrollese and Cocco, 2016).

Plant PV		
Parameter	**Value**	**Unit**
Nominal power of the module	320	W
Efficiency	16,5	%
Temperature coefficient	-0,41	% ºC-1
Type	Polycrystalline	
Effective area of the panel	1,940352	m-2
Nominal working temperature of the module	45	ºC
Nominal incident radiation in the module	800	W m-2
Ambient temperature NOCT	20	ºC
Nominal efficiency of the inverter	97,8	%
Power reduction factor	0,8	
Absorbance-transmittance coefficient	0,8	
Nominal convection coefficient NOCT	9,5	
Cell temperature under standard test conditions	25	ºC

The orientation of the fixed modules is northward with azimuth equal to 0º, while the calculation of irradiations on inclined surfaces from data on horizontal surfaces, with an inclination equal to latitude, the irradiation on the GI surface at the optimum inclination is calculated by the method described in (Duffie and Beckman, 2001).

The photovoltaic yield is affected by the temperature of the cell which is involved in the model through the equations proposed in (Duffie and Beckman, 2001), where T_C is the actual operating temperature of the photovoltaic module, T_A is the ambient temperature, T_{NOCT} is the nominal operating temperature of the cell, GI is global irradiance, GI_{NOCT} is global irradiance nominal and equal to 800 W m^{-2}, U_{LNOCT} and U_L are heat transfer coefficients under nominal and real conditions respectively, τ_α is the absorbance-transmittance coefficient.

$$T_C = T_A + (T_{NOCT} - T_{ANOCT}) * \left(\frac{GI}{GI_{NOCT}}\right) * \left(\frac{U_{LNOCT}}{U_L}\right) * \left(1 - \frac{\eta_{PV}}{\tau_\alpha}\right) \qquad \text{(eq. 1)}$$

The current PV yield η_{PV} and the heat transfer coefficient U_L is calculated by means:

$$U_L = 5.7 + 3.8 * v_{viento} \qquad \text{(eq. 2)}$$

$$\eta_{PV} = \eta_{PVnom} * (1 + \gamma * (T_C - T_{CREF})) \qquad \text{(eq. 3)}$$

Where v_{viento} is the wind speed of the place, η_{PVnom} is the nominal efficiency, γ is the temperature coefficient, and T_{CREF} is the operating temperature of the cell in reference conditions and equal to 25ºC. The output power of the PV panels is calculated using the following equation:

$$P_{PV} = n_{mod} * A_{mod} * GI * \eta_{PV} * \eta_{INVnom} * f_{PV} \qquad \text{(eq. 4)}$$

Where n_{mod} is the number of photovoltaic panels, A_{mod} is the effective area of each photovoltaic panel, η_{INVnom} is the nominal efficiency of the inverter, and f_{PV} is a power reduction factor, which takes into account panel dirt, cable losses, shading, snow cover, aging and other losses of secondary elements (Petrollese and Cocco, 2016).

2.4. Capacity factor

The capacity factor is the relationship between the predicted electrical output of the system in the first year of operation and the output of the nameplate, which is equivalent to the amount of energy the system would generate if it operated at its rated capacity every hour of the year. The annual capacity factor is calculated by:

$$CF = \frac{E_{planta-anual}}{P_{planta}*8760} \qquad \text{(eq. 5)}$$

Where $E_{planta-anual}$ is the actual annual production, and P_{planta} is the nominal power output of the plant (Zhai *et al.*, 2017).

2.5. Levelized Cost Of Energy (LCOE)

The levelized cost of energy is the price that must be received per unit of production as payment for energy production to achieve a specific financial return, or simply the price that the project must earn per megawatt-hour to reach equilibrium point. The LCOE calculation standardizes the units of measurement of the life cycle costs of electricity production thus making it easier to compare the cost of producing one megawatt hour per technology (Joseph Salvatore, 2013). The economic evaluation of the system is estimated through the LCOE which is deducted through (Hernández-Moro and Martínez-Duart, 2013) (Zhai et al., 2017).

$$LCOE = \left(\frac{IC + \left(\sum_{n=1}^{N} \frac{AC}{(1+i)^n} \right)}{\left(\sum_{n=1}^{N} \frac{E_{planta-anual} * (1-d)^n}{(1+i)^n} \right)} \right) \qquad \text{(eq. 6)}$$

Where IC is the initial cost of the plant, and consists of the direct cost IC_{dir} and indirect cost IC_{ind} of the plant.

$$IC = IC_{dir} + IC_{ind} \qquad \text{(eq. 7)}$$

AC is the annual cost of the plant, and consists of operation, maintenance and insurance costs. $E_{planta-anual}$ is the energy production of the first year of the plant, d is the annual degradation rate, i is the discount rate, and N is the expected useful life of the plant.

The direct cost of the photovoltaic plant consists of photovoltaic panels, inverters, system balance, and battery costs (Zhai *et al.*, 2017).

$$IC_{PVdir} = IC_{modulos} + IC_{inversores} + IC_{BOS} + IC_{BESS} \ \text{(eq. 8)}$$

On the other hand, each of these costs depends on different parameters that are shown in the following equation.

$$IC_{PVdir} = (c_{modulos} + 2 * c_{inversores} + c_{BOS}) * P_{PVneta} + c_{BESS} * E_{alm} \ \text{(eq. 9)}$$

Where c_{modulo} is the cost of the module, $c_{inversor}$ is the cost of the inverter, c_{BOS} is the cost of the Balance Of System (BOS), which covers all the additional equipment needed to convert direct current from solar modules to alternating current (Hernández-Moro and Martínez-Duart, 2013), c_{BEES} is the cost of the batteries, P_{PVneta} is the total power of the installed modules, and E_{alm} the necessary power of the battery bank, which is not considered in this work.

The indirect cost of the photovoltaic plant consists of the cost of the land $IC_{terreno}$, engineering and construction costs IC_{EPC}.

$$IC_{PVind} = IC_{terreno} + IC_{EPC} \qquad \text{(eq. 10)}$$

Where it can also be:

$$IC_{PVind} = c_{terreno} * n_{mod} * A_{mod} + c_{EPC} * P_{PVneta} \qquad \text{(eq. 11)}$$

Where $c_{terreno}$ is the cost of the land, n_{mod} the number of modules of the plant, A_{mod} is the area of the photovoltaic modules, c_{EPC} engineering cost and costs of construction.

The annual cost is defined in percentages of the initial cost for this system, which entail in operating costs, Maintenance $AC_{O\&M}$ and insurance expenses or contingencies AC_{cont}.

$$AC_{PV} = AC_{O\&M} + AC_{cont} \qquad \text{(eq. 12)}$$

Where

$$AC_{PV} = c_{O\&M} * P_{PVneta} + c_{cont} * IC_{dir} \qquad \text{(eq. 13)}$$

Where $c_{O\&M}$ is the cost for maintenance and operation and c_{cont} is the cost against contingencies.

The costs and financial parameters are shown in the following table 2.

Tab. 2: Estimated costs and financial parameters of a PV system (Fu, Feldman and Margolis, 2018) (Valenzuela *et al.*, 2017).

PLANT PV		
Cost	**Value**	**Unit**
Module	0,35	USD W-1
Inverter	0,06	USD W-1
BOS	0,2	USD W-1
Contingencies	3	%
EPC	0,06	USD W-1
O & M annual	15,4	USD kW-1
Rate of return	8	%
Degradation rate	0,7	%
Time of life	25	Year

3. Results

This section presents the results obtained for the simulation of the 60 MW PV plant with fixed axes and without energy storage.

3.1. Validation of the model

The simulation models previously shown have been compared with those obtained through the SAM tool, the parameters such as the capacity factor and the electrical energy generated with the model in Matlab and SAM maintain a margin of error less than 5% appreciated in table 3, they are shown in the following figure 3.

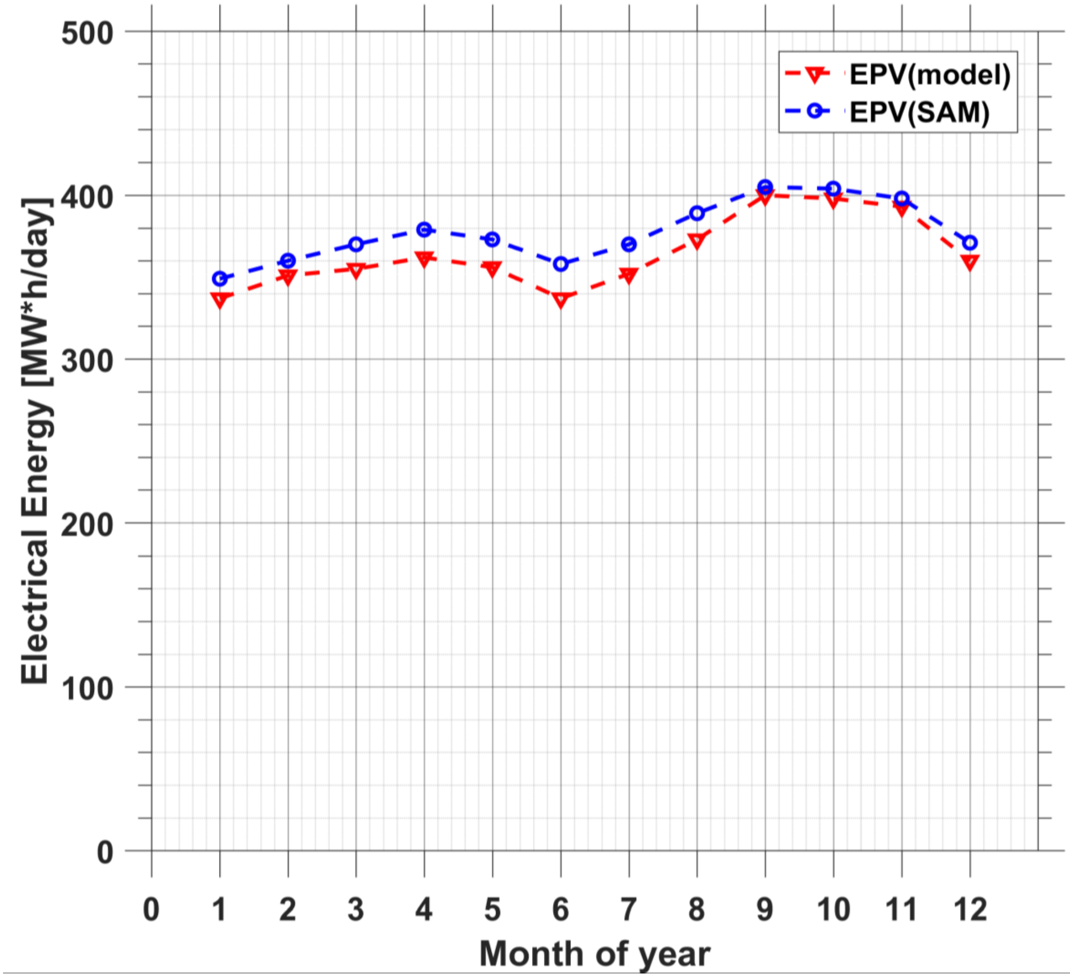

Fig. 3: Variation of the electrical energy generated in each month.

Tab 3: Comparison of the results obtained by the simulation model and SAM.

Parameter	Plant PV	Plant PV	Unit	Error
	Matlab	SAM		%
Capacity Factor	25.31	26.2	%	3.967
Energy annual	133050785	137623792	kWh	3.323

The main results for the study site obtained through the simulated model are shown in table 4 below.

Tab 4: Results obtained by the simulation model.

Plant PV		Unit
Parameter	Value	
Capacity Factor	25.31	%
Investment cost	0.730	MUSD MW^{-1}
LCOE	50.796	USD $MW^{-1} h^{-1}$

The following figures 4 and 5 also present the results obtained from the simulated model for different discount rates and considering different costs of the photovoltaic modules.

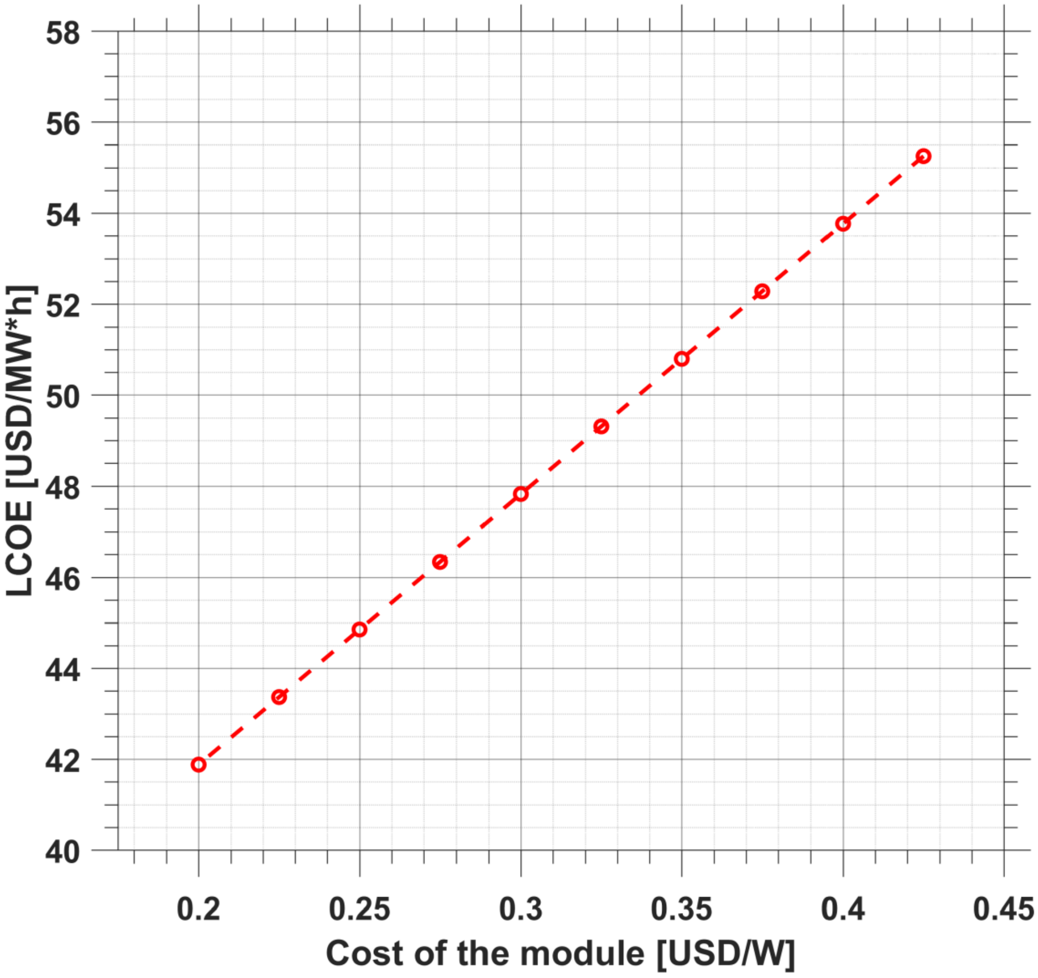

Fig. 4: Variation of the LCOE with the cost of the PV module.

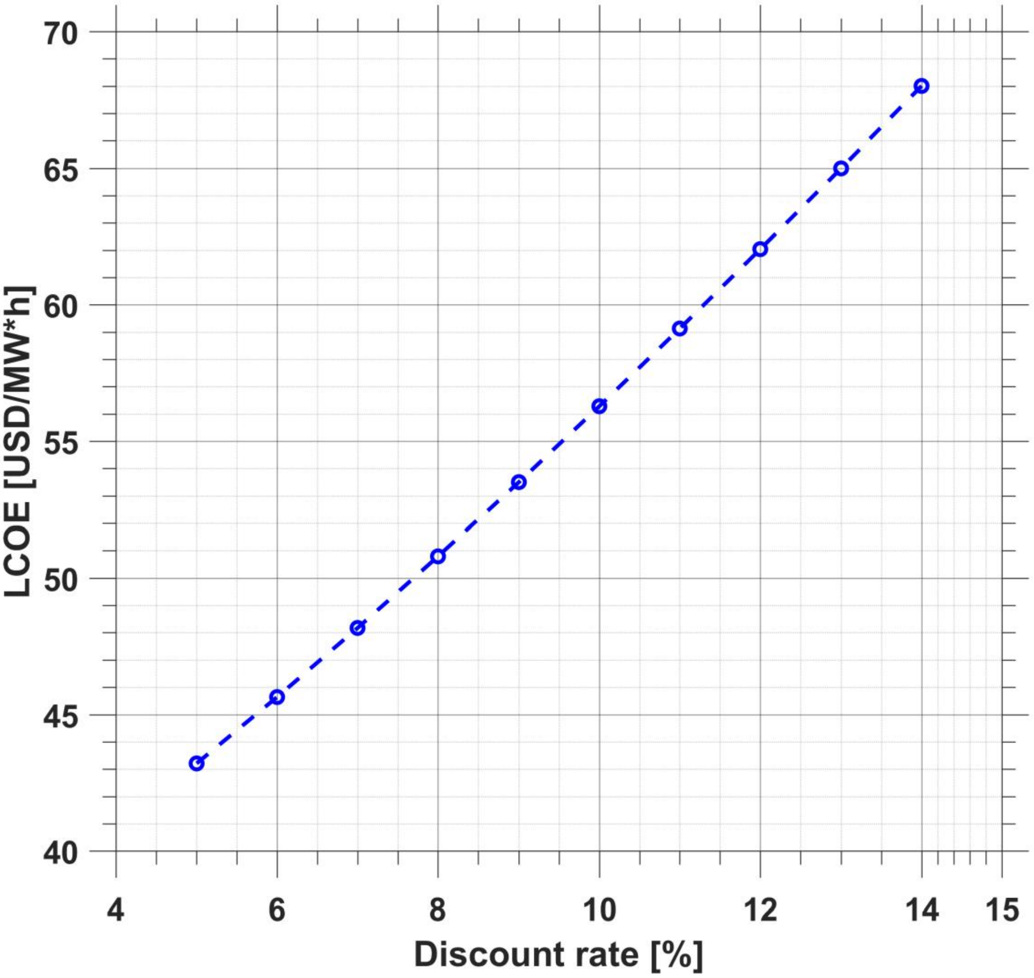

Fig. 5: Variation of the LCOE with the discount rate.

4. Conclusions

The west of Bolivia is a place that has outstanding levels of irradiation, which is currently generating interest for the implementation of solar power generation plants, particularly photovoltaic power generation projects due to its low cost of installation, however this type of systems presents a dynamic generation which is a problem, because you cannot control the atmospheric conditions of the place, consequently the variation of generation does not present a degree of reliability to the consumer, so for this situation is necessary to interconnect to the network to avoid mishaps mentioned.

Due to the fact that the electrical energy generated by the PV modules is strongly related to the hours of sunshine and the irradiation that the place presents, the result of the simulated model shows a capacity factor of 25.31% which is among the highest values that can be obtained in the installation of this type of technology.

The cost attributed to the PV modules affects the variation of the LCOE and in the investment cost of the plant, a projection in decrease of the cost of the PV modules gives as a result that this type of technology is more accessible. In the present work it was considered that the land is not a scarce resource and that the place of installation will be available without any cost attributed to it.

It is also possible to consider the analysis of a PV plant with follow-up which entails an increase in the energy generated as can be seen in the figure, but also implies an increase in the costs of installation and maintenance of the same. The most suitable type of project depends on several factors such as market prices, technical limitations and priorities of the plant owner.

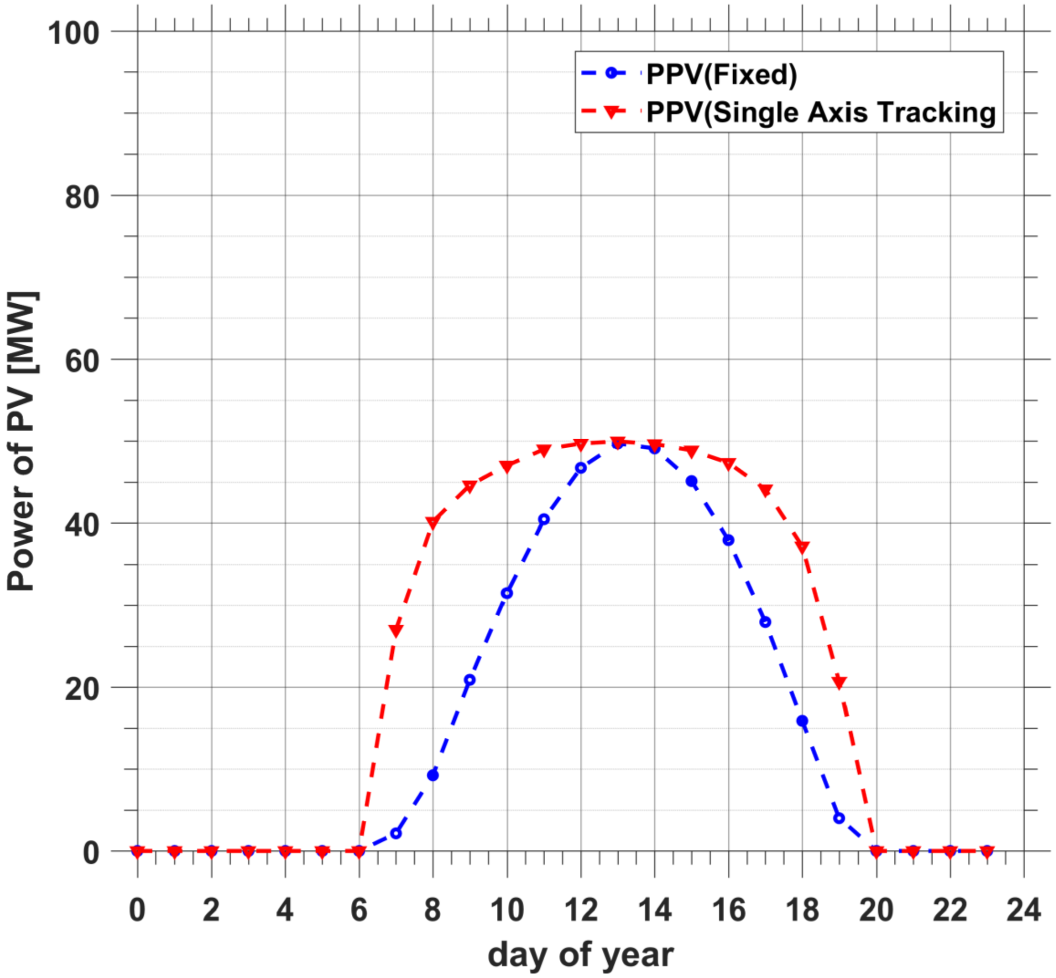

Fig. 6: Generation curve of fixed-axis PV plant and single-axis tracking (summer solstice).

The figure shows the daily power generated by the plant for fixed panels and for panels with east-west tracking through the axis of the inclined panel using the model cited in (Zhong *et al.*, 2011) (Okoye, Bahrami and Atikol, 2018). It is possible to appreciate that there is a considerable increase in electricity generation due to its greater reception of solar irradiation, however, it is also necessary to take into account the monetary value involved in the tracking system to consider this type of technology.

The mining sector demands the electricity sector an estimated power of 323 MW and an energy of 2,343 GWh, representing 39% of the total electricity demand of the productive sectors, until 2025 (Ministerio de hidrocarburo y energia, 2014), which means that the PV generation systems implemented in the altiplanic sector do not supply the total for feeding and therefore need a connection to the backbone of the country of Bolivia to supply the demand and give reliability to its system.

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