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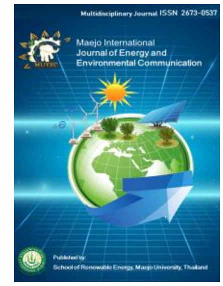

ARTICLE

Sizing photovoltaic systems interconnected to the grid in the industry

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A B S T R A C T

Renewable energy sources have been regarded as the best alternative for energy generation because they are environmentally friendly and can be renewed. Among the sources of renewable energy is the photovoltaic system. The generation of energy through clean energies such as photovoltaic systems connected to the grid have shown sustained growth for years in residences, commercial centers, and industry. Therefore, a practical study of a photovoltaic system connected to the grid of a specific industry in the San Juan del Río region was carried out to determine the effectiveness and the cost efficiency of running a photovoltaic system connected to a grid. We also investigated the fastest possible time to get return on investment. The return on investment was estimated using the peak solar hours, numbers of panels, inverter, conductors, and DC and AC protectors. Although, the cost of starting a photovoltaic system can be quite expensive, our analysis revealed that the return on the investment can start to come to effect within a very short period. The policy implication of this is that the government should encourage investment on the photovoltaic system through financial support to firm and other policies that can make delivery cheaper for the customers.

1. Introduction

Solar energy contributes largely towards meeting the energy needs of the world's population, especially in developing countries (Arunachala & Kundapur, 2020; Gautam & Saini, 2020). In particular, the development of photovoltaic (PV) microgrids, which can be independent, connected to the grid or off-grid, is considered one of the most viable solutions that could help developing countries to minimize problems that are related to power shortages (Abu-Rumman et al., 2020; Chang et al., 2021; Kefale et al., 2021). The sizing and location of the photovoltaic solar system must be optimal to obtain quality energy generation and must be connected

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to a distribution network (Kefale et al., 2021; Sharew et al., 2021). The quality impact in terms of voltage and current harmonic distortion has a significant effect on the quality of the grid power (Xiong et al., 2020).

The analysis of the flow of photovoltaic energy to the grid has been carried out using different generation load scenarios. These scenarios were used to study the performance of the grid, including the flow of active and reactive energy, the voltage profiles, the load of the distribution power transformers, transmission line ampacity levels, and active and reactive power losses (Ali et al., 2021; Daouda et al., 2021; Jiang et al., 2021; Khatib & Sabri, 2021; Sallam & Malik, 2018).

The sun is the largest source of energy in life, while at the same time it is the last source of most renewable energy sources (El-Ghonemy, 2012; Elnozahy & Salama, 2013). Every hour enough energy from the sun reaches the earth to meet the world's energy demand for a whole year. (Shaikh, 2017); The development of new solar energy technologies is considered one of the key solutions to meet a growing global demand for energy. However, the rapid growth in the field of solar technologies faces several technical barriers, such as the low efficiency of solar cells, low balance of systems, economic obstacles (for example, high initial costs and lack of funding mechanisms), institutional situations (for example, inadequate infrastructure and shortage of skilled labor) (Kabir et al., 2018),

A control strategy for improving voltage quality is using a residential power distribution network consisting of roof-top photovoltaic-wind hybrid systems, battery storage and electric vehicles. This strategy has helped to improve voltage profile, reduced voltage fluctuations, decrease voltage imbalances of the phases, and reduced number of tap operations, in the face of fast growth of distributed energy resources (DERs) penetration in the residential networks (Behravesh et al., 2019). Today, the grid-connected photovoltaic system is known as a leading technology among all resources. Detailed economic studies should be conducted in this regard to give more insight to the benefit of this technology A practical approach is the "optimum economic design", trying to find an electrically possible layout (Bakhshi-Jafarabadi et al., 2019).

Photovoltaic energy is used in the industrial sector (Alsamamra et al., 2021; Lu et al., 2021). The global demand for photovoltaic systems is increasing rapidly in various sectors. Therefore, the objective of this work is to establish the basis for calculating a photovoltaic system connected to the network of a specific industry in the region of San Juan del Río Querétaro, Mexico, where the return on investment is determined from the energy supplied during peak solar hours, the number of panels, inverters, conductors, as well as protections on the direct and alternating currentThis is line towards understanding how long it will take to have a return on investment after establishing a photovoltaic grid system.

2. Methodology

A weather underground tool which reports via the internet an average irradiance per day was used for the collation of data during a one-year period to estimate the peak solar hours of the industries in kWh/m/day. The result obtained corresponded to the peak solar hours for the San, Juan del Rio municipal in Queretaro.

From the data on monthly consumption and billing cost of each receipt issued by the federal electricity commission during the same year the average daily consumption in kWh and the average cost per kWh / $ are obtained.

The quantity of photovoltaic modules and central inverters for an isolated system is determined considering a saving of 100% of electrical energy from non-renewable sources, the power and nominal efficiency of the selected module. For the calculation of the direct current conductors, the theoretical section of the conductor is determined as a function of the conductivity, length, peak current, the voltage drop and tension of the branch or chain. The direct current protection is considered at 125% of the maximum intensity that the direct current line will carry. The return on investment is calculated (all costs are given in Mexican pesos) considering the list of materials and their quantities to be used for the generation of energy from the photovoltaic panels until their interconnection to the grid.

3. Results and discussion

Table 1 shows the average daily irradiation for each month during 2020 in San Juan del Río provided by the CEA-JAPAM IQUERETA13 meteorological station and with this the peak solar hours of the annual average are determined.

Table 1 Irradiation 2020.

Month	$kWh/m^2/day$
Jan	4.6
Feb	5.6
Mar	6.48
Apr	6.67
May	6.56
Jun	6.15
Jul	5.98
Aug	5.95
Sep	5.17
Oct	4.93
Nov	4.75
Dec	4.31
Average	5.5

The average daily consumption per month during a year were obtained from the data on monthly consumption of each bill issued by the federal electricity commission as shown in table two.

Table 2 Monthly consumption.

Month	Monthly consumption kWh	Average daily consumption kWh
Nov-19	25687	856.2
Dec-19	17422	580.7
Jan-20	27566	918.8
Feb-20	22552	751.7
Mar-20	26140	871.3
Apr-20	25836	861.2
May-20	27647	921.5
Jun-20	26156	871.8
Jul-20	26815	893.8

Aug-20	31199	1039.9
Sep-20	26102	870.06
Oct-20	30878	1029.2
Nov-20	24694	823.1

The above data showed the monthly and daily energy consumption in kWh

The costs for period per kWh in each month consumed is shown in Table 3. The table also includes information on the average cost per kWh and average consumption per day

Table 3 Electricity consumption costs.

Month	Billing cost $	Average cost per kWh $	Average daily consumption $
Nov-19	61354	2.38	2045.13
Dec-19	58469	3.35	1948.96
Jan-20	74385	2.69	2479.5
Feb-20	52008	2.30	1733.6
Mar-20	45919	1.75	1530.63
Apr-20	57119	2.21	1903.96
May-20	60429	2.18	2014.3
Jun-20	74827	2.86	2494.23
Jul-20	69709	2.59	2323.63
Aug-20	84635	2.71	2821.16
Sep-20	102013	3.90	3400.43
Oct-20	105853	3.42	3528.43
Nov-20	78877	3.19	2629.23

For the required panel and inverter calculation, the manufacturer's plate data was used for both the panel and the selected inverters. The manufacturer's plate data was also used for the determination of the peak sun hour (5.5 hours previously calculated), Panel power 0.350 kW (data from the chosen photovoltaic panel plate) and Nominal efficiency in 10 years of life = 91%, Inverter power 30 kW with an efficiency = 98.7% . If a savings of 100% is required, the following data need to be calculated:

3.1. Solar plant size

$$\text{(Average energy day} * \text{savings percentage /100)/ (peak sun hours)} = Pp$$

$$(869 \text{ kWh} * 100\%/100) \ / \ 5.5hr = 158kw$$

Where Pp: Plant power

3.2. Size of the plant considering the efficiency of the inverter

$$Pp + (Pp - (Pp * \text{inverter efficiency})) = Pp$$

$$158kw + (158kw - (158kw * .987)) = 160kw$$

The efficiency of the inverter may vary according to the manufacturer's specification.

3.3. Number of solar panels

$$(Pp)/\ panel\ power = number\ of\ paneles$$

$$(160Kw/0.350kw) = 457\ paneles$$

The number of resulting photovoltaic panels or modules may vary according to the power of the selected module.

3.4. Panel power in 10 years of life

$$\text{P}anel\ power * panel\ power\ in\ ten\ years\ of\ life = panel\ \text{power}$$

$$0.350kw * 0.91 = 0.318 \text{ kW}$$

3.5. Number of solar panels considering the loss of efficiency

$$160Kw/0.318 \text{ kW} = 503\ panels$$

503 photovoltaic modules are required if you want to maintain power generation or after 10 years you must install additional 10% of photovoltaic modules with respect to those initially estimated which were 457.

3.6. Plant power considering 503 solar panels

$$panel\ \text{power} * number\ of\ panels = Pp$$

$$0.350kw * 503 = 176.05 \text{ kW}$$

Daily energy production

$$Panel\ power * number\ of\ paneles * \text{peak sun hours} = Daily\ energy$$

$$0.350kw * 503 * 5.5hr = 968.27 \text{ kW}h$$

The energy generated daily hy the photovoltaic system in kw/hr was estimated to be sufficient for the energy need of the company located in San Juan del Rio Queretaro, Mexico.

3.7. Numbers of investors

$$Pp\ /\text{inverter power} = investors$$

$$176.05\text{kW} /30\text{kW} = 5.86 = 6\ investors$$

3.8. Conductors and protections calculations

3.8.1. Direct current conductors

The section of the conductor is determined by the following expression:

$$S = (28)\ (L)\ (I)/\ (\Delta V\ (\%)\ (U)\ (\sigma))$$

Where; S: is the theoretical section of the conductor measured in [mm^2], L: is the length of the conductor [m], I: is the maximum current that will flow through the conductors (the intensity considered is the short-circuit of the panels = 9.41 Amp), a value close to that of the working intensity of the panels, ΔV (%): is the voltage drop [V] that at most the connecting conductors between the photovoltaic generator can have in the direct current is 1.5%, σ: is the conductivity of the element that forms the conductor, in this case copper at 90ºC is 44m/Ω*mm², U: Voltage in the branch, in this section there is a voltage equal to the maximum power point voltage of each panel times the number of panels in series that make up each branch (38.6 V x 21panels) = 810.6 V.

Using the above equation in all cases the calculated gauge is close to a 12 AWG conductor so the gauge in all cases is 12 AWG.

3.8.2. Direct protection

125% of the maximum intensity that the direct current line will carry is considered. That is, the conductors are sized for a current equal to 125% of the short-circuit current of the photovoltaic module.

$$I_{max} = 125\% \times I_{sc}$$

Where I_{max}: is the maximum work intensity for which the conductors are dimensioned, Isc: is the short-circuit current of the panels and is equal to 9.41 A. Substituting values, we obtain:

I_{max} 9.41 $Amp * 1.25 = 11.76\ Amp$ commercially $15Amp$

3.8.3. Calculation of alternating current conductors

The current calculation of all the loads was carried out by means of the following equations, considering the number of phases and wires that its operation requires.

Single phase system:

$$I = w/(V_{fn}fp)$$

Biphasic System:

$$I = w/(V_{ff}fp)$$

Three-phase or four-wire system:

$$I = w/(V_{ff}fp\sqrt{3})$$

Where: I : Electric current (A), w : Electric charge (W), fp: Power factor (0.9), V_{fn} : Neutral phase voltage (V), V_{ff} : Voltage between phases (V).

Considering the length of each inverter of 0.5772 m plus the separation between each inverter placed of 0.3848 m. It gives 0.9012 meters which must be considered as shown in table four.

Table 4 Distance from the inverter to the load center (Own elaboration).

Appliance	Distance (meters)	Current (Amperes)	fp
Investor 1	5.19	37	0.9
Investor 2	6.152	37	0.9
Investor 3	7.114	37	0.9
Investor 4	8.076	37	0.9
Investor 5	9.038	37	0.9
Investor 6	10	37	0.9
Board electric	3	203	0.9

It is necessary to know how many phases each inverter has, to determine the cable gauge as shown in table five. As well as the number of threads:

Single phase system:

$$s = \frac{4IL}{\%eVf_n}$$

Biphasic two-wire system:

$$s = \frac{4IL}{\%eVf_f}$$

Three-phase three and four wire system:

$$s = \frac{2IL\sqrt{3}}{\%eVf_f}$$

Table 5 AC conductor gauge (Own elaboration).

Appliance	V_{ff}	%	S	AWG
Investor 1	220	3	1.007	6
Investor 2	220	3	1.194	6
Investor 3	220	3	1.381	6
Investor 4	220	3	1.568	6
Investor 5	220	3	1.755	6
Investor 6	220	3	0.944	6
Board electric	220	3	3.193	2

3.8.4. Alternating protections

For the calculation of protections, the same criteria are considered as for direct-line protections.

$$I * 125\% \quad 37Amp * 125\% = 46.25Amp$$

3.8.4.1. Return of investment

An initial cost of $ 2,955,454.49 what includes:

Table 6 List of items.

Number of units	Unit	Item
503	Part	Solar panel
06	Part	Investor 30 kW
01	Part	Board electric NF 125 A to 400 A, 30°C to 42 °C
05	Part	thermal magnetic circuit breaker 50 A.
01	Part	thermal magnetic circuit breaker 30 A.
150	Meter	6 AWG thw Gauge wire
12	Meter	2 AWG thw Gauge wire

24	Part	DC fuse holder with 15A fuses
24	Part	MC4 Type Solar Connectors (Male and Female)
310	Meter	12 AWG photovoltaic cable
150	Meter	10 AWG Bare wire
19	Part	66 mm industrial tray with joints
216	Part	Aluminum rail with joints and hardware
23	Part	Earth terminal ground

The return on investment is calculated from the energy produced per day = 968.275kW and average cost = 2.7 kWh.

Table 7 Annual savings.

Year	Efficiency	Produced energy kW/Year	Annual savings $	Debts $
1	0.991	350239.59	945646.9	2009807.59
2	0.982	347058.81	937058.8	1072748.81
3	0.973	343878.02	928470.7	144278.143
4	0.964	340697.24	919882.6	-775604.41
5	0.955	337516.46	911294.4	-135690.03
6	0.946	334335.67	902706.3	-1038396.3
7	0.937	331154.89	894118.2	-1932514.6
8	0.928	327974.11	885530.1	-2818044.6
9	0.919	324793.32	876942	-3694986.6
10	0.91	321612.54	868353.9	-4563340.5

Therefore, the initial investment is practically recovered in three years and two months. With a profit of 775604.41 pesos in the fourth year of operation of the system.

In this case, the minus sign that appears in the fifth column of table seven represents a favorable balance for the company. The operating and maintenance expenses during the first years are considered negligible as it is a new system.

4. Conclusion

Undoubtedly, the cost of conventional energy gives way to renewable energy due to its low production cost, although greater government support is required for the structuring of facilities for the cost of the different types of technologies that produce clean energy. This would increase the competitiveness of Mexican companies, providing greater growth to the country, in the case of the present photovoltaic system for production, the cost would be considerably reduced, generating greater profit after three years and two months.

The implementation of the photovoltaic system may be less feasible due to lack of economic resources for the initial investment, but at some point, industries will have power generation systems with renewable resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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