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Comparative study of system performance of two 2.4 kW grid-connected PV installations in Tepic-Nayarit and Temixco-Morelos in México

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Abstract

Grid-connected photovoltaic (PV) systems are needed to introduce photovoltaic energy into rural and urban areas in México. Two 2.4 kWp grid-connected PV systems have been installed for the present study. Each system consists of 10 modules of 240 Wp rated at 15.0% efficiency under standard conditions, covering a roof area of 16.45 sq. m. approximately. One system has been installed at the University of Nayarit in Tepic (21°29'N, 104°53'W, 920 m above msl) in the Pacific coastal area oriented toward the south inclined at 22° to the horizontal and with an azimuth of 9° to the southwest (building orientation). Its main purpose is to introduce the society to the use of renewable energy and the benefits that it represents towards sustainability. The installation also helps the faculty in teaching students topics related to the scientific and technological aspects of the photovoltaic solar energy conversion. The other system has been installed on a suburban house in Temixco-Morelos (18°51'N, 99°13'W, 1450 m above msl) in a hilly inland area with an inclination angle of 15° to the horizontal, and oriented 30^o from the south toward west (azimuth angle) due to architectural limitation. The purpose was to meet the total electrical energy need for a middle-class family and hence promote massive use of this type of system in this region of the country. Both systems are grid-tied through a 3 kW inverter. The supplied grid energy and performance ratio of the same type PV system in two different climatic locations are described in this work. During a twelve month period, of July-2012 to June 2013, the Tepic-installation generated 3888 kWh, whereas the Temixco-installation generated 4118 kWh. Monthly average daytime temperature and meteorological parameters for this period in Tepic-Nayarit and Temixco-Morelos, are also presented. The Temixco-Morelos PV system supplied nearly 90% of electrical energy need for the house. Results establish that grid-connected PV system is feasible over vast areas in Mexico.

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Keywords: Grid-tied, PV Systems, Sustainability, PV Mexico

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1. Introduction

More than 1000 million people in the world lack essential energy services to satisfy the most basic needs and help improve their social and economic status. The cost of grid for rural electrification extension is sometimes very high due to a low density of population. This prompts various organizations to explore alternative solutions (1) (2). A 2010 statistics for México shows that nearly 97.8% of the population of more than 112 million people has access to an electric grid: 100% in urban sector and 95% in the rural sector. Photovoltaic systems are needed to introduce photovoltaic energy into rural and urban areas because they signify an important saving of conventional energy (3). Grid-connected photovoltaic system represents an important potential use in all countries (4). The energy produced by a grid-connected photovoltaic system depends on: (i) climatic factors, (ii) inverter characteristics, and (iii) system-grid coupling, which depends on the characteristics of the energy produced by the inverter and on grid stability and availability (5). México has approximately 61.5 GW of installed capacity for electricity generation with a plant factor of ~ 0.6. The effective capacity was 39.36 GW at the end of 2012. During 2011, 73.6% of electricity was generated from fossil fuels, and 26.4% from no-fossil resources including hydroelectricity which provided 11%; nuclear, geothermal and wind energy provided the rest (6). The massive use of grid-connected PV systems is important in the whole country particularly in view of the Federal Electric Company (CFE) projection for a 10% of clean energy component in the national electric utility supply for 2025, in addition to projected hydroelectric, geothermal and wind energy components. If México decides to add the 10% of the additional electric energy needed for the next 10 years through renewable, we will need approximately 5 GW of effective additional generation capacity. And, if México decides to do that with photovoltaic, we will need 20 GW of installed PV modules by 2025, because, the plant factor for PV in México is 0.25 on an average. Furthermore, meeting peak energy demand in the urban sector through grid connected PV might eliminate the need for increased interstate transmission capacity. In this work, two 2.4 kWp grid-connected photovoltaic systems have been installed. One system has been installed at the Autonomous University of Nayarit in Tepic (21°29'N, 104°53'W, 920 m above msl) in the Pacific coastal area inclined at 22°. The integration of the system in the building structure has forced us to install the modules with an azimuth of 9° southwest. The other system has been installed in a suburban house in Temixco-Morelos (18°51'N, 99°13'W, 1450 m above msl) in a hilly inland area with an inclination angle of 15° to the horizontal and oriented 30° from the south toward west due to architectural constraint to adapt to the building roof topography.

2. Experimental

An adequate size of PV module capacity for a middle class single-family in México is considered here as 2.4 kWp. In this work, each system consists of 10 modules (Kyocera KD240GX-LFB) of 240 Wp of polycrystalline silicon cells rated at 15.0% module efficiency under standard conditions, covering a roof area of 16.45 sq. m. approximately. The inverter used is a Sunny Boy 3000US two-phase (120V, 60 Hz each) system with maximum power rated to 3.2 kW. Global irradiance is recorded by a Campbell Scientific Acquisition System using a Kipp and Zonen pyranometer. Meteorological parameters and their mean daily values for each month such as: ambient temperatures, wind speeds during the hours of sun, are also measured. The inverter output data are recorded by a Sunny Web Box Data Acquisition System, which permits statistical analysis of daily and monthly data from the *sunny portal* web site.

3. Results

Tables 1 and 2 show the monthly electric energy generated by the 2.4 kWp PV installations and fed to the grid (E_{PV}) in kWh/month, as recorded by the inverter-web box monitoring system; the average daily insolation (H) in kWh/m^2/day; the average daytime temperature (T), the relative humidity (R H), and the wind speed in m/s computed during the hours of sun for the period, for each month in Tepic-Nayarit and Temixco-Morelos.

Table 1. Monthly values of generated energy, average day insolation and daytime ambient temperature, relative humidity and wind speed for Tepic-Nayarit. Last row gives the average values for the 12 month period during July 2012 to June 2013.

Month	E_{PV} (kWh/month)	H (kWh/m^2/day)	T (°C)	R H (%)	Wind Speed (m/s)
July	320	5.7	24.4	68.4	3.1
August	304	5.3	24.6	71.0	3.1
September	311	5.2	24.6	70.2	3.0
October	364	5.5	24.6	65.8	3.2
November	304	4.5	23.6	57.5	3.0
December	274	4.0	21.2	53.3	2.9
January	288	4.2	20.9	51.3	3.0
February	312	5.7	21.6	43.2	3.3
March	341	6.1	23.3	29.5	3.6
April	386	6.9	23.7	38.6	3.7
May	366	6.9	25.4	38.0	4.1
June	318	6.3	25.2	62.2	3.8
Average	**324**	**5.5**	**23.6**	**54.1**	**3.3**

Table 2. Monthly values of generated energy, average day insolation and daytime ambient temperature, relative humidity and wind speed for Temixco-Morelos. Last row gives the average values for the 12 month period during July 2012 to June 2013.

Month	E_{PV} (kWh/month)	H (kWh/m^2/day)	T (°C)	R H (%)	Wind Speed (m/s)
July	339	6.4	24.0	57.2	1.7
August	330	6.2	24.0	62.8	1.8
September	343	5.8	24.4	59.6	1.8
October	359	5.7	24.1	49.9	1.7
November	301	4.9	22.9	42.2	1.5
December	308	4.9	23.4	35.5	1.5
January	322	5.0	23.7	33.9	1.6
February	352	6.2	26.0	25.2	1.9
March	374	6.2	25.5	25.8	2.1
April	374	6.8	28.6	23.0	2.2
May	370	6.6	27.8	33.5	1.7
June	345	6.4	25.2	54.8	1.7
Average	**343**	**5.9**	**25.0**	**42.0**	**1.8**

During the period of July 2012- June 2013 for which data is available from both systems, the Nayarit installation generated 3888 kWh. The daily mean energy for the system was 10.65 kWh. However, from Mar-May 2013 the PV system reaches its highest average daily production. These are months with highest daily insolation of 6.11, 6.89, and 6.89 kWh/m^2/day, combined with higher wind speeds 3.59, 3.75 and 4.15 m/s respectively. Such a combination results in a daily mean energy of 12 kWh for these spring months.

The Temixco-Morelos PV system supplied 4118 kWh to the grid during the same period, July 2012- June 2013, which means a daily energy output from the inverter at 11.28 kWh. It represents 5.5% more of generated energy compared with the Tepic-Nayarit system. It might also suggest that the 30° of south-toward-west azimuthal angle is helping it to achieve a better performance. During March to May 2013 the Temixco-Morelos installation also reaches its greatest global daily production. These are months with highest values of daily insolation of 6.0, 6.56 and 6.37 kWh/m^2, and high wind speeds of 2.1, 2.19 and 1.7 m/s, respectively. This combination helps to achieve a daily mean energy of 12.4 kWh. No direct correlation is looked at this time for the fact that the near-coastal location of Tepic-Nayarit puts its system at a 12.13% higher R H (54.08%) compared with that installed inland in Temixco (41.92%). The photovoltaic yield is obtained by dividing the energy supplied by the modules to the grid (E_{PV} in kWh) by the available energy (E_i in kWh/m^2) defined as the daily irradiation H (5).

$$Y_{PV} = \frac{E_{PV}}{E_i * A}$$

The Specific yield can be obtained as follows:

$$SY_{PVS} = \frac{E_{PV}}{kW_p}$$

The daily values for the incident radiation at the horizontal plane (E_i) at the plane of the PV array; the PV system yield (Y_{PV}); and the Specific PV system yield (SY_{PVS}) for Tepic-Nayarit and Temixco-Morelos installations are presented in Table 3 and 4, respectively. The average specific daily yield is 4.45 kWh/kWp for the Tepic-Nayarit array, and 4.7 kWh/kWp for the Temixco-Morelos array, representing distinct geographic locations in Mexico. This suggests that an average specific daily yield of 4.5 kWh per kWp of installed capacity of polycrystalline silicon PV modules may be accepted as a guideline for PV system design for the central-southern regions of México (7) (8).

Table 3. Daily average of incident radiation at the horizontal plane (E_i), at the plane of the PV array ($E_{i(22°)}$), the PV system yield (Y_{PV}) and the Specific PV system yield (SY_{PVS}) for the PV array installed at Tepic-Nayarit.

Month	**E_i (kWh/m^2/day)**	**E_i (22°) (kWh/m^2/day)**	**Y_{PV} (%)**	**Y_{PV} (%) 22°**	**SY_{PVS} (kWh/kWp)**
July	5.7	5.3	10.9	11.8	4.3
August	5.3	4.8	11.3	12.2	4.1
September	5.2	4.8	12.1	13.1	4.3
October	5.5	5.1	13.0	14.0	4.8
November	4.5	4.2	13.5	14.6	4.2
December	4.0	3.7	13.2	14.2	3.7
January	4.2	3.8	13.5	14.6	3.8
February	5.7	5.3	11.9	12.8	4.8
March	6.1	5.7	10.9	11.8	4.6
April	6.9	6.4	11.3	12.2	5.4
May	6.9	6.4	10.4	11.2	4.9
June	6.3	5.8	10.3	11.1	4.4
Average	**5.5**	**5.2**	**11.8**	**12.8**	**4.4**

Table 4. Daily average of incident radiation at the horizontal plane (E_i), at the plane of the PV array ($E_{i(15°)}$), the PV system yield (Y_{PV}) and the Specific PV system yield (SY_{PVS}) for the PV array installed at Temixco-Morelos.

Month	**E_i (kWh/m^2/day)**	**E_i (15°) (kWh/m^2/day)**	**Y_{PV} (%)**	**Y_{PV} (%) 15°**	**SY_{PVS} (kWh/kWp)**
July	6.4	6.2	10.3	10.7	4.5
August	6.2	5.9	14.8	15.3	4.4
September	5.8	5.6	12.0	12.4	4.8
October	5.7	5.6	12.2	12.6	4.8
November	4.9	4.7	12.4	12.9	4.2
December	4.9	4.7	12.3	12.7	4.1
January	5.0	4.9	12.5	13.0	4.3
February	6.2	6.0	12.2	12.7	5.2
March	6.2	6.0	11.8	12.2	5.0
April	6.8	6.6	11.1	11.5	5.2
May	6.6	6.4	11.0	11.4	4.9
June	6.4	6.2	10.9	11.3	4.8
Average	**5.9**	**5.7**	**12.0**	**12.4**	**4.7**

The performance ratio is one of the most important variables for evaluating the efficiency of a PV plant. Specifically, the performance ratio (PR) is the ratio of the actual to the theoretically possible energy outputs. It is largely independent of the orientation of a PV plant and the incident solar irradiation on the PV plant. For this reason, the performance ratio can be used to compare PV plants supplying the grid at different locations all over the world (9) (10) .

The PR is calculated by using the following formula:

$$PR = \frac{Actual\ Plant\ Output\ [kWh]}{Nominal\ Plant\ Output\ [kWh]}$$

Here the calculated nominal plant output is composed of the incident solar irradiation at the generator surface of the PV plant multiplied by the relative efficiency of the PV plant modules. The obtained PR values are 84.3 % for the Tepic-Nayarit PV plant and 81.8 % for the Temixco-Morelos PV plant. This means that approximately 16% and 18% of the incident solar energy in Tepic and Temixco respectively, is not converted into usable energy during the twelve month period.

April is the month with the highest values of average daily insolation and, hence, the best global daily production as observed in tables above. Figure 1 (A) shows the PV system performance of both PV arrays for a typical day during April 2013 and (B), the solar global radiation data in W/m^2 for both sites same day. For this day the generated energy fed to the grid was reported by the inverter web box as 14.4 kWh/day for Tepic-Nayarit system and 14.5 kWh/day for Temixco-Morelos system. The delay in the morning hours for the Temixco-Morelos system to catch up with the sun due to 30^o south-toward-west orientation of the array is compensated by the delay in easing up on production in the evening hours.

As additional general information it is important to mention that the main purpose of the PV system installed at Temixco-Morelos was to meet the total electrical energy need for a middle-class family and provide, through PV, more than 90% of the electrical energy needed for the house. This could help promote massive use of this type of system in this region of the country. This goal was achieved.

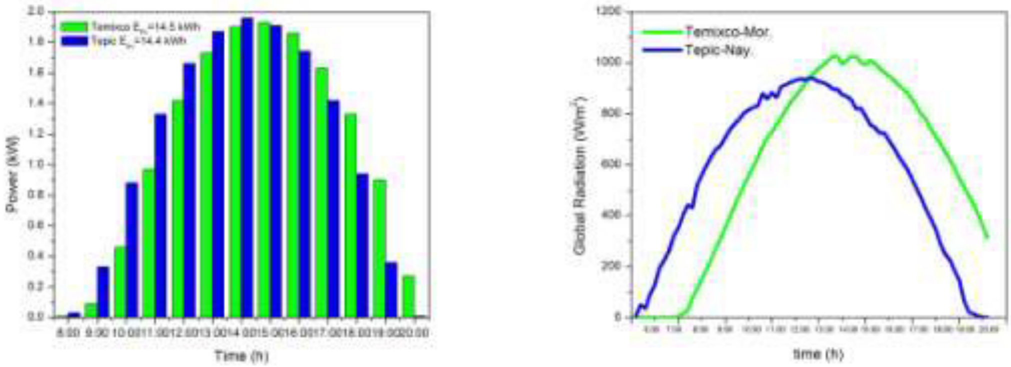

Figure 1. (A) Performance of the PV system installed at Tepic-Nayarit and Temixco-Morelos for a typical day of April and (B) Global radiation data recorded for the same day both sites.

Table 5 shows the invoices for the electric energy consumption of the Temixco-Morelos house before and after the PV system installation.

Table 5. Invoice for the electric energy consumption of the Temixco-Morelos house before and after the PV system installation.

Period	**Energy Consumption (kWh)**	**Price Mexican $**
Aug, Sept 2011	739	$ 3,251.00
Oct, Nov 2011	694	$ 3,136.00
Dec 2011, Jan 2012	663	$ 3,102.00
Feb-2012-Jan 2013	PV regularization period	
Feb,March2013	42	$ 48.00
Apr, May 2013	94	$ 94.00
June, July 2013	115	$ 100.00

It is seen that from data in Table 5 that the PV installation helps to reduce the energy consumption from the grid for this household to 12% compared with the previous records. No change in the usage pattern during the period 2011-2013 is reported. And hence, the main objective of this domestic PV installation in a middle class suburban home in central Mexico is met. The installation and regularization period comprised of an increase in the PV capacity to 2.4 kWp, raising the whole structure by 90 cm to avoid afternoon shadow cast on some of the modules, the installation of bidirectional metering instrument, and training of technicians and staff in meter reading and invoicing grid-connected PV systems. It is important to mention that this being among the first PV system in the locality, all these adjustments took nearly one year to regularize. The final invoice for any period includes some government subsidy. The exchange rate for the period may be considered as: $US 1= $MX 12.5.

4 Conclusions

Two 2.4 kWp polycrystalline silicon photovoltaic systems have been installed in two distinct geographic locations in Mexico, in the near-coastal Tepic-Nayarit and in the inland-hilly Temixco-Morelos. During the July 2012 – Jun 2013 period, the mean daily energy generated has been 10.82 kWh by the Tepic-Nayarit PV system and 12.4 kWh by the Temixco-Morelos PV system. A better yield is observed for the Temixco-Morelos PV System, due to better meteorological conditions and the azimuthal angle deviation of 30° from south-toward-west. However, the performance ratio of 84.28 % calculated for the PV system installed in Tepic-Nayarit is higher than the performance ratio of 81.83 % obtained for the Temixco-Morelos PV system. The average daily specific system yield for the central northwest region in Mexico is 4.5 kWh per kWp polycrystalline PV module. This is among the best values worldwide, and suggests immense benefit that can be derived from a massive use of PV technologies in Mexico. Thus, grid-connected PV in the urban and suburban areas or stand-alone PV systems for the remote agricultural communities in Mexico is both feasible, and should form part of the national sustainable policies.

Solar hot water and domestic grid-connected PV generation are two activities in which the citizens can directly participate and contribute to the national prestige and obligation. In order to achieve the goal set for renewable energy use, the Mexican government should implement active promotion policy for PV application investment, especially small scale grid-connected PV projects and provide sustainable price by way of feed-in-tariff. PV research and innovation should be very much a national project in México; it will benefit the entire population and secure sustainable development.

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