Peña Gallardo, Rafael; Ospino Castro, Adalberto; Ramírez, Juan Segundo et al.

Article

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Reference: Peña Gallardo, Rafael/Ospino Castro, Adalberto et. al. (2020). Economic and energy analysis of small capacity grid-connected hybrid photovoltaic-wind systems in Mexico. In: International Journal of Energy Economics and Policy 10 (2), S. 7 - 17.
https://www.econjournals.com/index.php/ijeep/article/download/8449/4859.
doi:10.32479/ijeep.8449.

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2020, 10(2), 7-14.

Economic and Energy Analysis of Small Capacity Grid-connected Hybrid Photovoltaic-wind Systems in Mexico

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Received: 23 July 2019 **Accepted:** 03 December 2019 **DOI:** https://doi.org/10.32479/ijeep.8449

ABSTRACT

The integration of renewable energies in the electric power system, as a solution to the growing demand for electricity in developing countries, has become a vital issue, such is the case of Mexico. The purpose of this work is the assessment of the economic and energy feasibility of a residential house grid-connected hybrid photovoltaic (PV)-wind system, in Mexico. The hybrid PV-wind system design is based on the existing renewable energy resources and considering a typical load profile. Also, an economic analysis is presented based on the two schemes approved for the sale of the surplus of the energy generated in Mexico: Net billing and net metering. The results obtained demonstrate the viability and profitability of the proposed small-size system. However, the results corroborate that government incentives are crucial to making the proposed system more attractive and affordable for residential users.

Keywords: Feasibility Study, Hybrid Generation System, Net Billing, Net Metering, Photovoltaic Energy, Wind Energy

JEL Classifications: Q2, Q42, Q5

1. INTRODUCTION

Worldwide, the use of renewable energy sources (RES) as an alternative for the generation of electricity has been increased in recent years (Robles-Algarin et al., 2018). RES brings great benefits in the energy matrix of many countries, generating integral strategies to combine different types of renewable and cleaner energies, in order to satisfy the growing energy demand and tending to more rational and efficient use of the energy. The inclusion and technological development of hybrid generation systems, in which two or more RES are exploited (e.g. photovoltaic [PV] and wind energy) (Muñoz et al., 2015; Adefarati and Bansal, 2016), can create scenarios with a greater diversification of energy generation, and boost the development of new economic models that may have strategic value in the future. At the same time, hybrid systems can help to mitigate the environmental impacts caused by the generation, distribution, and final use of energy (Algarín et al., 2017; Paez et al., 2017; Pagola et al., 2019).

In Mexico, in 2013 was approved the energy reform, whose objective, in the case of electricity generation, is to have a 25% of power generation by means of the use of clean energies in 2018, 30% in 2021, and 35% in 2024 (SENER, 2018). This reform allows the electricity generation by private producers under certain schemes, which are: Self-supply, independent producer, small producer, cogeneration, and export and import of energy with other countries (Cámara de Diputados México, 2013).

The self-supply scheme is being promoted by the government as a good alternative for the generation of electricity for the industry and home consumers. Through the FIDE (which stands for Trust for the electric power saving) projects based on solar and wind energy can be financed (FIDE, 2019). These two types of energy resources where selected due to their great availability across the country (Vega-Sanchez et al., 2018) and because the process of conversion of the energy is considered environmentally friendly (Perez-Arriaga and Batlle, 2012). Other types of energy sources are not allowed to be used at this moment under this scheme.

One of the main impediments of these two RES is their intermittency. In this way, hybrid PV-wind power generation systems have been proposed to cope with this problem (Pagola-Torres et al., 2016). This because it has been documented that the significant potential of the wind is during the night and for the PV system during the day (Vega-Sanchez et al., 2018); therefore, their combined use leads to higher efficiencies than those obtained with a single power source (Ravikumar and Vennila, 2017).

Nevertheless, it is essential to perform detailed site assessment studies in the process of design and selection of the main components of the hybrid PV-wind power generation systems (Hernandez et al., 2013; Banda et al., 2014), since the resources have high variability and unpredictability, and special attention needs to be focused on the evaluation of the feasibility of installation and the benefits obtained.

This work presents the energy and economic assessment of a residential grid-connected hybrid PV-wind power generation system for Mexico. The methodology used for this purpose is based on meteorological measurements of solar radiation, wind speed, temperature, energy generation from the RES, a typical load profile from a residential consumer, and the value of the energy. The feasibility of the proposed hybrid system is evaluated based on the analysis of an energy balance. The economic analysis is carried out taking into account the schemes approved for the sale of the surplus of the energy in Mexico. In addition, the financing granted by the government is discussed.

2. RENEWABLE ENERGY RESOURCES

To carry out this study the city of San Luis Potosi (Mexico) was selected because it has similar weather conditions and energy consumption patterns to other Mexican cities. San Luis Potosi is the capital and most populated city of the state of San Luis Potosi. The city is located in the north central area of the State. Its geographical coordinates are a latitude of 22° 08′ 59″ North and a longitude of 100° 58′ 30″ West. Its annual average temperatures reach a maximum of 31.8°C and a minimum of 10.3°C. The geographical conditions of the city are adequate for the electricity generation using PV modules and wind turbines because the city location is close to the tropics, which favors the collection of solar radiation and also there is a significant wind power potential throughout the year (Ospino-Castro et al., 2018).

Figure 1 shows the measurements of solar radiation in the city of San Luis Potosi. The measurements were taken in the years 2008-2016. The data was organized in the main components of the solar radiation, that is, the monthly average daily extraterrestrial radiation *Bodm*, the global radiation *Hdm*(0), the direct radiation *Bdm*(0), and the diffuse radiation on a horizontal surface *Ddm*(0); the temperature is also included in this chart. From this figure, it can be observed the great solar potential with values of *Hdm* at 25°C above the 5 kWh/m^2-day; radiation that is suitable for the installation of PV systems.

In Figure 2 can be seen the sun pattern throughout the year. This graph allows defining the best orientation of the PV panels. In this case facing to the south, with an optimal annual angle of $\beta = 25°$. According to the radiation components, the maximum utilization of the peak solar hours (HSP) for the PV modules in the city of San Luis Potosi is 6.9 h.

Figure 3 shows the averaged radiation on an inclined surface with isotropic sky (Denegri et al., 2012; Shukla et al., 2015), that is, the relationship between the direct component of solar radiation on an inclined surface and the direct radiation on a horizontal surface. The method used in this paper was developed in (Liu and Jordan, 1961); for the special case of a flat surface inclined toward the horizon, the method was modified in (Milanese et al., 2017). In this case, the value of the monthly global average daily radiation over an inclined surface ($H_{dm(\beta)}$), oriented towards the south, with

Figure 1: Solar radiation components and temperature

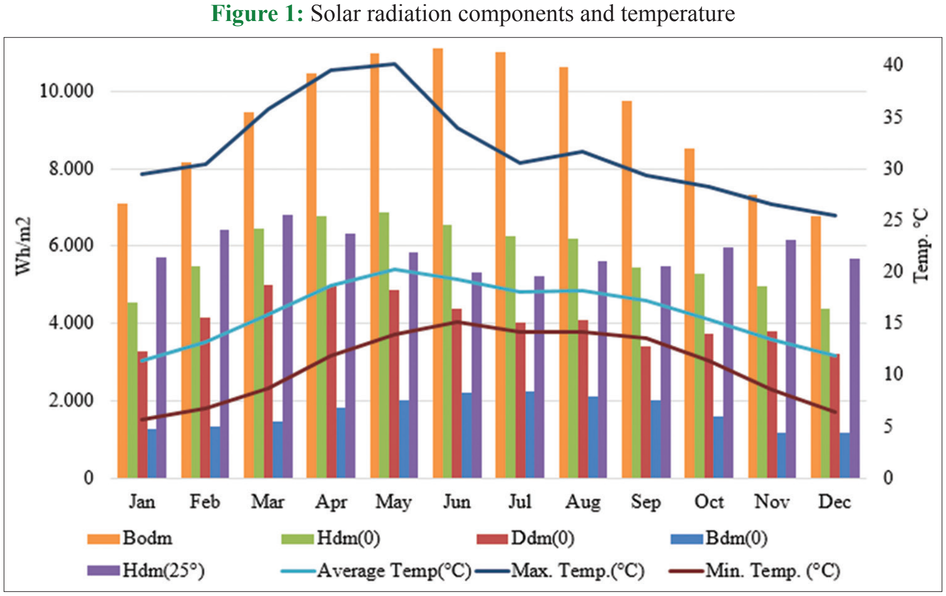


Figure 2: Sun position throughout the year in the city of San Luis Potosi

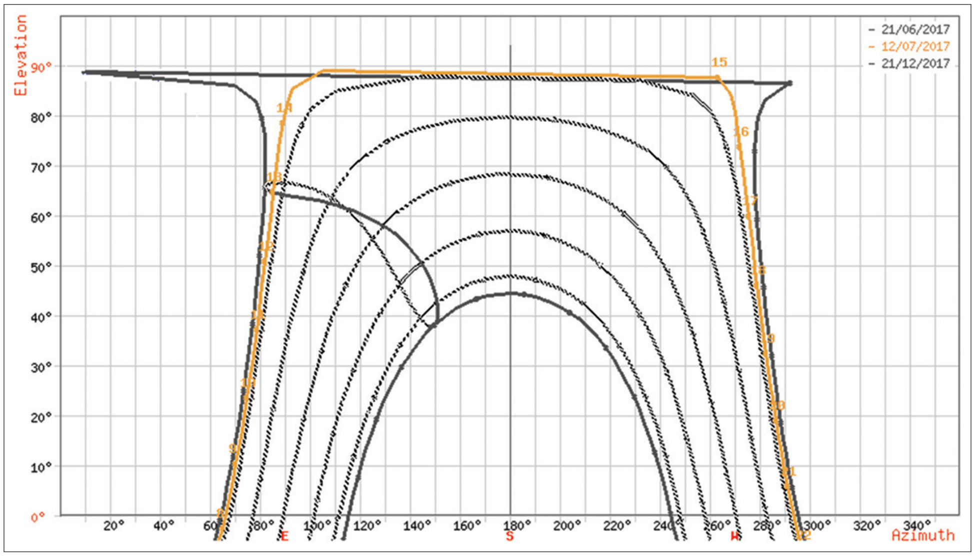
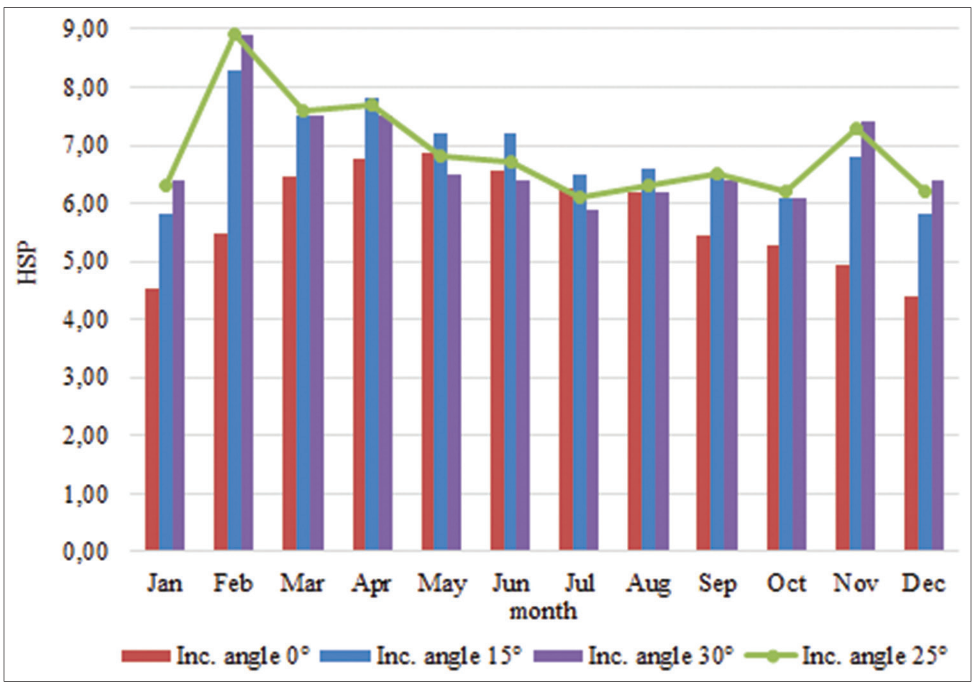


Figure 3: Estimation of HSP at different angles of inclination



zero azimuth angle from the monthly average daily radiation received on a horizontal plane was calculated. This is an essential data to identify the month with the worst scenario regarding with the amount of sunlight that can be captured by the PV module, at a specific angle of inclination. In Figure 3 can be seen that July is the month with the smallest amount of sunlight captured, with 6.1 h and considering an angle $\beta = 25°$; it is important to consider not only the low insolation but a possible high energy demand in this scenario (Noriega-Angarita et al., 2016; Smets et al., 2016).

On the other hand, the wind resource is characterized at a minimum height of 10 m above the ground, this in order to know the components of the wind speed, which allows estimating the energy potential on the city over a year. The frequency and direction distributions of the wind speed are obtained; then they are used to calculate the expected power generation from the proposed wind system (Alavi et al., 2016; Maklad and Glencross-Grant, 2017).

Figure 4 shows the wind speed time series obtained from measurements recorded every 10 min in the city of San Luis Potosi. Hourly averages of the wind speed compose the time series. The hours of the day with the highest and lowest wind speed value are determined, as well as the direction of the wind. This information is vital for the operation and selection of the wind generator (Hernandez et al., 2013).

The wind rose and frequency histogram of occurrence at different speeds are calculated and help to assess the wind potential available in the site of study. The Weibull and Rayleigh distributions are commonly used to describe the wind speed probability of occurrence because they give an excellent approximation of the real behavior (Islam et al., 2011; Akgül et al., 2016; Mohammadi et al., 2016). The value of the wind speed where the distribution curve reaches its peak is the most frequent wind speed measured in the data. The cumulative distribution curve shows the amount of time in which the wind speed is below a certain level.

The Weibull and Rayleigh distributions for the measured data are shown in Figure 5. The analysis of the Weibull parameters show that 6.8 m/s is the most probably average monthly wind speed in the city, while the Rayleigh parameters lead to a similar result with a value of 6.7 m/s; both distributions have a good fit of the actual measured data represented by the cumulative histogram. Also, this figure shows the wind rose obtained. The wind rose indicates the predominant direction of the wind and the frequency of wind speed values (Milanese et al., 2017); this information is important to orient the wind turbines and to increase the wind energy capture, incrementing the efficiency of the system and reducing losses. In the city of San Luis Potosi, the predominant annual wind direction is located from 90° to 180° sectors, from east-southeast, with 71.9% of the sample moving in this direction. The most common speeds are in the range between 5 and 10 m/s, representing the 43.1% of the total of the sample; speeds in the range between 10 and 15 m/s represent the 17.1%; wind speeds that deliver more

Figure 4: Behavior of the wind speed time series

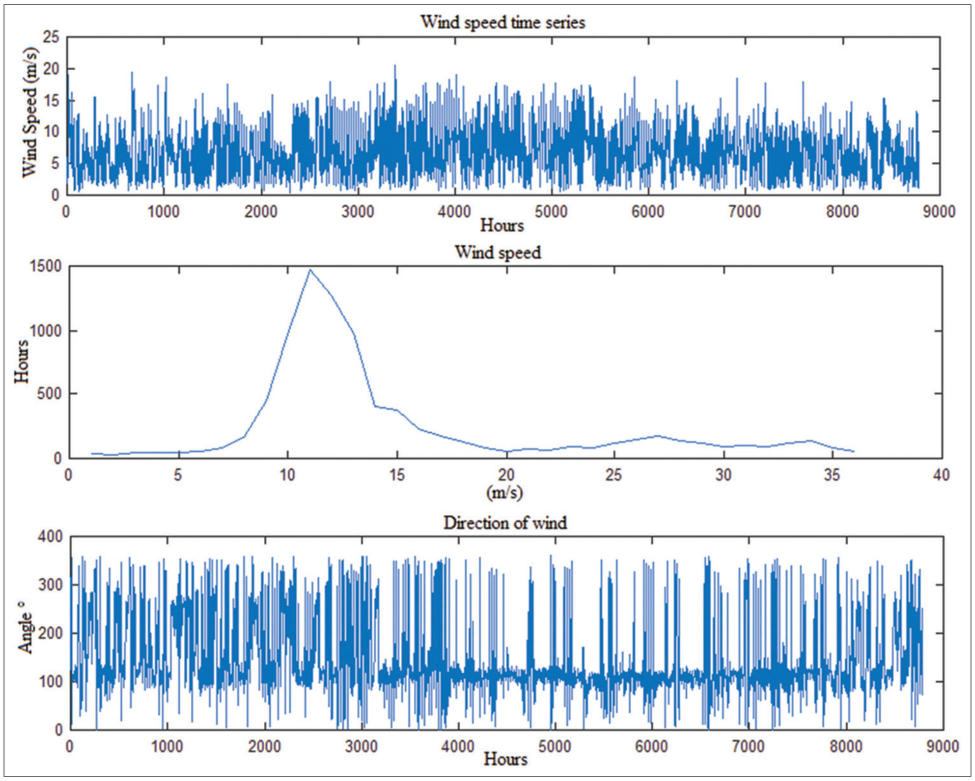
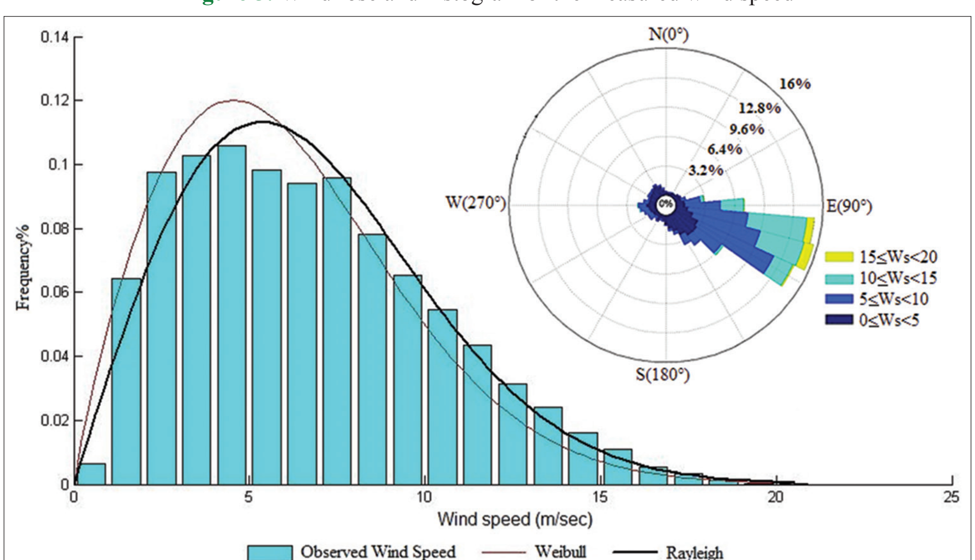


Figure 5: Wind rose and histogram of the measured wind speed



energy generation with an appearance frequency higher than 2.1% are in the range of 15 and 20 m/s; periods of calm, with values below to 5 m/s have a frequency of appearance of 37.7%.

3. ENERGY GENERATION AND LOAD PROFILE

In Mexico by law, the electricity generation for particular owners at a residential level is only possible using technologies based on wind and solar energy. These systems must be connected to the grid avoiding the use of storage systems (Ibarra-Yunez, 2015). In this context, hybrid renewable energy systems based on solar and wind energy have great potential to provide a more reliable power source to residential users than a system based on a single renewable resource.

Considering the analysis of the available renewable resources in the city of San Luis Potosi, a hybrid PV-wind power generation system is proposed. A wind generator of 1.8 kW of capacity was selected because it can operate with wind speeds in the range of 5-10 m/s, at the height of 10 m in urban areas. On the other hand, the selected PV system has a capacity of 3 kWp, which fulfills the needs of the project. In Figure 6 is shown the estimate of the average monthly electric power generation delivered to the grid per day by the hybrid system. Please note that the generation of electricity in the day by the PV system complements the electricity generated by the wind system during the night, which leads to a more efficient system.

It is important to mention that the selection of the proposed hybrid generation system is not only based on the available renewable resources, it is also based on a typical load profile of a residential house in the center of Mexico. The data was obtained from the studies reported in (Maqueda and Sánchez, 2011) and (Ortiz-Velázquez et al., 2017). In these studies, it is considered an average electric power consumption of 1.2 kWh per day, data obtained from the analysis of measurements made in houses in the center of the country.

The energy generated by the proposed hybrid generation system and the load profile considered for this paper is shown in Figure 7. It can be observed that the electricity generated matches the consumption in most of the hours of the day, except from 2:00 to 8:00 h and from 20:30 to 23:00 h, but there is a surplus of energy generated in the rest of the day that compensates the lack of energy.

4. COST OF ENERGY

The initial costs considered in the proposed generation system connected to the network correspond to the values of the equipment, assembly structures, installation, and interconnection rates (Ramli et al., 2016).

In the case of the PV system, the cost of each Watt of power installed may vary depending on its construction, configuration, and brand (Qolipour et al., 2017). In this work was selected a PV array composed by polycrystalline modules of 250 watts, Kyocera; where the cost of the installed Watt is projected on average in a

Figure 6: Average monthly generation per day by the hybrid photovoltaic-wind system

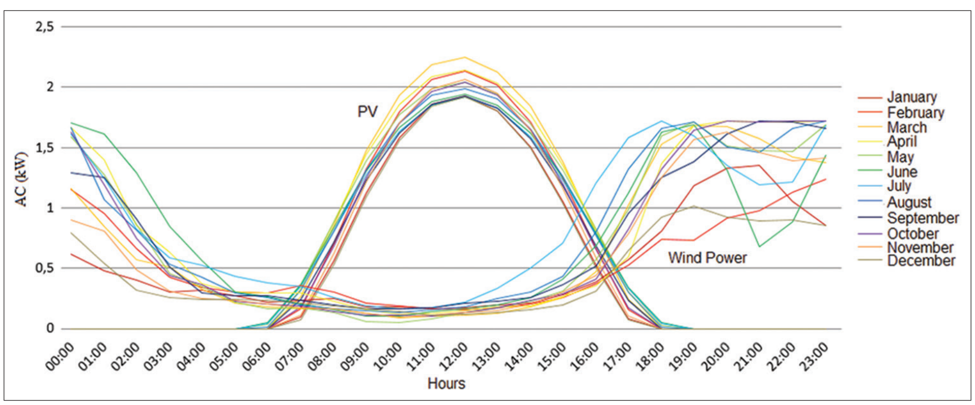
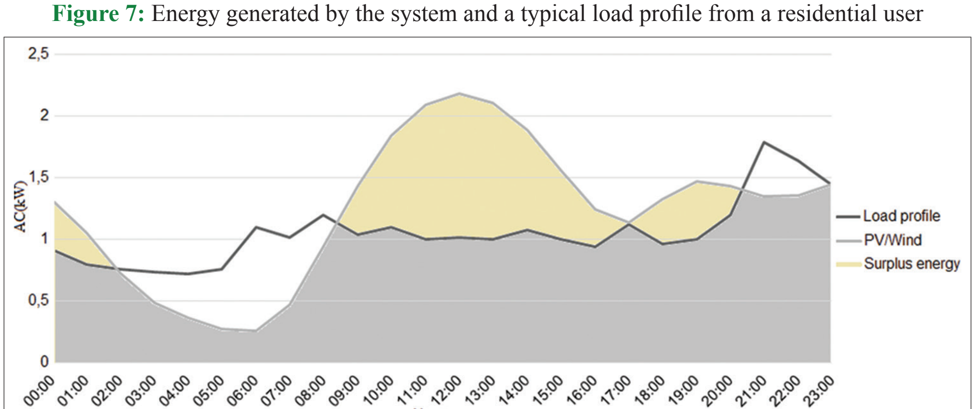


Figure 7: Energy generated by the system and a typical load profile from a residential user



price of $0.67 USD according to (SIE, 2016). These modules have a guarantee of 25 years and an efficiency loss of <20% within this term. The manufacturer guarantees in the first 10 years of operation a minimum efficiency of 90%, then after 25 years of service a minimum efficiency of 80%.

Regarding the wind system, in the last decade, the installation costs have been reduced. In this study is considered an average value of $0.60 USD for each Watt installed for residential applications (Ataei et al., 2015; Baneshi and Hadianfard, 2016). Hence, a generation system of a capacity of 1.8 kW is implemented, the estimated useful life is higher than 20 years (Bhattacharjee and Acharya, 2015). According to the manufacturer's datasheet, it is guaranteed its correct operation with minor maintenance for 20 years (Dufo-López and Bernal-Agustín, 2008). The technical specifications of the hybrid PV-wind system are provided in (Ospino-Castro et al., 2018).

In the installation costs of the proposed system, the values of the PV modules, the wind turbine, and the inverters are considered, but also the cost associated to the replacement of parts, and operation and maintenance (O&M). In this type of projects, there is a high initial investment, but the O&M costs are low, due to the absence of associated costs for fuel. An annual O&M cost of 0.5% is considered in the installation cost (Choi et al., 2018). The calculation of the replacement cost involves a cash flow that is not annual but is determined by the component's useful life. This replacement cost involves those components of the system, whose lifespan is less than the duration of the project, in this case, 25 years. According to the specifications of the manufacturers, a useful life of 10-15 years is guaranteed for the inverter and controllers of the PV system and wind turbine. It is common to replace these components every 5-10 years due to damage suffered by malfunction of these devices (Keating et al., 2015). Regarding the electrical system and the assembly structures, the useful life is higher than 25 years, with adequate maintenance. Therefore, the only devices that must be replaced are the wind controller and inverter of the PV system, whose reinvestment of capital will be made every 10 years, assuming that the costs of the equipment and its installation is about 30% of the initial costs (Choi et al., 2018).

The parameters considered to establish the period necessary to recover the investment will depend mainly on three factors: The installation cost, the generation yield, and the income generated by the installation. To obtain the financial indicators needed in the economic analysis, such as, net cash flow, energy sales, accumulated profits, annual accumulated profits, payback time, net present value, discontinue rate K, and internal rate of return (IRR), the level of influence of the price of energy is quantified with respect to the profitability of the project, where an annual increase of 4% is estimated (Ramli et al., 2016). The annual projection of the O&M costs, that is, all those direct costs that allow the optimal functioning of the PV-wind system, in accordance with the manufacturer's recommendations, are associated with the consumer price index, with an average value of 6.2% in the last 5 years according to Worldwide Inflation Data (WID, 2018). For general operating expenses independent to the proposed system, it is established an initial value of 1% of the total of the installation; this expense may be related to insurance, fiduciary or administration, operating permits or interconnection contract.

It is important to mention that according to the current regulations established in Mexico, the project is considered feasible if the return of the investment is made in <7 years (FIDE, 2019).

5. ENERGY AND ECONOMIC BALANCES

To assess the feasibility and profitability of the hybrid PV-wind generation system connected to the grid, it is necessary to know the benefits obtained with the installation of the proposed system; this is conducted through the calculus of energy and economic balances. The information contained in these balances helps to determine the feasibility of the project.

5.1. Energy Balance

Table 1 shows the energy generation projection obtained in a typical year considering the measurements of wind speed and solar radiation, as well as the characteristics of the selected components. In the case of the PV system, the 1-year average performance ratio (*PR*) considered is 74%. This value is used to estimate the system power losses. The generated monthly average electric power

Table 1: Energy balance of the proposed generation system

Indicator	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
PV system													
$W_{Grid,mth}$ (kW)	2	2	2	2	2	2	2	2	2	2	2	2	24
$E_{Grid,mth}$ (kWh)	433	431	495	444	426	385	395	420	402	450	451	434	5166
PR (%)	75	74	73	72	72	73	74	74	76	75	75	76	74
η_{inv} (%)	90	90	90	90	90	90	90	90	90	90	90	90	90
η_{Array} (%)	13	13	13	12	12	13	13	13	13	13	13	13	13
η_{Sys} (%)	11	11	11	11	11	11	11	11	11	11	11	12	11
Wind system													
$W_{Grid,mean}$ (kW)	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.6	0.6	0.6	0.5	0.4	7.44
$W_{Grid,max}$ (kW)	1.4	1.2	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.6	1.0	18
$E_{wind,mth}$ (kWh)	302	273	287	295	336	349	431	337	359	313	282	264	3828
$E_{Grid,mth}$ (kWh)	272	246	258	265	302	314	388	304	323	281	254	238	3445
CF (%)	24	21	23	25	27	29	32	27	27	25	22	20	25
η_{inv} (%)	90	90	90	90	90	90	90	90	90	90	90	90	90
CF_{hr}	513	503	518	470	513	487	549	509	541	520	517	533	6173
PD (W/m^2)	305	303	302	404	522	560	563	478	340	382	303	233	4694

of the PV system ($W_{Grid,mth}$) and its annual grid-injected energy ($E_{Grid,mth}$) are 2 kW and 5.166 kWh, respectively. The inverter daily average efficiency (η_{inv}) considered was 90%; therefore, the array estimated efficiency (η_{Array}) varies from 12% to 13%, and the system efficiency (η_{Sys}) is around 11%. These values of efficiency are reasonable considering the daily global irradiation of the city.

On the other hand, using the curve of the selected generator and the Weibull distribution was calculated the energy generated by the wind system (Hernandez et al., 2013). The monthly capacity factor (CF) varies from month to month due to the influence of the wind speed on the electric output power. In this particular case, CF varies from 21% to 32%. The wind generator works 6173 h/year (C_{Fhr}); April is the month with the least utilization with 470 h and July is the highest with 549 h. The estimated monthly average delivery energy to the grid ($E_{Grid,mth}$) and the total 1-year average power generated ($W_{Grid,mean}$) is about 3445 kWh and is 7438 kWh, respectively. The highest grid power injection ($W_{Grid,max}$) at the top wind speeds of each month is in between 1 kW and 1.7 kW. The energy generated by the wind system ($E_{wind,mth}$), without the connection system losses, goes from 264 kWh to 431 kWh and the expected power density (PD) varies from 233 W/m^2 to 563 W/m^2.

5.2. Economic Balance

Currently, in Mexico, there are two schemes for the sale of the surplus of the energy generated to the wholesale electricity market through the CFE (which stands for Federal Electricity Commission) (Madrigal, 2017).

The first scheme is net metering, where the CFE measures the electricity generated by the renewable energy system, as well as, the user's consumption and makes a net balance. If the user consumes more than his production, the difference between consumption and production is charged. If the user's production is equal to its consumption, the user will only pay the fees for using the electric transmission network. But, if the production is greater, a credit balance in kWh is created in favor of the user, and it can be used for a maximum period of 12 months in case of the production is less than the consumption.

The other adopted scheme since 2017 is called net billing (Madrigal, 2017). The users who have a production surplus will be able to sell this surplus at a local marginal price (LMP). Where the LMP is the wholesale price at the connection point, and this price is fixed based on the demand and the technology used to generate the last kWh injected into the transmission system.

Considering the schemes mentioned above, three possible scenarios were created. These scenarios consider the way in which the proposed system can be financed. The first scenario considers an investment of 100% by the user using his own funds, the second case a 50% of investment by the user and the rest financed by an external entity (e.g. a credit from the bank), and the third case a 60% of investment by the user and the rest funded by the government.

5.3.1. Scenario 1. Investment of 100% by user's own funds

Figures 8 and 9 show the economic balance obtained with the net metering and net billing schemes, respectively. Table 2 summarizes the results obtained in both schemes for this scenario. In the net metering scheme, the investment made in the installation of the generation system is recovered in 5.5 years, while in the net billing scheme is in 7.8 years, resulting in an IRR of 18.31% and 11.53%, respectively. In this case, the net metering scheme is better because is in terms of energy and the net billing in terms of money and includes the LMP, which results in a nonattractive scheme for home users.

The effect of the replacement of the inverter at ten and 20 years can be appreciated in Figures 8 and 9 and reflected in the behavior of the IRR. After 25 years there is a net cash flow of $13,667.90 in the net metering scheme and $7,333.59 in net billing scheme, values that confirm that the first scheme is a better option.

5.3.2. Scenario 2. Investment of 50% by the user's own funds and 50% financed by an external entity

Another possible way to finance this type of projects is by using a credit, for example through the bank. Figure 10 shows that after 25 years the total income received when recovering the total investment and completing the payments to the financing entity is of $13,427.94 USD in the net metering scheme. The payback is in 5.8 years and the IRR has a value of 18.31%.

Figure 8: Scenario 1, net metering scheme economic balance results

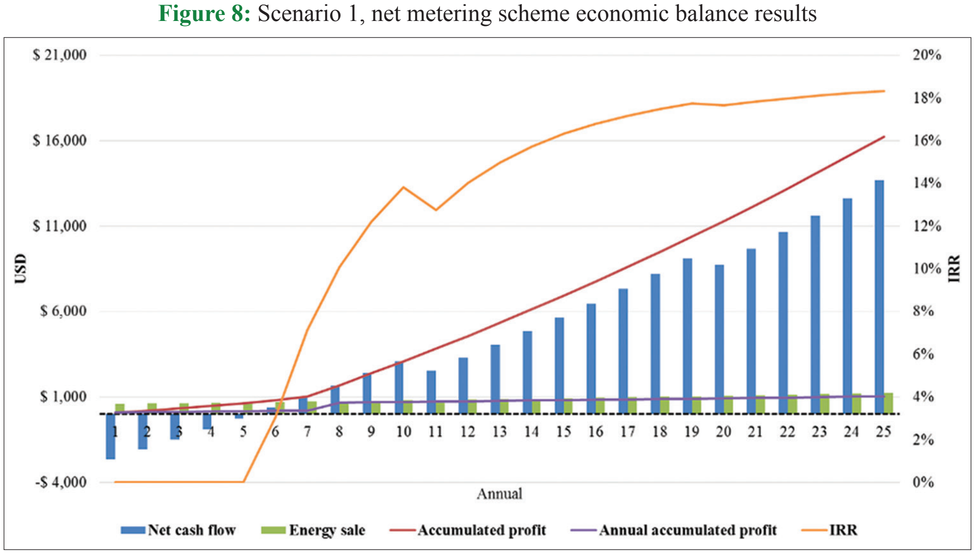


Figure 9: Scenario 1, net billing scheme economic balance results

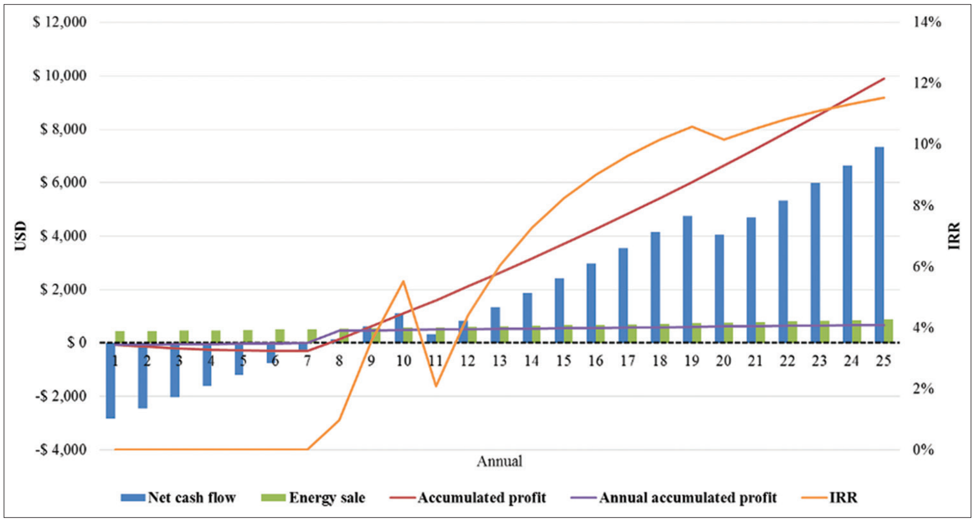
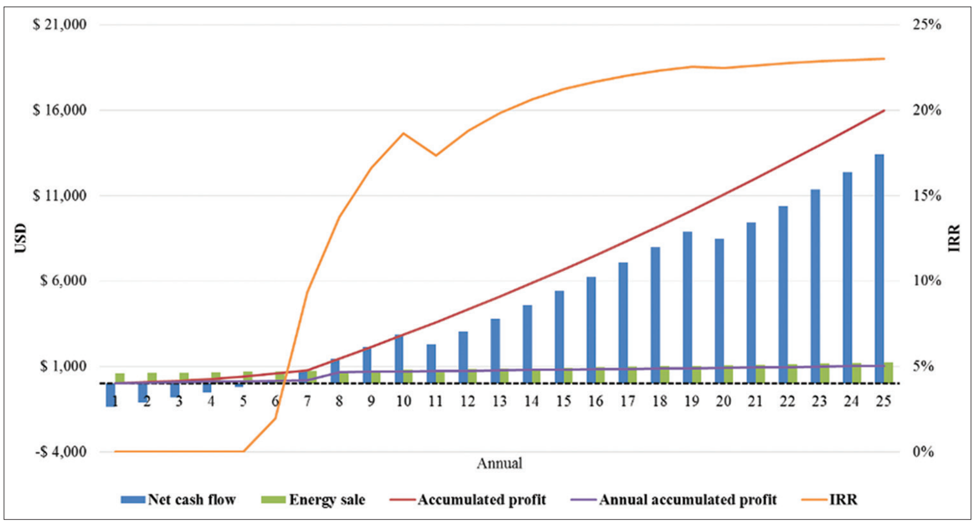


Figure 10: Scenario 2, net metering scheme economic balance results



On the other hand, in Figure 11 is shown the results obtained with the net billing scheme for this scenario. The investment made is recovered in 8.5 years and it has a higher value than the previous scenario due to the interests paid to the financing entity.

Despite the fact that scenario 1 is a better option for the installation of the proposed system in comparison with this one, from Table 3 can be seen that the results obtained are still competitive. The benefit of this option lies in considering that only a few people in Mexico would have the possibility to pay the whole generation system using their own funds. But it is important to mention that the interest rate considered in this study is the lowest in the market and increases with the passage of time, which has a direct impact on the payback.

Table 2: Summary of the results obtained for scenario 1

Indicator	Net metering	Net billing
Discount rate	0.00%	0.00%
Net cash flow (USD)	$13,667.90	$7,333.59
IRR	18.31%	11.53%
Payback (years)	5.5	7.8

Table 3: Summary of the results obtained for scenario 2

Indicator	Net metering	Net billing
Discount rate	3.38%	3.38%
Net cash flow (USD)	$13,427.94	$7,093.63
IRR	18.31%	13.39%
Payback (years)	5.8	8.5

5.3.3. Scenario 3. Investment of 60% by the user's own funds and 40% financed by a government entity

In this scenario is considered the financing by a government entity. In Mexico, these projects can be financed through the FIDE and SEDATU (Secretariat of Territorial Agrarian and Urban Development) with a preferential low-interest rate (SEDATU, 2018; FIDE, 2019). However, it is important to mention that the funds financed by the government are subsidized, with the aim of encouraging investment in this type of technology at home users' level and help to achieve the goals established in the energy reform of the country.

The economic balances for this case study can be consulted in Figures 12 and 13, for the net metering and net billing scheme,

Figure 11: Scenario 2, net billing scheme economic balance results

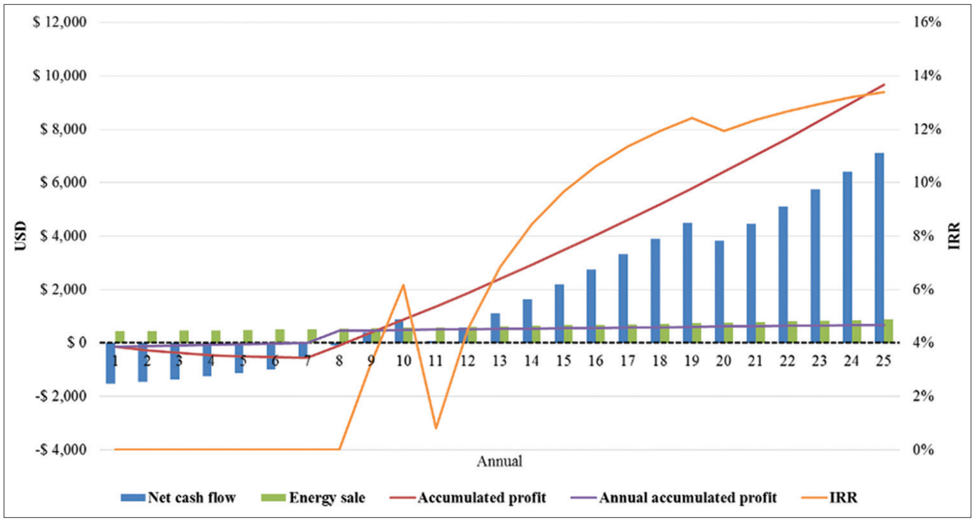


Figure 12: Scenario 3, net metering scheme economic balance results

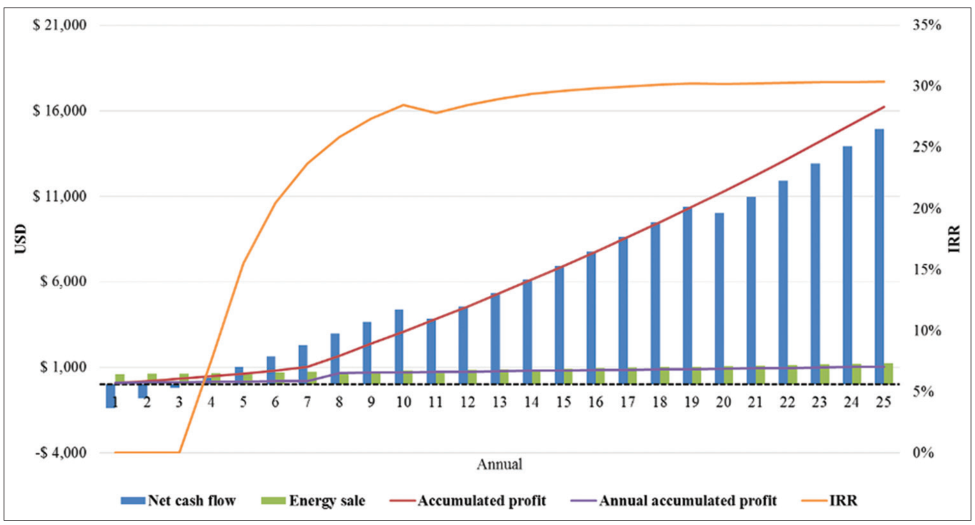
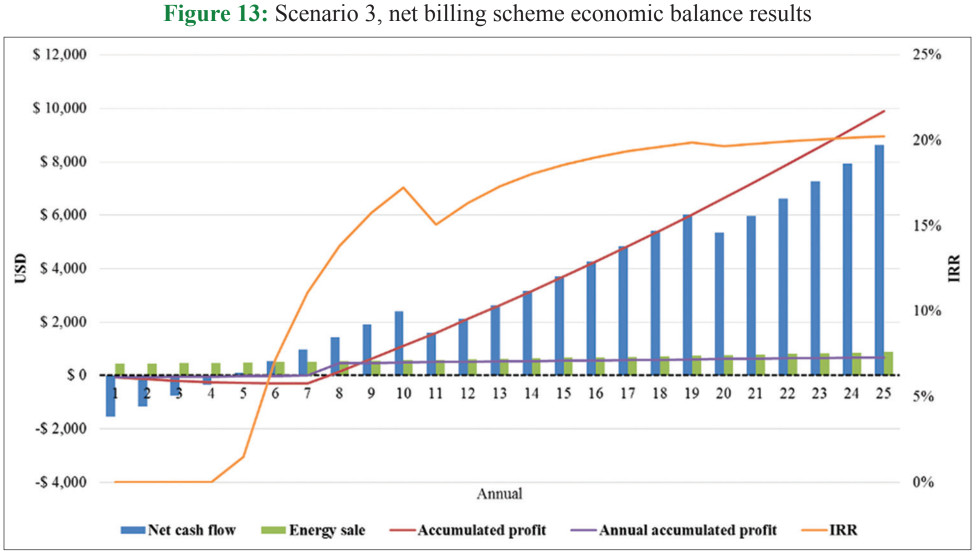


Figure 13: Scenario 3, net billing scheme economic balance results



respectively. As can be seen from Figure 12, the payback is in 3.3 years with an IRR of 30.39%. Also, with the net billing scheme, the return on the investment is in 4.7 years, as shown in Figure 13. This is the best scenario because it is supported by government funds and helps to increase the penetration of distributed generation systems based on renewable energy in the electrical network.

Table 4: Summary of the results obtained for scenario 3

Indicator	Net metering	Net billing
Discount rate	0.00%	0.00%
Net cash flow (USD)	$14,954.30	$8,619.99
IRR	30.39%	20.23%
Payback (years)	3.3	4.7

Table 4 summarizes the results obtained for this scenario. The net cash flow for the net metering option is $14,954.30 USD after 25 years, resulting in to be the best option, even in the net metering scheme with a net cash flow of $8,619.99 USD. This scenario demonstrates the importance of the government in generating policies to support the development of projects based on renewable energy.

6. CONCLUSIONS

In this paper, technical and economic analysis of a grid-connected hybrid PV-wind system was presented, in order to evaluate the feasibility of implantation of this type of systems in Mexico. The analyses were carried out by taking into consideration the available RES, in specific the solar irradiation and the wind speed.

Three scenarios were considered. These were generated based on the actual conditions of the public policies about the generation of electricity at a residential level using RES. The energy analyses show that almost all the energy consumption can be met with the proposed system connected to the grid.

On the other hand, the economic balance performed shows that the net metering scheme is the best option for the connection of the proposed system with the grid. This because is in terms of an energy balance instead of buying/selling energy. Besides, considering the government subsidies, the time for the return of the investment is shorter, less expensive for the user, and the profits will be higher in the lifetime of the generation system. In specific, in the third scenario with the net metering scheme, the payback is in 3.3 years, with a net cash flow of $14,954.30 USD.

The obtained results confirm the viability of the proposed project, as well as increased attractiveness and affordability for medium/low-income users with government incentives. Furthermore, this study was carried out with the data available from the city of San Luis Potosi, but it can be applied to other cities in Mexico with similar weather conditions and energy consumption patterns.

7. ACKNOWLEDGMENTS

The authors want to acknowledge the Universidad Autónoma de San Luis Potosí through the Facultad de Ingeniería, and the Departamento de Energía of the Universidad de la Costa (CUC), for the facilities granted to carry out this research.

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