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Distributed generation with a photovoltaic generating plant interconnected to a medium voltage network in the marginalized town of Xbilincoc, Campeche

Generación distribuida con central generadora fotovoltaica interconectada a red de media tensión en el poblado marginado de Xbilincoc, Campeche

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Abstract

In this paper, it is proposed to lay the foundations for the implementation of a Photovoltaic Systems Interconnected onto Network Distribution Systems that benefits the marginalized population of the town of Xbilincoc, Campeche. Through Distributed Generation (DG) it will be possible to direct the electrical energy produced by this plant for its own consumption and / or sale to the electrical company denomined Comision Federal de Electricidad (CFE), depending on the analysis of consideration for services that is most convenient for the producers. The power generating plant will be managed by the fishing cooperative formed by the commissioner and the most active fishermen of the town and the economic resources necessary for its construction and commissioning will be through a financing mechanism granted by a governing body denomined Fideicomiso de Ahorro de Energía (FIDE) and when it has been paid in full, the economic benefits for families will be to ensure that the cost of their consumption of electric energy does not increase, and to strengthen the economic development of the town of Punta Xen by administering the resources obtained from the sale of electrical energy to the CFE.

Distributed generation, Self-consumption, Marginalized population

Resumen

En este artículo se propone el proyecto para la implementación de un Sistema Fotovoltaico Interconectado a Red (SFVIR) que beneficie a la población marginada de la localidad agrícola de Xbilincoc, Campeche. A través de la Generación Distribuida (GD) será posible direccionar la energía eléctrica que produce esta planta para su autoconsumo y venta de los excedentes a la Comisión Federal de Electricidad (CFE), dependiendo del análisis de contraprestación de servicios que le sea más conveniente a los productores. La planta generadora será administrada por la cooperativa agrícola formada por el comisario y agricultores más activos del poblado y los recursos económicos necesarios para su construcción y puesta en servicio serán a través de un mecanismo de financiamiento otorgado por el Fideicomiso de Ahorro de Energía (FIDE) y cuando ya se haya pagado en su totalidad, los beneficios económicos serán para las familias asegurando mantener energía eléctrica en los hogares sin costo y lograr fortalecer el desarrollo económico del poblado mediante la administración de los recursos obtenidos de la venta de la energía eléctrica a la CFE.

Generación distribuida, Autoconsumo, Población marginada

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Introduction

This article proposes the design and implementation of a photovoltaic power plant interconnected to the distribution network of the Federal Electricity Commission (CFE) in the rural town of Xbilincoc, Hopelchén, Campeche in order to provide electricity to households for self-consumption and to market part of that energy through its sale to the Federal Electricity Commission. This energy will be used for daily household chores and the surplus that is not consumed will be sold to the CFE to obtain economic resources that will be invested in the installation of public services in the town in order to improve the quality of life of the inhabitants.

Through the Rural Electrification Department, the CFE will build a 4.5 km-long branch of the distribution line to supply medium voltage to the town and will build the internal 34500/220-127 V distribution network. Through the Distributed Generation concept, the village will have quality electric power on site because the energy will not travel long distances from generation to the point of consumption, thus eliminating line losses.

Problem statement

The town of Xbilincoc, in the municipality of Hopelchén, in the State of Campeche is a marginalized population that currently does not have public electricity service, its only source of electricity consumption is through individual photovoltaic panels of 180 W, of which 3 panels are installed per house, which is insufficient to cover the basic needs of the inhabitants.

In terms of electricity consumption, the houses only have a few incandescent bulbs, fluorescent bulbs, and a small refrigerator.

There is a history of using isolated photovoltaic panels in the community in 2006; however, due to the lack of maintenance and training for the villagers, the batteries and other accessories were damaged, causing the system in each home to function inefficiently and in some cases to fall into disuse. The Federal Electricity Commission's power grid is located approximately 4.5 km from the town and the authorities have taken steps over the years to get the CFE to supply electricity, but so far these efforts have not been successful.

As a result of the above, it is proposed to implement an electric power generating plant with a photovoltaic system interconnected to the grid (SFVIR) and thus cover and satisfy the basic socioeconomic needs of the population. With the operation of the SFVIR, through an agricultural cooperative scheme, acting as an Independent Power Producer (IPP), it will be possible to generate and sell electricity to a Qualified Supplier and this in turn, will sell it to the CFE Basic Supply and the capital obtained from sales for economic growth will be used to promote employment and sustainable development of the population, which will contribute to the population to have a better quality of life, and better productivity in their main local activity that they currently develop as agriculture.

In Mexico we have the opportunity to take advantage of renewable natural resources to develop technologies and create generating power plants with lower capacity and higher efficiency than conventional power plants, which is a very attractive alternative both technically and economically. There are also many public financing mechanisms such as FIDE, CONUEE, GIZ, FOTEASE, FSE, FSUE, etc., that grant credit or financing through development projects to combat poverty, creating links between States, Municipalities and the Federal Government to establish agreements and conventions.

It is an opportunity for the town of Xbilincoc to achieve this, so the villagers must be made deeply aware of its implementation and the socioeconomic benefits that will be obtained for them and for the environment.

Theoretical framework

The legislation on electric energy has evolved in recent years, from only allowing the monopoly of the CFE, to the new legislation implemented in 2016 that allows the participation of private companies in the Wholesale Electricity Market (MEM) to promote competition between Producers and Marketers and thus break the monopoly of the CFE.

In the previous legislation, i.e., with the Electric Energy Public Service Law (LSPEE), there was the figure of the Independent Power Producer (PIE), who was only allowed by the energy regulator, the Energy Regulatory Commission (CRE), to sell its electric energy to the CFE.

Now with the new Electricity Industry Law (LIE), the figure of Prosumer appears, which is a PIE that uses the energy it generates for self-consumption, cogeneration and sale to the CFE. Another advantage of this new legislation is that the Prosumer can generate energy in High, Medium or Low Voltage, so that a low voltage user can now be a low voltage producer. The Prosumer can be a natural person or an organization (small or medium company) named as a legal entity. Both have the same possibilities to consume or sell the electricity they produce in the Wholesale Electricity Market (MEM).

The greatest growth potential for the new energy generation scheme is in solar energy with photovoltaic systems. Industrial, small and medium-sized companies in the country are on the way to producing the energy they consume; however, the lack of financing and the slow return on investment discourage this important generation alternative.

In Mexico there are 4.2 million economic units (Secretaría de Economía, 2019), of which 99.8 percent of them are small or medium-sized enterprises (SMEs) that contribute 42 percent of the gross domestic product and generate 78 percent of employment in the country.

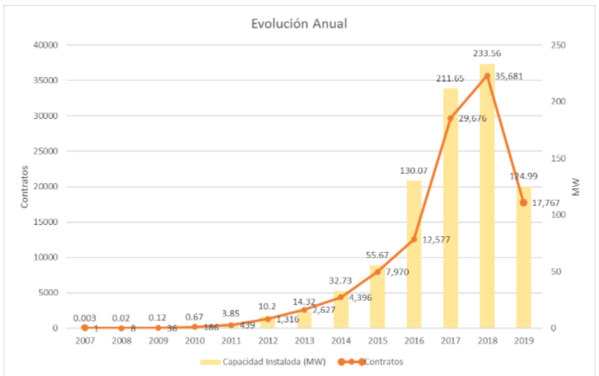
In March 2019, the CRE disclosed that there are 94,844 such rooftops in Mexico, with a total capacity of just over 692 Megawatts (MW). In 2018 alone, more than 35 thousand were installed, representing a 60 percent growth in the country in one year. For distributed generation (DG), these contracts contemplate an installed capacity of 570.20 MW, while those of small and medium scale reached 247.65 MW. This is shown in Table 1.

Likewise, the migration towards Distributed Generation can be seen in Graph 1, with the increase in installed capacity and in the contracts granted to the PIEs.

By state, Jalisco, with 17,97 thousand 97; Nuevo León, with 11,45 thousand 45; and Mexico City, with 7,376, were the states with the highest number of contracts.

	Installed capacity (MW)	Contracts (Thousands)
Small and medium scale	247,65	29.556
Distributed Generation	570,2	83.104
	817,85	112.660

Table 1 Annual evolution of small and medium scale contracts and Distributed Generation
Source: Energy Regulatory Commission, March 2019



Graphic 1 Annual evolution of installed capacity/contracts, according to CFE's subsidiary productive company data
Source: Energy Regulatory Commission, March 2019

By installed capacity, Nuevo León, with 91.34 MW; Jalisco, with 88.86 MW; State of Mexico, with 74.83 MW; as well as Mexico City, with 64.68 MW, were the most relevant entities in 2018.

It is important to consider that, in the years 2019 and 2020, this growth has been slowing down, justifying that Distributed Generation with clean energies, such as wind and solar photovoltaic are intermittent and do not provide reliability to the National Electric System (SEN). Examples of restrictions are the CENACE and SENER agreements of April 29 and May 15, 2020 (SEGOB, 2020) due to the issue of the energy counter-reform. In addition, the issue of the Sars-CoV2 virus pandemic (Covid-19) contributed to the decrease in the execution of contracts by the CFE.

In Distributed Generation, there are generating plants with fossil and clean energies. Table 2 shows that the smallest generating plants are hydroelectric, gas, biomass, diesel or fuel oil, wind and biogas, while the largest generating plant is solar photovoltaic.

Technologies	Capacity (MW)	No. Contracts	Percentage (%)
Hydroelectric plants	0,009	4	0
Gas	0,077	9	0,01
Biomass	0,81	10	0,1
Diesel or Fuel Oil	0,72	13	0,01
Wind power	0,19	19	0,02
Biogas	3,97	49	0,49
Solar Photovoltaic	812,6	112.500	99,3

Table 2 Scheme of participation of technologies, in terms of capacity, contracts and percentage
Source: Energy Regulatory Commission, March 2019

Methodology

For this project, a methodology was used, starting with a socioeconomic analysis of the population, followed by a load census, then a planning of the distribution network within the village along with the interconnection branch, the solar photovoltaic plant was sized and finally a cost analysis that is presented to the Energy Saving Trust Program (FIDE) to obtain funding for the solar photovoltaic plant with its payback time in order to verify the time in which the benefits will already be for the population.

The purpose of this study is to lay the groundwork so that other marginalized populations can access financing and rural electrification programs in order to become electricity prosumers that participate in the Wholesale Electricity Market and obtain economic benefits that increase their quality of life.

Distributed generation and the grid code

DPCA (Distribution Power Coalition of America) defines it as any small-scale generation technology that provides electricity at points closer to the consumer or to the transmission or distribution grid. On the other hand, the IEA (International Energy Agency) considers as DG only that which is connected to the distribution grid at low voltage and associates it with technologies such as engines, mini- and micro-turbines, fuel cells and solar photovoltaic energy. Under this scheme, the SFVIR will be efficient.

The Connection Provisions of the Grid Code are applicable to all Load Centers connected at Medium and High Voltage. The above, regardless of the contracted demand, i.e., compliance with the Grid Code is not differentiated for Basic Supply users, Qualified, Qualified Wholesale Electricity Market Participant Users, Intermediary Generation, prosumers, etc. Our SFVIR must comply with these requirements in order to be interconnected to the National Electric System.

Socioeconomic status and load census

The occupation of 100% of the heads of household is farmer, and their average income is very low, between $4500.00 and $7500.00 per month (source: the villagers themselves and the commissioner), so they do not have a fixed income or insurance to provide welfare for their families. The average family consists of 6 people: father, mother and 4 children, so the economic income is insufficient. Many young people and some heads of household have had to migrate to nearby towns in search of work. In addition, they lack public electric power services, which is why it is necessary to give them the opportunity to build and let them manage the photovoltaic generating plant, after training and commissioning.

A study was made of the houses that have electric energy service from the three old panels they have. This is shown in the following table.

No. of dwellings	100W incandescent bulb	54 W fluorescent lamp	700 W refrigerator
19	zero	4	1
11	2	2	1
4	4	zero	zero

Table 3 Results of the census of electrical load in dwellings
Source: Own elaboration

As can be seen in both studies, the families do not have sufficient economic resources to support themselves and, in addition, they lack efficient public electricity service, and there is no public lighting, making it dangerous for people to pass through at night.

Distribution network in the village

Through the Rural Electrification Department of the CFE and the authors of this article, the project of the Distribution Network of the town of Xbilincoc was elaborated, who will bid the contest for its construction. Table 4 below shows some of the structures, devices and conductors to be installed.

Airborne equipment chart				
No.	**NEW POST**	**DEVICES**		
		MEDIA	**RETENTIONS**	**LANDS**
1	12-750	AD3G/3RF3A	2-RDA	TIE
2	12-750	TS3N		
3	12-750	TS3N/RD2	RDA	TIE
4	12-750	AD2N	RDA	
5	12-750	TS3N		
6	12-750	RD2N/RD2	RDA-REA	TIE
7	12-750	TS3N		
8	12-750	RD2N/RD2	RDA-REA	TIE

Table 4 Sample of some structures, devices and conductors of the distribution network in the town of Xbilincoc
Source: Own elaboration

Distribution Branch for the village

The CFE distribution circuit that will feed the town is called Ukúm (Circuit CMO05030) with a voltage of 34.5 kV, but it is 4.5 km from the interconnection point of the town, so it is required to build a feeder branch for the town. In the same way as the village distribution network, this branch will be built with resources from the Rural Electrification Department of the CFE. Table 5 shows some of the structures, devices and conductors to be installed.

Airborne equipment chart				
No.	**NEW POST**	**DEVICES**		
		MEDIA	**RETENTIONS**	**LANDS**
1	13C-600	CT1G/CT2		
2	13C-600	HA3G	2RDA	1
			2RSA	
3	13C-600	CT1G/CT2		
4	13C-600	CT1G/CT2		1
5	13C-600	CT1G/CT2	TEMPESTAD	
6	13C-600	CT1G/CT2		1
7	13C-600	CT1G/CT2		

Table 5 Sample of some structures, devices and conductors of the distribution branch of the Xbilincoc village
Source: Own elaboration

The Photovoltaic Generating Station and its photovoltaic arrays Due to the need for electrical energy in the houses of the town of Xbilincoc, 4 PV modules of 440 Wp were considered for each house, so there will be a load of 1.76 kW per household. There are 34 homes in total, so the power demand of the village will be

$$P_{town} = 440\,W_p \cdot 4\,modules \cdot 34\,homes = 59{,}840\,W \quad (1)$$

And thinking of producing 50% more for direct sale to CFE, we will have:

$$P_{Total} = 150\%\,P_{town} = 1.5(59{,}840\,W) = 89{,}760\,W = 89.76\,k \quad (2)$$

The number of PV modules is obtained from:

$$No.modules\ FV = \frac{89{,}760\,W}{440\,W} = 204\,modules \quad (3)$$

In our design, three 24 kW PV arrays and one 17.5 kW array are proposed. Each 24-kW array will have strings of 14 modules (440 W each) in series and two strings in parallel for each MPPT. The inverter has 2 MPPTs. Therefore, each inverter will have 56 modules. A FRONUIS SYMO 24.0-3 480 inverter is proposed for each array.

The 17.5 kW array will have strings of 20 modules (440 W each) in series for each MPPT. The inverter has 2 MPPTs. Therefore, the inverter will have 40 modules. A FRONUIS SYMO 17.5-3 480 inverter is proposed for this array.

Electrical characteristics					
Power (Wp)	Voc (V)	Vmp (V)	Isc (A)	Imp (A)	Efficiency (%)
440	48.7	40.3	11.4	10.92	19.92
Mechanical and physical characteristics					
Cell type	Cell arrangement	Dimensions (mm)	Weight (kg)	Module temp. (°C)	Air mass
Polycrystalline, Generation III	2x (12x6) (144 cell)	2108x1048x40	24.9	25	1.5

Table 6 Electrical and mechanical characteristics of the PV module
Source: own elaboration

Selection of the photovoltaic module

A polycrystalline photovoltaic module, CanadianSolar brand, model HiKu SUPER HIGH POWER POLY PERC MODULE of 440 W, with the characteristics shown in Table 6, is proposed.

Inverter selection

The inverter for the solar PV plant is selected. On this occasion, an inverter is proposed that meets the DC requirements of the PV arrays shown above and the mppt connection points, in addition to the AC requirements. For the 3 arrays of 24 kW, three-phase central inverters for interconnection to the grid of FRONIUS model SYMO 24.0-3 480 have been selected, with the characteristics shown in Table 7.

Inverter Fronius Symo 24.0-3 480

PV Power (kWp)	Number of MPPT	Total usable input current (MPPT1+MPPT2) (A)	Maximum Icc per PV series (A)	Vcd MPP range (V)	AC output voltage (V)	AC output current (A)
19 – 31	2	51	49.5/37.5	500 - 800	480	28.9

Table 7 Input and output electrical characteristics of the PV inverter
Source: Own elaboration

Similarly, for the 17.5 kW array, the inverter for the solar PV plant is selected. An inverter is proposed that meets the DC requirements of the PV arrays and the mppt connection points, in addition to the AC requirements. Three-phase central inverters have been selected for interconnection to the grid, FRONIUS model SYMO 17.5-3 480, with the characteristics shown in Table 8.

Fronius Symo 22.7-3 Inverter 480

PV Power (kWp)	Number of MPPT	Total usable input current (MPPT1+MPPT2) (A)	Maximum Icc per PV series (A)	Vcd MPP range (V)	AC output voltage (V)	AC output current (A)
14.0 – 23.0	2	51	49.5/37.5	500 - 800	480	21.0

Table 8 Input and output electrical characteristics of the PV inverter
Source: Own elaboration

Calculation of conductors

The calculation of the feeder that goes from the distribution board to each inverter was performed. For each inverter that controls 56 PV modules, we have:

$$I_{nom} = \frac{P}{\sqrt{3}V_L cos\theta} = \frac{24640}{\sqrt{3}(480\ V)(0.9)} = 32.93\ A$$

We calculated the Corrected Icorrected, taking the following factors to comply with NOM-001-SEDE-2012: T.C.F. = Temperature correction factor = 0.88, D.F. = Demand factor = 1.0 and A.C.F. = Clustering correction factor = 1.0.

$$I_{corr} = \frac{I_{nom}(F.D.)}{(F.C.T.)(F.C.A.)} = \frac{32.93A(1)}{(0.88)(1)} = 37.42\ A$$

According to table 310-15(b)2(a) of NOM-001-SEDE-2012 on the ampacity of conductors, we have a feeder that has a nominal temperature of 75° C THHW caliber 8 AWG, with an ampacity of 50 Amperes and a cross section of 8.37 mm2. We verify that it meets the voltage drop criterion, taking the distance of the inverter farthest from the distribution board, which is 38 m. and we have:

$$\%e = \frac{2\sqrt{3}\,L\,I_{nom}}{s\,V_f} = \frac{2\sqrt{3}(38m.)(32.93\ A)}{(8.37\ mm^2)(480V)} = 0.028\% < 3\%$$

According to our calculation, the 8 **AWG** gauge **THHW** conductor complies with NOM-001-SEDE-2012 for the positive and negative poles. Also for the inverter controlling 40 PV modules the same gauge was considered.

Calculation of the protections

The thermomagnetic circuit breaker for each of the three 56-module PV arrays was obtained from:

$$I_{máx} = I_{protection} = 125\%\ I_{nom} = 1.25\ (32.93\ A) = 41.16\ A$$

Three **3P-50 Amperes** thermomagnetic circuit breakers, **type I-Line**, are required.

For the inverter of 40 PV modules, we have:

$$I_{nom} = \frac{P}{\sqrt{3}V_L cos\theta} = \frac{17600}{\sqrt{3}(480\ V)(0.9)} = 23.52\ A$$

With a switch of:

$$I_{máx} = I_{protection} = 125\%\ I_{nom} = 1.25\ (23.52\ A) = 29.4\ A$$

One **3P-30 Ampere** thermal magnetic breaker, **type I-Line**, is required.

The main switch of the I-Line panel shall be of:

$$I_{nom} = 3(32.93\ A) + 1(23.52\ A) = 122.31\ A$$

Also:

$$I_{nom} = \frac{P}{\sqrt{3}V_L cos\theta} = \frac{89760}{\sqrt{3}(480\ V)(0.9)} = 122.31\ A$$

The main switch will be:

$$I_{max} = I_{protection} = 125\%\ I_{nom} = 1.25\ (122.31\ A) = 152.88\ A$$

One **3P-175 Ampere** thermal magnetic breaker, **type I-Line,** is required.

The Distribution Panelboard shall be three-phase I-Line type with its 3P-175 and 32-space main breaker, model JG250M141B in Nema-1 enclosure.

Transformer rating and fuse strip

To obtain the transformer capacity, 15% free for future loads is considered, and is given by:

$$kVA = 115\% \frac{kW_p}{cos\theta} = 1.15\left(\frac{89.76\ kW_p}{0.9}\right) = 114.69\ kVA$$

Therefore, a three-phase distribution transformer of 150 kVA, 480-254/34,500 V. step-up, Star-Delta connection, with overvoltage protection based on three ADA 33 kV surge arresters is required.

The CFE Medium Voltage connection will be aerial type, with 2 AWG AAC conductor, with 3 fuse cutouts (CCF) for 34.5 kV and with fuse strip of:

$$I_{primary} = \frac{P}{\sqrt{3}V_L cos\theta} = \frac{89760}{\sqrt{3}(34500\ V)(0.9)} = 1.66\ A$$

Three 2 Amp fuse strips are required.

Figure 1 illustrates the arrangement diagram of the 89.76 kWp generating station.

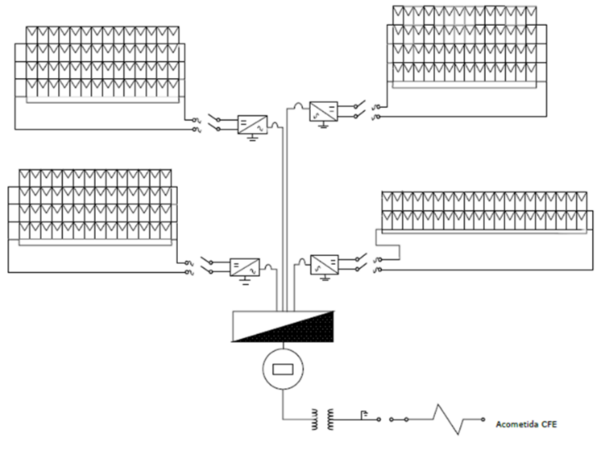


Figure 1 SFVIR to operate as distributed generation
Source: own elaboration.

Cost and financing of the photovoltaic generating plant

For the construction of the photovoltaic power plant, financing was requested from the Fideicomiso de Ahorro de Energía (FIDE), which will provide the capital for the total cost of the SFVIR in the amount of US$91,829.84 through a contract between the Federal Government's Proyecto Servicios Integrales de Energía (PSIE) and the fishermen's cooperative, of which approximately US$45,914.92 would be provided by the Federal Government as an "investment" subsidy. The PSIE was designed to support rural electrification strategies and measures established by the Secretariat of Energy (SENER) and defined as a priority by the federal administration.

Projected production of energy generated and its benefits

Table 9 shows an estimate of the monthly energy generation projection. The production depends on the solar resource, given in average monthly peak solar hours, and the number of days in the month.

The monthly solar resource data was obtained from NREL (The National Renewable Energy Laboratory). The annual energy generated will be 193,865.42 kWh per year under ideal conditions; but in reality the actual weather conditions vary with the weather, there are cloudy days, rainy days, some garbage falling on the PV modules, among other inconveniences, so it is considered empirically a 20% loss (Weber, *et al*., 2020), giving an annual energy generation of 155,092.33 kWh.

Month	kWp installed	Peak solar hours	Days per month	kWh generated per month
January	89.76	5.25	31	14,608.44
February	89.76	5.86	28	14,727.82
March	89.76	6.48	31	18,030.98
April	89.76	6.52	30	17,557.05
May	89.76	6.30	31	17,530.12
June	89.76	6.01	30	16,183.73
July	89.76	6.06	31	16,862.32
August	89.76	6.15	31	17,112.74
September	89.76	6.11	30	16,453.01
October	89.76	5.76	31	16,027.54
November	89.76	5.58	30	15,025.82
December	89.76	4.94	31	13,745.85
			Annual production	**193,865.42**

Table 9 Monthly projection of energy generation
Source: Own elaboration

Let us remember that, of this production, approximately 50% will be sold to the CFE, under the NET BILLING scheme and will be in accordance with what is registered in the bi-directional meter per month. The electric energy generated with renewable energies and sold to the CFE has a price between 80 and 120 dollars per MWh (SENER, 2020). Being solar photovoltaic the cheapest, we will take the price of 80 dollars per MWh and this gives us an estimated annual economic resource of

$$Annual\ amount = 50\%\ Annual\ production\ in\ MW \cdot (80 \frac{dollars}{MW})$$

$$Annual\ amount = 0.5(155.092\ MW)\left(80 \frac{dollars}{MW}\right) = 6203.68\ dollars$$

This capital will be used to be applied in two areas:

1. 50% will be used to pay the financing granted by the PSIE for the implementation of the photovoltaic power plant, so they would stop paying the investment in 7.4 years and from then on, the net sales will be for the villagers.

2. The other 50% will be used to improve the quality of life of the families of Xbilincoc, through the implementation of public services and social programs that support the well-being of the families.

The energy will be sold to a qualified supplier who will sell it to the CFE. With the implementation of the photovoltaic power plant, the town of Xbilincoc will emerge from marginalization, thanks to the support provided by CFE Rural Electrification, PSIE and the project developed in this article.

Conclusions and recommendations

The project developed provides a methodology for the implementation of a Photovoltaic System Interconnected to the Grid through Distributed Generation in marginalized populations, this project includes a branch and a distribution network to supply electric energy in Medium and Low Voltage to the town of Xbilincoc, Hopelchén, Campeche. This photovoltaic power plant will bring well-being and progress to the families of the town and will be built with subsidized financing from the Federal Government.

The calculations and considerations made to obtain the capacity and all the elements of a SFVIR are a methodology with important and conclusive results for companies in the industrial, commercial, residential and service sectors to join the Wholesale Electricity Market as prosumers.

Future research areas identified in this article are:

- Define a methodology for prosumers to comply with the requirements of the Grid Code.

- Implement a methodology for the commissioning of a SFVIR.

- Implement a preventive maintenance program for a SFVIR in marginalized populations.

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