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Energy efficiency using Distributed Generation; Cafeteria of Engineer Faculty Campeche, Mexico

Eficiencia energética con Generación Distribuida Fotovoltaica (GD-PV); Cafetería de la Facultad de Ingeniería de la Universidad Autónoma de Campeche, México

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Abstract

In the present work, an integral design of the cafeteria located at Faculty of Engineering of Autonomous University of Campeche is carried out. Four scenarios of Photo Voltaic (PV) generation have been studied. A 14 PV modules arrangement of 440 each, with azimuthal angle of 180º and a slope angle of 15º; the other is similar to the previous, but the slope angle was 19.85º. The following was a 24 PV modules arrangement of 440, with an azimuthal angle of 218º and a slope angle of 15º. The last arrangement consists of 24 PV modules arrangement of 440, with azimuthal angle of 218º and a slope angle of 19.85º. Where all of them are associated with the economic aspect to obtain greater efficiency of the plant with minimum recovery time. The free software System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) has been employed. Complete seasonal analysis has also been performed considering Gran Demanda Media Ordinaria en México (GDMO de CFE in Mexico) within the period January 2020 to March 2021. The best results are energy generation 17,570 kWh. Capacity factor 19%. Energy performance 1,671 kWh/kW. Performance relation 0.74. Leveled cost 5.39 ¢/kWh. And return on investment in 0.6 years. The GD-PV plant prevents the emission into the atmosphere of 778.85 kg of CO_2 equivalent.

Distributed generation, Energy efficiency, Grid-connected photovoltaic systems, Photovoltaic distributed generation

Resumen

En el presente trabajo se realizó un diseño integral de eficiencia energética en la cafetería de la Facultad de Ingeniería de la Universidad Autónoma de Campeche, México. Se analizaron 4 esquemas diferentes: un arreglo fotovoltaico de 14 módulos de 440 cada uno, ángulo azimutal de 180º y ángulo de inclinación de 15º; el otro fue similar al anterior pero con ángulo de inclinación de 19.85º. El siguiente fue de 24 módulos de 440, ángulo azimutal de 218º y ángulo de inclinación de 15º; por último arreglo fotovoltaico de 24 módulos de 440, ángulo azimutal de 218º y ángulo de inclinación de 19.85, asociados al aspecto económico, para obtener la mayor eficiencia de planta en el menor tiempo de recuperación. Se empleó el software libre System Advisor Model (SAM) desarrollado por el National Renewable Energy Laboratory (NREL). Contempló las tarifas económicas con análisis temporal completo, horario en tarifa Gran Demanda Media Ordinaria en México (GDMO de CFE en México). Los datos de facturación de la Comisión Federal de Electricidad fueron de enero de 2020 a marzo de 2021. Los mejores resultados son: Generación de energía, 17,570 kWh. Factor de capacidad 19%. Rendimiento energético 1,671 kWh/kW. Relación de desempeño 0.74. Costo nivelado 5.39 ¢/kWh. Retorno de inversión 0.6 años. La planta GD-PV previene la emisión a la atmósfera de 778.85 kg of CO_2 equivalente.

Generación distribuida, Eficiencia energética, Sistemas fotovoltaicos interconectados a red, Generación distribuida fotovoltaica

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Introduction

The Faculty of Engineering of the Universidad Autónoma de Campeche currently has an outdoor cafeteria. It currently has a transparent polycarbonate roof. However, the accrediting institutions of the Bachelor's degree programs have made the recommendation that the Faculty should have a more adequate cafeteria with, among other things, an air conditioning system. A multidisciplinary cabinet projected the construction of a new cafeteria that has all the amenities for a healthy recreation and relaxation of students, teachers and administrative staff. In this work an integral design was made to guarantee energy efficiency in the cafeteria of the Faculty of Engineering of the Autonomous University of Campeche, Mexico.

The architectural project consists of designing an enclosed space with capacity for approximately 80 people (diners and dependents). For these infrastructure dimensions, the number of people contemplated and that the building was planned with few windows that are exposed to solar radiation. It is considered to have a total heat gain of approximately 16 kW-thermal (4.5 TR, 54,000 BTU/h). So with 2 units of 10.6 kW-thermal (3 TR, 36,000 BTU/h, commercial capacities) we will have a total of 21.2 kW-thermal (6 TR, 72,000 BTU/h) sufficient to remove the total heat from the cooler.

During the engineering project development stage, it is very necessary to visualize different possible scenarios in the installation of a photovoltaic generating plant, such as the optimal inclination, the minimum height of the modules with respect to the surface, among others, and in turn all of them invariably associated to the economic aspect, in such a way that the highest plant efficiency is obtained in the shortest recovery time. To plan all these scenarios is an arduous task that requires the help of a computer program. In this sense, we used the System Advisor Model (SAM) software developed by the National Renewable Energy Laboratory (NREL) of the United States of America, for two important reasons: it is free and contemplates the economic rates that allow us to analyze the optimal performance of the plant, as well as its return on investment. The SAM program allowed the complete temporal, hourly analysis of the Gran Demanda Media Ordinaria en México (GDMO of CFE in Mexico) tariff during the 8760 hours of the year.

The tariff part is the most complex part of the programming, but it allows to do it; other similar programs do not have this analysis capacity. It allowed a finer analysis by relating the energy yield equations to an economic analysis (cash flow, net present value, payback time, cost benefit and internal rate of return). Distributed Generation (DG) from renewable energies has increased worldwide as an efficient tool to lower electric energy costs, since it reduces transmission costs, as well as increases the electric efficiency of the Load Center where it is installed. It represents a direct help to companies and governmental institutions to be more competitive on the one hand and to reduce their operating expenses on the other hand; this favors economic development.

Distributed Photovoltaic Generation (DG-PV) has become one of the main ways to generate electricity with renewable sources (Pinargote, D. F. G., et al 2021). In addition to delivering electric power directly to the grid, it provides other added values such as mitigating greenhouse gases and performing as a thermal barrier on the roofs of the buildings that house them. In other words, they prevent solar radiation gain in buildings, a fact that is especially relevant in hot-humid climates such as that of the state of Campeche, Mexico. By taking advantage of DG-PV in an educational institution in the state of Campeche where the reduction of energy consumption for air conditioning is imperative, and one of the main challenges to overcome is to curb heat gains from solar radiation, it becomes very attractive.

These actions generate net economic benefits to justify the payment of the initial investment. Distributed Generation (DG) is defined as: "the generation of electric energy that is interconnected to a distribution circuit containing a high concentration of Load Centers (CRE 2017)", according to the Electricity Industry Law and the Interconnection Manual of DG Plants with capacity less than 0.5 MW. DG includes that which is performed by an exempt generator, in other words, the owner of one or more power plants with capacity less than 0.5 MW that do not require a permit to generate electric power. DG can be located in the facilities of Load Centers or outside them (SENER, 2016). It is estimated that the world distributed solar PV, will establish itself at more than twice its capacity in the next lustrum.

It accounts for almost half of the total solar PV expansion. DG-PV installations in educational and government institutions, residential homes, commercial buildings and industry will bring major changes to electrical systems. The accelerating expansion in the ability of consumers to generate their own electricity represents a niche opportunity for service providers.

Justification

Electricity consumption for air conditioning in educational institutions in Campeche and in general with hot humid climates represents one of the highest costs during operation. During the last five years, electricity consumption at the Universidad Autónoma de Campeche represents 60% of the total consumed each month.

In Mexico, in recent years, the contracting of DG-PV has increased considerably. Up to 2019, 35,661 new PV-GD contracts were signed, which is equivalent to just over 233 MW new installed in Mexico; this represents an average annual growth rate of approximately 20%.

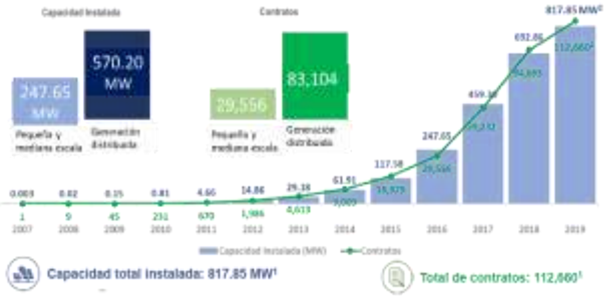

Figure 1 Evolution of contracts and installed capacity in Mexico
Monitor of commercial information and price index of Distributed Solar Generation in Mexico, March 2019

(Monitor of commercial information and price index of Distributed Solar Generation in Mexico, 2020). Figure 1.

Taking as a reference the Monitor of commercial information and price index of Distributed Solar Generation in Mexico, March 2020, from 2017 to the first semester of 2019, we present the regions that installed the largest amounts of DG-PV where it is very clear that the states of the Mexican Republic with the largest accumulated installed capacity are Jalisco, North Gulf, North, Bajio and South Valley of Mexico, Figure 2.

We also observe from Figure 2 that the state of Campeche has a very small accumulated installed capacity, less than 5 MW. However, the state of Campeche has a good solar radiation resource, with irradiation ranging from 4.5 to 6 kWh/m^2 per day. Data provided by NREL.

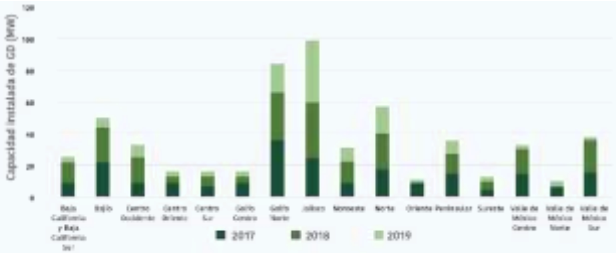

Figure 2 Evolution of DG-PV capacity in Mexico by region of the country
Commercial information monitor and price index for Distributed Solar Generation in Mexico, March 2021

The conditions of good irradiance in the state of Campeche as well as the energy needs and a small accumulated installed capacity, leads us to the conclusion that there is a large niche of opportunities for the installation of Photovoltaic Distributed Generation Systems.

On the other hand, the state of Campeche has a humid-warm climate; therefore, it is very necessary to use large amounts of electrical energy for high, medium and low temperature refrigeration processes. In a study conducted by the Autonomous University of Campeche to the Secretary of Economic Development of the state of Campeche in 2020 (Victor-Lanz et al), indicates that at least 60% of electricity consumption in small and medium industries, homes, schools and universities, is due to cooling processes in any of its forms. Particularly the state's educational institutions spend large amounts of their annual budget for the payment of electricity for air conditioning.

For example the Faculty of Engineering of the Autonomous University of Campeche, during 2019 had an average monthly billing of 150,000 Mexican pesos (approximately 7,500 U.S. dollars). Data taken from CFE receipts). In that sense, a circumstance that is very relevant is to avoid excessive heat gain from solar radiation on roofs and walls. It is known (Victorio Santiago Díaz et al, 2005) that approximately 50 to 60% of the total gain in buildings is due to solar radiation from roofs and walls.

In air conditioning engineering applications, an average solar gain per roof of 550 w/m^2 can be considered as the energy captured in a square meter of surface, in a horizontal position with the sun at the zenith and considering a clean atmosphere with a low degree of turbidity.

We conclude that GD-PV systems have an added value in hot-humid climates, and installed on roofs; they operate as thermal barriers that absorb direct solar radiation, avoiding excessive heat gains from solar radiation in buildings. As a direct consequence of the above, less electrical energy is required for air conditioning processes. In this way, energy efficiency is promoted.

With regard to energy efficiency, according to Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ-2014) in its guide of good practices for energy saving and efficient use of energy, it is defined as: obtaining the same energy goods and services, but with much less energy, with the same or higher quality of life, with less pollution, at a lower price than at present, extending the life of resources and with less conflict.

Objective

To demonstrate that by implementing Distributed Generation with photovoltaic systems (DG-PV) together with aspects of bioclimatic architecture, energy efficiency is achieved in the cafeteria of the Faculty of Engineering of the Autonomous University of Campeche.

Hypothesis

By implementing a GD-PV plant, with its most optimal configuration, in the cafeteria of the Faculty of Engineering of the Autonomous University of Campeche, energy efficiency and reduction of its production costs are achieved; as well as avoiding the emission of CO2 equivalent to the atmosphere.

Problem Statement

It is desired to reduce the energy consumption of the cafeteria located in the Faculty of Engineering of the Autonomous University of Campeche, in the state of Campeche.

The state of Campeche is geographically located in the Yucatan Peninsula between parallels 17°49' and 20°51' north latitude; and between meridians 89°06' and 92°27' west; air conditioning processes demand high energy values to be carried out. The environmental conditions at the site are important adverse factors during this process.

The location of the cafeteria is in the Faculty of Engineering of the Universidad Autónoma de Campeche. It is geographically right at 19°.84'58" north latitude, -90°.47'74" longitude (west), less than 1000 meters from the coast with an average temperature of 31±0.1ºC and a relative humidity of 75±1%, also average (INEGI, 2015), at 50 meters with respect to sea level. The architectural project consists of design an enclosed space with capacity for approximately 80 people (diners and dependents).

For these infrastructure dimensions, the number of people contemplated and that the building was planned with few windows that are exposed to solar radiation. It is considered to have a total heat gain of approximately 16 $kW_{thermal}$ (4.5 TR, 54,000 BTU/h). So with 2 units of 10.6 $kW_{thermal}$ (3 TR, 36,000 BTU/h, commercial capacities) we will have a total of 21.2 $kW_{thermal}$ (6 TR, 72,000 BTU/h) sufficient to remove the total heat from the cooler. The cafeteria has 2 cassette type air conditioning units, which allow a better distribution of the cold air conditioning, which have an elegant presentation, which are very quiet (53/51/48 dB(A) continuous ambient noise level should not exceed 68 decibels, measured at the worker's ear position through the use of a sound level meter). According to, 01-13-95 Mexican Official Standard NOM-081-ECOL-1994, which establishes the maximum permissible noise emission limits for fixed sources and their measurement method.

Two 16 SEER high energy efficiency mini-split condensing units are also installed for this project. Ceiling mounted, with ecological refrigerant R410a. It also has lighting and miscellaneous equipment. Given this situation of energy demand, the possibility of installing a Photovoltaic Distributed Generation plant (GD-PV) was considered.

Description of the Photovoltaic Distributed Generation System (GD-PV)

This is an electric power generating plant produced with photovoltaic modules. It is installed on a flat roof of 89.10 m^2. The first photovoltaic array (AFV) has two strings of seven modules, each of 440 Wp. This results in a total of 14 photovoltaic modules connected in series (Canadian brand), a total installation of 7.56 kWp installed. It has an anti-island voltage inverter for interconnection to the grid of the brand and model Fronius Symo of 8 kWp figure 3. Each photovoltaic module has an area of 2 m^2. Figure 4 shows the one-line diagram of the system.

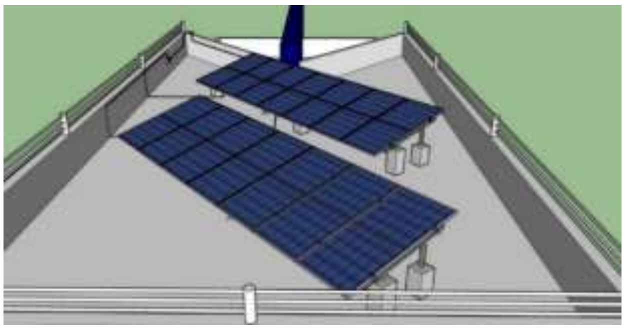

Figure 3 The photovoltaic array (AFV) has a total of 14 photovoltaic modules connected in series (Canadian brand) and an anti-islanding voltage inverter for interconnection to the grid of the Fronius Symo 5kWp brand and model
Own Elaboration.

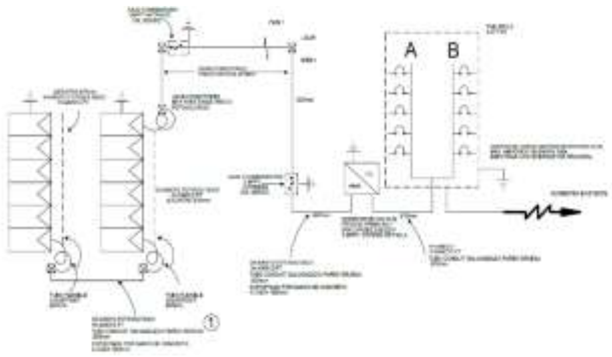

Figure 4 One-line diagram of the Distributed Photovoltaic Generation plant. It consists of 14 modules with a total installed capacity of 5.18 kWp
Own Elaboration

The next proposed photovoltaic array was to place 24 modules of 440 each, with an azimuthal angle of 218º, aligning them parallel to the side walls of the building and an inclination angle of 15º, a total installation of 10.56 kWp. It has an anti-islanding voltage inverter for interconnection to the grid of the brand and model Fronius Symo of 10 kWp.

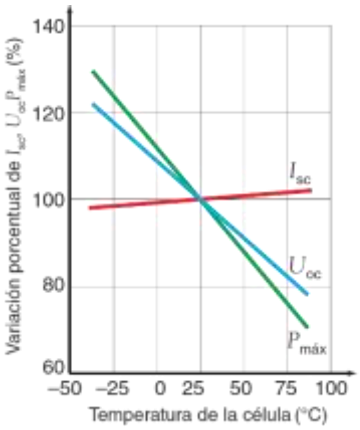

Figure 5 Percentage variation of open circuit voltage, short circuit current and maximum power of a photovoltaic module with respect to temperature
Castejón 2012

The PV installation was designed with an inclination of 15 degrees with respect to the horizontal plane to optimize the PV performance with respect to mechanical stresses (Rayenari-D.C. et al., 2015); hence each module shades an area of 1.93 m2. The total PV installation produces a shaded roof area of about 27 m2. The photovoltaic plant is fully oriented to the south, its azimuthal declination is correct. The photovoltaic modules are placed at a height of 0.60 m with respect to the roof, in order to favor air circulation under them, thus ensuring that they do not overheat and considerably increase their production efficiency (Agustín Castejón-2012, Cruz Arellano, M. & Castillo Téllez, M. 2021). Figure 5, recalling that as the modules heat up, taking as a reference the value of 25 ºC, their open circuit voltage (Voc) decreases linearly and with a steep slope. Power in turn is intimately influenced by Voc. In such a way that if the temperature is increased to values higher than 75 ºC, more than 20% of the nominal power is lost.

Similarly Rayenari D. C. et al, (2015) recommend for higher photovoltaic efficiency in the months of March to August, the tilt should be readjusted to 10 or 5 degrees. Up to 5% efficiency gain is possible. In addition, stagnation zones are avoided due to no wind circulation Potter et al (2011).

Mathematical modeling of heat gain through the freezer roof

According to Victor Lanz G. et al (2018), in hot humid climates heat gain in building roofs represents 40% and another 10% by walls facing the direct solar radiation received by a building throughout the day.

Therefore, it is very important to quantify the heat gain from roofs. The following equations are presented to quantify roof heat gains as a combined effect of conduction, convection and radiation (Çéngel et al-2012).

$$\dot{Q} = \dot{Q}_{habi-techo,conv+rad} = \dot{Q}_{cond,techo} = \dot{Q}_{techo-amb,cond+rad} \tag{1}$$

$$\dot{Q}_{habi-techo,conv+rad} = h_i A\left(T_{habi} - T_{s,int}\right) + \varepsilon A\sigma\left(T^4_{habit} - T^4_{s,int}\right) \tag{2}$$

$$\dot{Q}_{cond,techo} = kA\frac{T_{s,int} - T_{s,ext}}{L} \tag{3}$$

$$\dot{Q}_{techo-alrededor,cond+rad} = h_o A\left(T_{s,ext} - T_{amb}\right) + \varepsilon A\sigma\left(T^4_{s,ext} - T^4_{amb}\right) - \alpha\dot{q}_{solar} \tag{4}$$

Where $\dot{Q}$ is the total heat flux, k thermal conductivity, α absorptivity, $h = kW/m^2\ ^oC$ convective heat transfer coefficient, σ the Steffan-Boltzman constant, A heat transfer area, $\dot{q}_{solar}$solar radiation and T temperature. It is estimated that, each square meter of roof receives a radiation of 550 w/m^2 x day, and there are 27 and 46.32 m2 of area shaded by the PV plant for the cases of 14 and 24 modules respectively. It can then be estimated that a daily roof heat gain of approximately 14.85 kW is avoided for the 14-module case and 25.48 kW for the 24-module case. As a reference, mini split air conditioners of one ton of refrigeration have a thermal capacity to remove heat of 3.54 kWh. The shaded area represents approximately 30% of the total roof for the case of 14 modules and 51% when we have 24 modules.

Bioclimatic aspects of energy efficiency in the cafeteria

Another aspect considered to increase the energy efficiency of the cafeteria was to place green roofs and walls in the areas with the highest incidence of solar radiation. The proposal for green roofs and walls was made with vegetation native to the Yucatan Peninsula that can withstand the climatic conditions of the region.

Figure 6 Overall view of the cafeteria with the proposed SFV, roofs and green walls
Own Elaboration

Figure 7 View of the rear wall of the cafeteria with the SFV proposals and green wall
Own Elaboration

Proposed methodology for the analysis of photovoltaic electric energy production.

In this work we used the free software called System Advisor Model (SAM) created by the National Renewable Energy Laboratory (NREL) of the United States of America. With this program we evaluated the energy capacity of several photovoltaic configurations to compare them and decide which one is the most optimal for installation.

During the engineering project development stage, it is very necessary to visualize different possible scenarios in the installation of a photovoltaic generating plant, such as the optimal inclination, the minimum height of the modules with respect to the surface, among others, and in turn all of them invariably associated to the economic aspect, in such a way that the highest plant efficiency is obtained in the shortest recovery time. To plan all these scenarios is an arduous task; this task is easier with the help of a computer program. In this sense, we use the SAM software for two important reasons: it is free and it contemplates economic rates.

This allows us to analyze the optimal performance of the plant, as well as its return on investment. The SAM program allowed the complete temporal analysis of the Great Ordinary Mean Demand in Mexico (GDMO of CFE in Mexico) during the 8760 hours of the year. The tariff part is the most complex part of the programming, but it allows to do it; other similar programs do not have this analysis capacity. It allowed a more accurate analysis by relating the energy yield equations to an economic analysis (cash flow, net present value, payback time, cost benefit and internal rate of return). Four different schemes were analyzed, firstly, it was a photovoltaic array of 14 modules of 440 each, with an optimal azimuthal angle (Castejón & Santamaría, 2010) of 180º (i.e. aligned to the true north-south axis) and a tilt angle of 15º (Rayenari-D.C. et al., 2015), the other was similar to the previous one but the tilt angle was 19.85º equivalent to the latitude of Campeche.

The next was to place the PV array of 24 modules of 440 each, with an azimuthal angle of 218º, aligning them parallel to the side walls of the building and a tilt angle of 15º and finally the PV array of 24 modules of 440 each, azimuthal angle of 218º and tilt angle of 19.85º. The program was fed with the billing data issued by the Federal Electricity Commission (CFE), in GDMO tariff, for the period from January 2020 to March 2021. It corresponds to the consumption of the Faculty of Engineering during that period, Table 1. Costs are expressed in U.S. dollars.

Billing month	Total consumption (kwh)
January 2020	21,238
February 2020	22,803
March 2020	30,881
April 2020	28,791
May 2020	9,469
June 2020	10,752
July 2020	10,124
August 2020	10,686
September 2020	10,938
October 2020	14,400
November 2020	15,788
December 2020	15,996
January 2021	14,418
February 2021	15.441
March 2021	13.953

Table 1 Details of the energy consumption used in the SAM Program to make the economic estimates. Taken from CFE receipts
Own Elaboration

Two subarrays:	1	2
Strings	1	1
Modules per string	7	7
String Voc (DC V)	340.90	340.90
Tilt (deg from horizontal)	15.00	15.00
Azimuth (deg E of N)	180	180
Tracking	no	no
Backtracking	-	-
Self shading	no	no
Rotation limit (deg)	-	-
Shading	no	no
Snow	no	no
Soiling	yes	yes
DC losses (%)	4.44	4.44

Table 2 Details of the photovoltaic installation with 14 modules of 440 each, azimuth angle of 180º and tilt angle of 15º. SAM program.

The first two options considered were because they were placed at the optimum azimuthal angle. However, arranged in this way and for space reasons, only 14 modules fit. The last two options allow a greater number of modules to be placed, although a small percentage of efficiency is lost (5%).

Analysis of the information and results obtained

After the four scenarios were proposed and the program was fed with the necessary data, we proceeded to run the program with each of them. The results obtained are presented in the following tables.

Metrics	Values
Annual energy (year 1)	10.451 kWh
Capacity factor (year 1)	19.40%
Energy yield (year 1)	1.696 kWh/kW
Performance ratio (year 1)	0.77
COE level (nominal)	5.40 ¢/kWh
Electricity payment without the system (year 1)	$314,513
Electricity payment with the system (year 1)	$303,184
Net savings with system (year 1)	$11,329
Net present value	$202,761
Simple return period	0.6 años
Net capital cost	$8,256

Table 3 Simulation results, PV installation with 14 modules of 440 each, azimuth angle of 180º and tilt angle of 15º. *SAM program.*

Metrics	Values
Annual energy (year 1)	10.465 kWh
Capacity factor (year 1)	19.40%
Energy yield (year 1)	1.699kWh/kW
Performance ratio (year 1)	0.77
COE level (nominal)	5,39 ¢/kWh
Electricity payment without the system (year 1)	$314,513
Electricity payment with the system (year 1)	$303,156
Net savings with system (year 1)	$11,357
Net present value	$203,283
Simple return period	0.6 años
Net capital cost	$8.256

Table 4 Simulation results, PV system with 14 modules of 440 each, azimuth angle of 180° and tilt angle of 19.85°. *SAM program.*

Metrics	Values
Annual energy (year 1)	17.649 kWh
Capacity factor (year 1)	19.10%
Energy yield (year 1)	1.671kWh/kW
Performance ratio (year 1)	0,78
COE level (nominal)	5.48 ¢/kWh
Electricity payment without the system (year 1)	$314.513
Electricity payment with the system (year 1)	$295.398
Net savings with system (year 1)	$19.115
Net present value	$342.210
Simple return period	0.6 años
Net capital cost	$14.153

Table 5. Simulation results, PV system with 24 modules of 440 each, azimuth angle of 218° and tilt angle of 15°. *SAM program.*

Metrics	Values
Annual energy (year 1)	17.570 kWh
Capacity factor (year 1)	19.00%
Energy yield (year 1)	1.664 kWh/kW
Performance ratio (year 1)	0.78
COE level (nominal)	5,50 ¢/kWh
Electricity payment without the system (year 1)	$314,513
Electricity payment with the system (year 1)	$295,467
Net savings with system (year 1)	$19,046
Net present value	$340,946
Simple return period	0.6 años
Net capital cost	$14,153

Table 6. Simulation results, PV installation with 24 modules of 440 each, azimuth angle of 218° and inclination angle of 19.85°. *SAM program.*

Some of the results obtained in this section are specified.

Capacity factor (CF) is defined by NREL as:

$$CF = \frac{Annual\ energy\ production \left[\frac{kWh}{year}\right]}{Installed\ capacity\ x\ 24 \left[\frac{hours}{day}\right]\ x\ 365 \left[\frac{day}{year}\right]}$$

Energy yield is given by (Theristis et al., 2018) as the energy produced between each installed peak kilowatt.

The performance or performance ratio (performance ratio) is a magnitude, independent of the location, of the quality of a PV installation. It is a quality factor. It is expressed as a percentage and shows the ratio between the actual yield and the nominal yield of the PV system. It indicates what proportion of the energy is actually available after deduction of energy losses (thermal and cable losses) and own consumption for operation. The coefficient of performance provides information on the energy efficiency and reliability of the PV system.
The levelized cost (LCOE) is given by (Lai et al., 2019), equation 6.

$$LCOE = \frac{sum\ of\ whole\ life\ costs}{sum\ of\ the\ electrical\ energy\ produced\ in\ its\ entire\ useful\ life}$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{6}$$

Where:
I_t: Investment expenses in year t.
M_t: Operating and maintenance expenses in year t.
F_t: fuel expenses in year t.
Et: electric power generated in year t.
r: discount ratio.
n: expected life time.

From the comparative tables, from 7 to 13, we observe that, of the proposed configurations, the one that produces the most annual energy is the one with 24 modules with an azimuth angle of 218° and an inclination angle of 15°. That is, the installation is not at the angles considered optimal for this latitude. It is evident that, for this configuration, the fact of having 10 more modules with respect to the installation of 14 panels results in a higher energy production, but the paradigm of installing according to the established canons was broken, even with the understanding that we would have a 5% of total losses. Table 7.

14 modules, azimuth angle 180, inclination 15°.	14 modules, azimuth angle 180, inclination 19.8°.	24 modules, azimuth angle 218, inclination 15°.	24 modules, azimuth angle 218, inclination 19.8°.
10,451 kWh	10,465 kWh	17,649 kWh	17,570 kWh

Table 7 Simulation results, PV installation. Energy generation. *SAM program.*

In Table 8, we observe that the configurations of 14 modules with an azimuthal angle of 180° and inclination angles of 15 and 19.8°, are the ones with the highest capacity factor. This result is congruent if we consider the definition previously presented. In other words, we have higher energy production with less installed kW.

14 modules, azimuth angle 180, inclination 15°.	14 modules, azimuth angle 180, inclination 19.8°.	24 modules, azimuth angle 218, inclination 15°.	24 modules, azimuth angle 218, inclination 19.8°.
19,40%	19,40%	19,10%	19,00%

Table 8 Simulation results, PV installation. Capacity factor. *SAM program.*

From Table 9, we observe that the installation of 24 modules, azimuth angle of 218° and tilt angle of 15°, is the one with the highest energy yield.

14 modules, azimuth angle 180, inclination 15°.	14 modules, azimuth angle 180, inclination 19.8°.	24 modules, azimuth angle 218, inclination 15°.	24 modules, azimuth angle 218, inclination 19.8°.
1,696 kWh/kW	1,699 kWh/kW	1,671 kWh/kW	1,664 kWh/kW

Table 9 Simulation results, PV system. Energy yield. *SAM program.*

In Table 10, we observe that the installation of 24 modules, azimuth angle of 218° and tilt angle of 15°, is the one with the highest performance ratio factor. This indicates that this configuration has the lowest number of thermal and wiring losses and therefore the highest energy efficiency.

14 modules, azimuth angle 180, inclination 15°.	14 modules, azimuth angle 180, inclination 19.8°.	24 modules, azimuth angle 218, inclination 15°.	24 modules, azimuth angle 218, inclination 19.8°.
0,77	0,77	0,78	0,78

Table 10 Simulation results, PV installation. Performance ratio. *SAM program.*

On the other hand, in Table 11, we find that the installation of 14 modules with an azimuthal angle of 180° and an inclination angle of 19.8°, is the one with the best levelized cost value. That is, it is the configuration that will offer the highest energy production at the lowest cost throughout its useful life.

14 modules, azimuth angle 180, inclination 15°.	14 modules, azimuth angle 180, inclination 19.8°.	24 modules, azimuth angle 218, inclination 15°.	24 modules, azimuth angle 218, inclination 19.8°.
5.40 ¢/kWh	5.39 ¢/kWh	5.48 ¢/kWh	5.50 ¢/kWh

Table 11. Simulation results, PV installation. Levelized cost. *SAM program.*

Tables 12 and 13 provide information on net money savings and payback periods and what can be seen is that the configuration of 24 modules, azimuth angle of 218° and tilt angle of 15°, delivers the highest amount of money saved in one year of operation. And all configurations have the same payback time.

14 modules, azimuth angle 180, inclination 15°.	14 modules, azimuth angle 180, inclination 19.8°.	24 modules, azimuth angle 218, inclination 15°.	24 modules, azimuth angle 218, inclination 19.8°.
$11,329	$11,357	$19,115	$19,046

Table 12 Simulation results, PV installation. Net savings. *SAM program.*

14 modules, azimuth angle 180, inclination 15°.	14 modules, azimuth angle 180, inclination 19.8°.	24 modules, azimuth angle 218, inclination 15°.	24 modules, azimuth angle 218, inclination 19.8°.
0.6 años	0.6 años	0.6 años	0.6 años

Table 13 Simulation results, PV installation. Return period. *SAM program.*

Energy produced by the DG-PV

The energy produced by the DG-PV, E_prod in the 5.5 hours of solar radiation of a solar day (NREL, 2010), is given by equation 7.

$$E_{prod} = W_{peak} \cdot hr_{rad} \cdot No_{módpv} \tag{7}$$

where W_{peak} is the peak power of a PV module in Watts, hr_{rad} is the hours of solar radiation in a day, and $No_{módPV}$ represents the number of PV modules included in the DG-PV plant. From the above, the energy produced by the DG-PV, in both configurations, is given by:

$$E_{prod} = 0.440\ kW\ (5.5\ hr)\ (14\ mód) = 33.88\ kWh/day$$

$$E_{prod} = 0.440\ kW\ (5.5\ hr)\ (24\ mód) = 58.08\ kWh/day$$

Estimated CO2 avoided to be sent to the environment due to DG-PV

Within an energy efficiency study, the amount of carbon dioxide (CO_2) emissions released into the environment due to electricity generation must be included. In Mexico, the Energy Regulatory Commission (CRE) and the Ministry of Environment and Natural Resources (SEMARNAT) annually estimate the National Electric System Emission Factor based on Article 12 of the Energy Transition Law Regulation (Chamber of Deputies, 2017). The last factor published in the Official Journal of the Federation was in 2017 being this of:

0.582 kg de CO_2 / kWh

In addition, an emission factor caused by the production of energy with photovoltaic modules has been considered; an analysis model called Global Emissions Model for Integrated Systems (GEMIS, 2018) was used in the calculations, which applies a factor of:

0.135 kg de CO_2 / kWh

And Reich, et al. (2007), invites to choose a value from a range of emissions between:

0.030-0.317 kg de CO_2 / kWh

Empirically we choose the GEMIS factor for our calculations, because it is within Reich's range. During a billing month, the total energy consumed by the Faculty of Engineering and purchased from DG-PV is:

$$E_{cons} = 58.08\frac{kWh}{day}(30\ days) = 1742.4\ kWh$$

Then, the CO_2 emissions avoided to be sent to the ϵ_{cons}ϵ_cons by the energy consumed through DG-PV is:

$$\epsilon_{cons} = 0.582\frac{kg\ CO_2}{kWh}(1742.4\ kWh) = 1014.07\ kg\ CO_2$$

The CO_2 emissions producedϵ_{prod} caused by energy production with DG-PV are:

$$\epsilon_{prod} = 0.135\ \frac{kg\ CO_2}{kWh}(1742.4\ kWh) = 235.22\ kg\ CO_2$$

Finally, the net CO_2 emissions ϵ_net avoided to be sent to the atmosphere is the difference between ϵ_{cons} y ϵ_{prod}:

$$\epsilon_{net} = \epsilon_{cons} - \epsilon_{prod} = 1014.07\ kg\ CO_2 - 235.22\ kg\ CO_2 = 778.85\ kg\ CO_2$$

This is a significant figure, as it shows that 778.85 kg of CO_2 are no longer being emitted into the environment, which is a significant contribution to the reduction of the carbon footprint.

Conclusions

This article presents an energy efficiency study of the Cafeteria of the Faculty of Engineering of the Autonomous University of Campeche with the proposal of a Photovoltaic Distributed Generation plant (GDF-PV) analyzing several proposed configurations with the help of the open program called System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL).

Four different schemes were analyzed: one PV array of 14 modules of 440 each, with an azimuthal angle of 180° and a tilt angle of 15°, the other was similar to the previous one but the tilt angle was 19.85° equivalent to the latitude of Campeche. The next two were arrays of 24 modules of 440 each, with azimuthal angles of 218° and inclination angles of 15° and 19.85°.

- It is estimated that a daily roof heat gain of 14.85 kW is avoided in the case of 14 modules and 25.48 kW in the case of 24 modules. The shaded area represents approximately 30% of the total roof for 14 modules and 51% for 24 modules.

- The best annual energy generation of the DG-PV plants is obtained with a value of 17,649 kWh in the configuration of 24 modules of 440 W, with azimuth angle of 218° and tilt angle of 15°. According to the simulations with the SAM program.

- The 24-module photovoltaic system, with an azimuth angle of 218° and an inclination angle of 15°, has the highest energy yield with a value of 1,671 kWh/kW, understood as the energy produced for each kilowatt peak installed.

- The 24-module photovoltaic plant, with azimuth angle of 218º and tilt angle of 15º, is the one with the highest performance ratio factor, indicating that it has the lowest number of thermal and wiring losses and is therefore the one with the highest energy efficiency.

- All four DG-PV plant configurations have the same payback time of 0.6 years.

- The best PV plant configuration was the 24-module configuration, with azimuth angle of 218º and tilt angle of 15º, which has the highest number of favorable factors and is therefore the most energy efficient.

- The GD-PV plant avoids the emission of 778.85 kg of CO2 equivalent into the atmosphere.

- To increase the energy efficiency of the cafeteria, green roofs and walls were installed in the areas with the highest incidence of solar radiation. The roofs and green walls were built with vegetation native to the Yucatan Peninsula to withstand the climatic conditions of the region.

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