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Evaluation of a grid-connected photovoltaic system and in-situ characterization of photovoltaic modules under the environmental conditions of Mexico City

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In this work we present the results of the monitoring and statistics of a grid connected photovoltaic (PV) system located on the roof of the building occupied by the "Instituto de Ciencia y Tecnología del Distrito Federal" (ICyTDF), at the historical center of Mexico-City (DF). The on-grid connected photovoltaic system has 6150 Watts peak (Wp). This system ensures a daily mean reduction of 30 kW.h in the consumption of electric energy at the ICyTDF facilities; which results in a significant saving of fossil fuels and avoiding the emission of greenhouse gases. This system can generate an annual average of 10.8 MW.h of electrical energy, equivalent to burning 0.87 tonnes of oil which would lead to the emission of approximately 2.1 tonne/year of CO_2 into the atmosphere. The ecological impact of the photovoltaic system installed in the ICyTDF is equivalent to a forest area with more than 700 adult trees (7 hectares of forest). We also report the analysis of the PV-performance in real time of several commercial solar modules, manufactured with different materials and technologies, these results may give an indication of the comparative performance of the technologies under the environmental conditions of México City. Four different solar modules made of monocrystalline silicon, polycrystalline silicon, amorphous silicon and CdS/CdTe technologies were tested. The outcome of this study is that a better performance was noted for modules made of amorphous silicon technology under temperature variations typical of Mexico City's environmental conditions.

Keywords: Photovoltaic system; photovoltaic solar modules; grid-connected photovoltaic system; solar modules technology.

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1. Introduction

Photovoltaic (PV) systems connected to the electrical network constitute the application in the photovoltaic solar energy area that has experimented greater expansion in the last years [1]. According to estimations of the European Commission for 2011, most of the photovoltaic energy generated in Europe will come from network connected facilities [2]. Germany heads the list of European countries that generate more electrical energy via PV (28 GW of installed capacity in April 2012). Mexico surpasses Germany in average solar insolation. The solar potential of Mexico is the third greatest one of the world according to reports of the Mexican Department of Energy (SENER) and the German Technical Cooperation Agency (GTZ) in 2006 [3]. The average solar potential of the country is 5 kW·h/m^2 per day, which is representative of Mexico City's conditions.

On the other hand, the behavior of a particular solar module will depend not only of the material and technology used, but also of the environmental work conditions like temperature, specific solar insolation, wind speed, suspended particles, etc. These conditions have a direct influence in the in-situ behavior of the electrical parameters of modules manufactured with different technologies. Some of the environmental parameters of Mexico City are: temperature variations from 14 to 18°C during a single day and average relative humidity between 30 and 60% along the year [4]. The average concentration of the main gas pollutants in Mexico City's atmosphere are: ozone (O_3)-0.175 ppm, carbon monoxide (CO)-4.5 ppm, nitrogen dioxide (NO_2)-0.15 ppm, sulphur dioxide (SO_2)-0.06ppm and suspended particles PM_{10} (125 mg/m^3) [5,6]. The quantitative influence of the gas pollutants in the electrical parameters of the modules is difficult to evaluate, however these facts have to be taken into account along with the temperature and solar insolation in the analy-

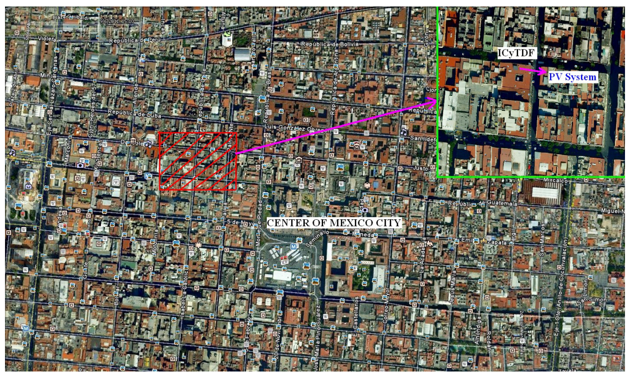

FIGURE 1. ICyTDF geographic location with respect to the center of Mexico City.

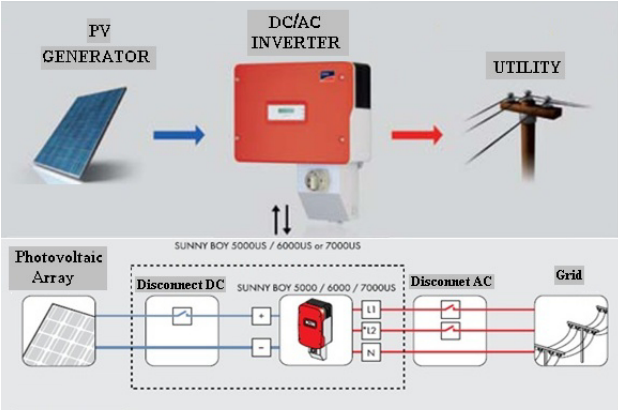

FIGURE 2. Schematic details of the on-grid PV system characteristics installed in the ICyTDF.

sis of the dependence of the electrical parameters with the environmental conditions. For these reasons we have studied the behavior of the electrical parameters of solar modules fabricated with different technologies under the specific environment of Mexico City.

In this work, an analysis of the statistical data from a grid-connected photovoltaic (PV) system is presented to evaluate its environmental benefits in terms of energy saving and avoiding greenhouse gas emissions in Mexico City. Moreover, a comparative analysis of different PV technologies (bulk monocrystalline and polycrystalline silicon cells, amorphous silicon and CdTe thin film solar cells) was performed to determine which technology has the best performance under the specific environmental conditions of Mexico City. With the perspective of a future growth in the installation of on-grid photovoltaic systems in the urban zone of Mexico City, this analysis would be useful a reference frame for sizing and decision-making on which would be the appropriate technologies used in such systems.

2. Analysis of results in the installed PV system

This project was developed through the collaboration between the Instituto Politécnico Nacional (IPN), Universidad Nacional Autónoma de México (UNAM) and the Instituto de Ciencia y Tecnología del Distrito Federal (ICyTDF). The project consisted on the sizing and installation of a photovoltaic (PV) system on the roof of the building occupied by the ICyTDF, situated in the historical center of Mexico City. The installed system is connected to the grid of the Federal Commission of Electricity (CFE) with 6300 Wp. Figure 1 shows the ICyTDF geographic location with respect to the center of Mexico City located at 19°27' latitude and 2,250 m altitude and also a zoom that displays the PV system installation on its roof. Schematic details on the characteristics of the system are shown in Fig. 2 where the energy flow from the sun to the consumption network can be appreciated. The PV system of the ICyTDF, was installed following all the established norms for this type of constructions with historical value, taking into account the geographic situation and the urban surroundings of the historical center of Mexico City.

The statistical data of the PV system performance are provided by the SB-SMA monitoring system installed alongside. This system are formed by a communication system Sunny WebBox, an Inverter Sunny Boy 6000US with efficiencies of 98 % in a range of temperature from – 40°C to + 60°C and a Sunny Sensor box. This monitoring system sends daily data from in-situ measurements. Figure 3 shows the graph of the daily average energy produced by the PV system each month during the year 2010. It is possible to appreciate that the months with greater energy production are March and October with daily average energies of 33 and 30 kW·h, respectively. On the other hand, this average diminishes to 20-25 kW·h during rainy months with a smaller solar incidence (June to September). From this data, we can calculate the average solar insolation hours under real performance conditions. Another important analysis is related to the accumulated energy production for each month, which is of interest to determine the real amount of grid injection. In Fig. 4 the total monthly energy produced by the system throughout its first year of operation is shown. This energy was calculated as the sum of the total daily energy produced by the system. As before, the periods of greater power production correspond to the months of March and October with averages over 1100 kW·h, while in the rainy period this average falls to 800 kW·h. This represents a monthly average energy production of 950 kW·h injected directly to the grid by the PV system during 2010.

Thirty solar modules Kyocera KD210GX-LP with polycrystalline silicon technology were installed in the PV system with a nominal 6300 Wp. The typical environmental pollution throughout the year in Mexico City causes the deposition of a fine dust layer onto the system practically in a permanent way. An estimated loss of around 10% due to dust is typically taken into account for the calculations of the global yield of

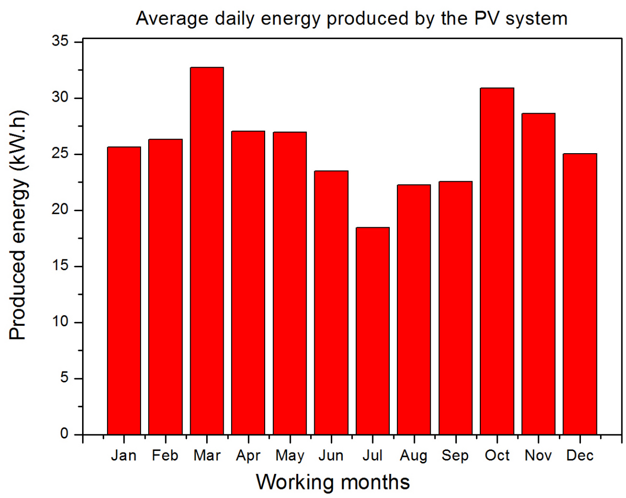

FIGURE 3. Average daily energy produced by the PV system during the year 2010.

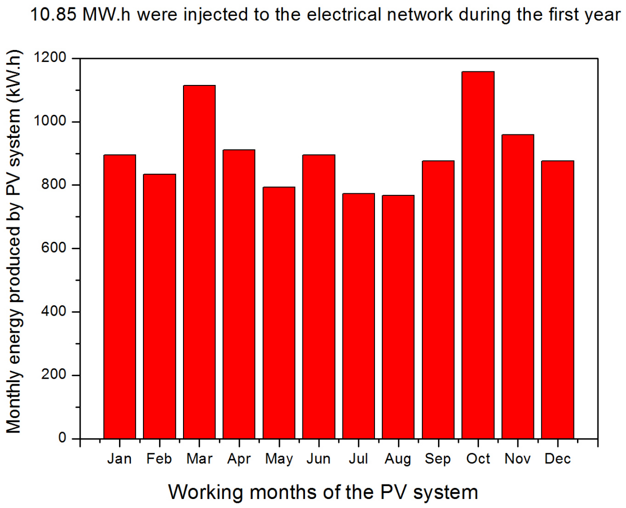

FIGURE 4. Total monthly energy produced by the PV system throughout its first year of operation.

PV systems under ambient conditions. Also, ohmic and/or Joule heat losses between 2 and 3% must be considered due to the long distance and the type of electrical cable installation used to connect the photovoltaic system to the cabinet with the monitoring system [7]. These aspects are taken from the literature and were not calculated in this work. Considering these losses, the maximum output power of the PV system is less than the nominal.

Based on international standards that consider an average solar radiation density incident on Earth's surface equivalent to 1 kW/m^2 (solar irradiance), we can calculate with certain exactitude the average of daily hours in which this standard is met in the center of Mexico City. In this case, we work with the concept of solar insolation (kW·h/m^2·day) instead of solar irradiation (kW/m^2). Solar insolation is a measure of the power that hits a given surface. It is typically reported in W/m^2. For solar PV it is often reported as the amount of energy (kWh) that can be generated per peak power rating (kW) of the solar cell in question. Solar insolation is obtained by integrating the curve of the solar radiation in a day. Figure 5 shows the monthly average of hours with a radiation density equivalent to 1 kW/m^2 in a day, from which we calculate a global average during all year of 4.8 hours per day with this radiation density on the center of Mexico City. Again, from this figure we can see that average insolation is increased to over 5.5 hours / day in the months of March and October. This estimate is important because it provides data representative of Mexico City's specific conditions and it can be used to make projections and sizing of PV systems to be installed in Mexico City and the metropolitan area.

On the basis of the collected statistical data, during its first year of work, the direct injection to the grid of the ICyTDF PV system was about 10.85 MW·h, which represents the saving of 0.87 tonnes of petroleum or 1.24 equivalent tonnes of coal. The equivalent tonne of petroleum (TEO) is a power unit which represents the energy that in an exothermic process can be obtained from burning one tonne of petroleum. As this can vary according to the composition of the oil mixture, a conventional value has been taken as: 41.84×10^9 J = 12.4 MW·h [8]. The combustion of one TEO for electricity production implies the emission of 5.43 tonnes of CO_2 to the atmosphere, as well as other polluting gases and particles. On the other hand, since trees are photosynthetic organisms they absorb CO_2 and water from the surrounding environment and they transform them into organic matter, releasing oxygen (O_2), according to the Sachs equation [9]: $6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$, where $C_6H_{12}O_6$ is glucose. Thus, according to UNEP (United Nations Environment Programme), a tree can absorb around 3 kg of CO_2 per year, depending on the size [10].

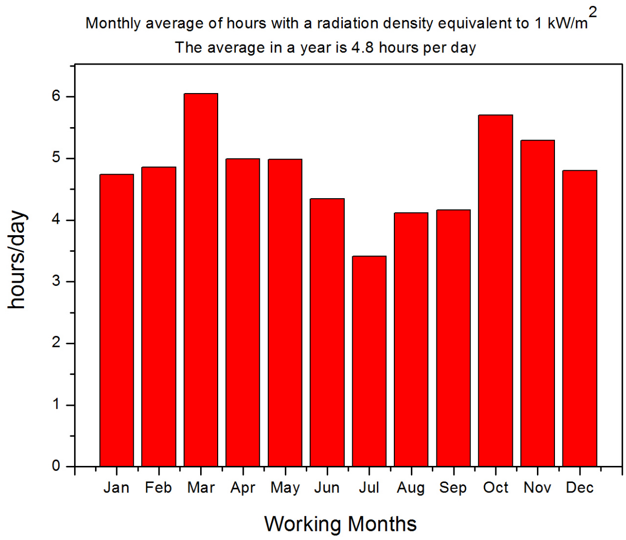

FIGURE 5. The monthly average of hours with a radiation density equivalent to 1 kW/m^2 in a day, from which we calculate a global average during all year of 4.8 hours per day with this radiation density on the center of Mexico City.

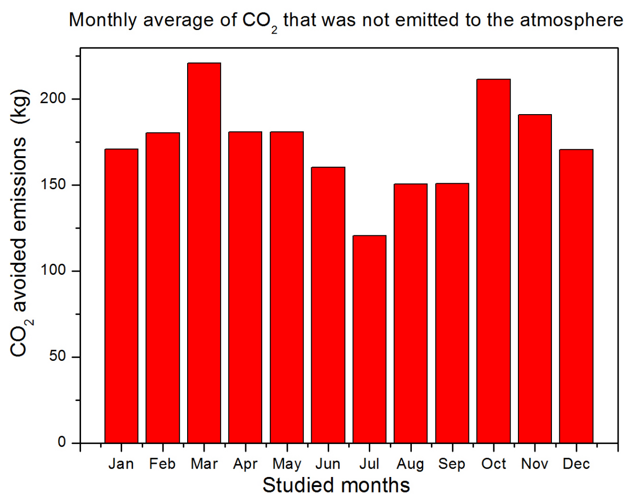

FIGURE 6. Statistics of the monthly average of CO_2 that was not emitted to the atmosphere due to the installation and use of the ICyTDF PV system.

From the accumulated statistical data it was possible to calculate the daily, monthly and annual production of the photovoltaic system working under real conditions of Mexico City and make an estimate of the TEO equivalency of this energy production, along with the amount of CO_2 emissions that are avoided. Figure 6 shows the statistics of the monthly average of CO_2 that was not emitted to the atmosphere due to the installation and use of the ICyTDF PV system. This data is obtained directly from the monitoring system, using an internal set of conversion equivalencies. The monitoring system calculation of CO_2 equivalencies are related to the percentage of avoided emissions reported by the electricity company (CFE). The electricity sector is responsible for almost a third of the CO_2 emissions of the country [11]. The sector emits 55% of sulphur dioxide (SO_2) and nitrogen oxides (NO_x), and between 27% and 30% of the carbon dioxide (CO_2). As it can be seen, from the yearly statistics we can determine by integration that the annual average amount of CO_2 that was stopped from being released to the atmosphere due to the use of the photovoltaic system was 2.1 tonnes. This last result is different from the theoretical values calculated of 4.7 tonnes, considering the equivalencies reported in Ref. 5. The difference can be caused by the conversion data discrepancies between the standards used by the monitoring equipment and other international standards. In any case, the avoided emissions of CO_2 due to the installation of the photovoltaic system in the ICyTDF are equivalent to a forest area with more than 700 adult trees (7 forest hectares).

Considering the results presented in this work, we can project that the installation of 100 photovoltaic systems per year with a capacity of 10 kW of installed power in roofs of governmental and non-governmental buildings, would represent an approximated production of 1752 MWh per year. Having 100 installed systems would be equivalent to saving 137 tonnes of petroleum per year, avoiding more than 744 tonnes of CO_2 emissions (248000 adult trees). If the program were permanent, it would mean that in the next 10 years thousand tonnes of CO_2 would not be emitted to the atmosphere, due to the saving of thousand tonnes of petroleum used nowadays to produce electricity.

3. Characterization of different photovoltaic modules under the environmental conditions of Mexico City

An automated system was developed for the characterization of commercial PV panels, which allows obtaining I-V characteristics of up to 4 photovoltaic solar modules simultaneously [12]. The system is governed by a program developed in the graphical language LabVIEW©, which activates the measurements and turns off the system automatically. In addition, it takes module temperature (not air temperature) and solar radiation measurements every minute by means of a LM35 sensor and a calibrated solar cell, respectively. The program shows I-V curves, the module temperature and solar radiation in real time and saves the data in text files. This system was designed in the Escuela Superior de Física y Matemáticas of IPN (ESFM-IPN). Figure 7 shows the front panel of the control program, where the information of the measured data can be appreciated. The data are refreshed until a new measurement is initiated for the modules. The same figure displays the module temperature and solar radiation graphs, which are updated every minute. The right part shows radiation incident on the module surface and in situ module temperature indicators. All data are stored in a file corresponding to the day of measurement.

To study the behavior of the modules' electrical parameters with incident sunlight, we work with the concept of solar insolation defined above. Solar radiation measurements were made with the sensor placed on the surface of one of the solar modules. All modules were placed South-facing with an angle of 20 degrees, defined by the latitude of Mexico City. Figure 8 shows typical I-V characteristics of the four modules measured from 9:00 to 17:00 hours each day. The bulk silicon technology modules are characterized for high values of short circuit current, while the thin films technology modules are characterized for high values of open circuit voltages as can to be seen in the graphs shown in Fig. 8. The temperature variation on the surface of modules was studied for all the months and the average temperature from 10:00 to 16:00 hours was 30°C, while the average solar radiation was of order 5 kW·h/m^2 per day.

One of the critical parameters to consider in the operation of a commercial photovoltaic module is the dependency of its electrical parameters with the environmental temperature. The values of the short circuit current, open circuit voltage, fill factor, maximum power and efficiency were measured as a function of the module temperature. These data were taken at a fixed value of incident solar radiation (82.1 mW/cm^2), which was the most common value of measured radiation in our experimental set. The temperature coefficient expresses the variation in the solar cell parameters measured at temperatures above 25°C with respect to these same parameters measured at 25°C. Generally, manufacturers include the module parameters measured at 25°C under standard illumination as part of their data sheets. However,

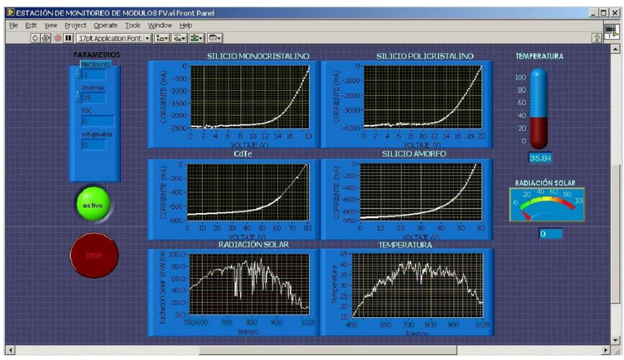

FIGURE 7. Front panel view of the control program developed for in-situ measurement of modules.

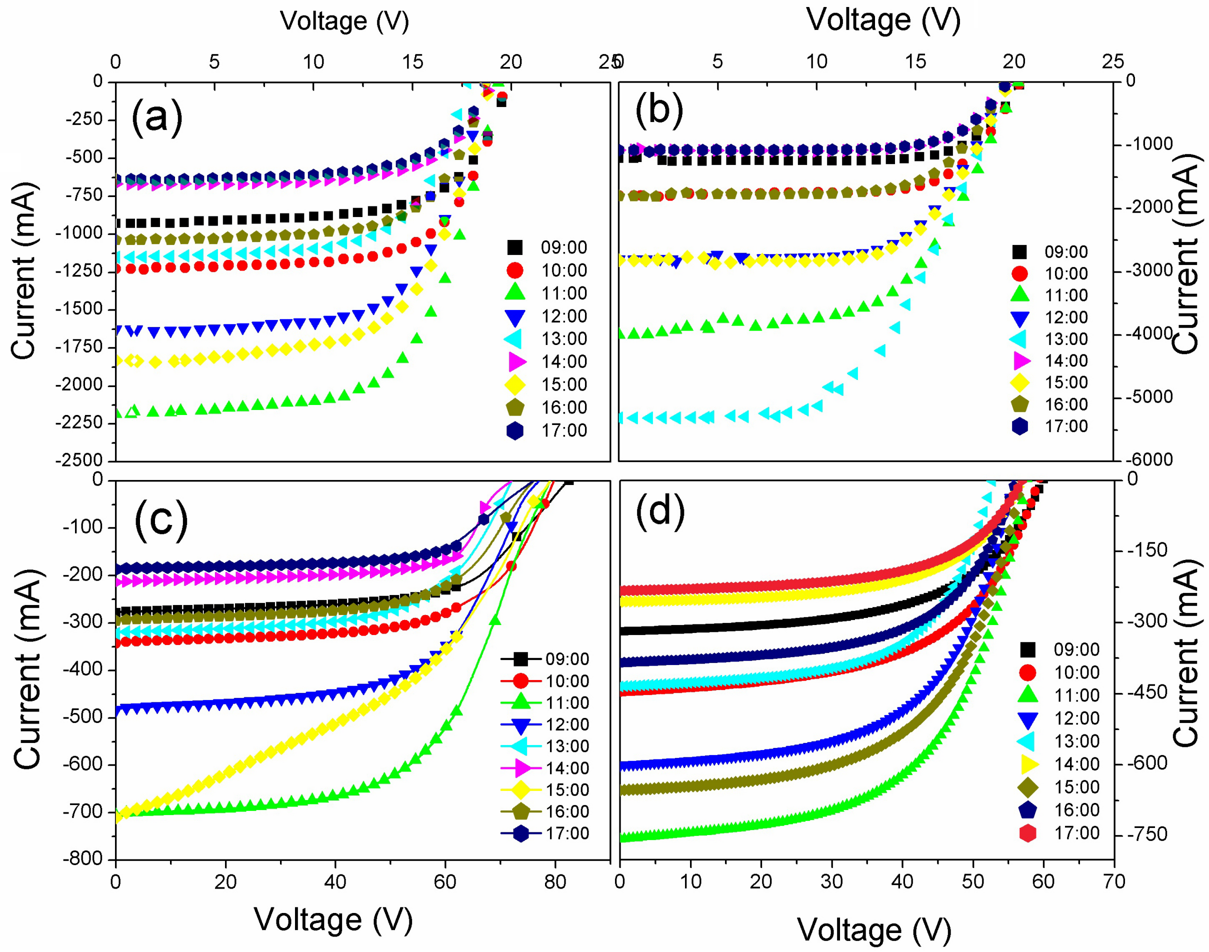

FIGURE 8. Typical I-V characteristics of the four modules taken at different hours of the day: (a) bulk monocrystalline silicon; (b) bulk polycrystalline silicon; (c) thin film CdTe and (d) thin film amorphous silicon.

these measurements are performed under controlled conditions which differ from the real ambient conditions and spectral irradiation in which the module operates. That is why we take the value of the parameters measured at 25°C as the reference in this work. In this way, the temperature coefficient of each electrical parameter indicates how increasing temperature from the reference value affects its performance.

For the four modules, the short circuit current and the current density at the maximum power did not show a clear dependence with the temperature. Therefore, the temperature coefficient of the short circuit current could not be determined. This parameter is small in general (about mA/°C), and its determination is at the precision limit for the current measurement instruments. For this reason, it was not possible to get the current temperature coefficient. On the other hand, the short circuit current is the electrical parameter with the more pronounced dependency of the environmental conditions such as the spectrum of the incident light, the cloudy conditions and air mass. These parameters are very difficult to measure under our experimental conditions.

The temperature coefficients of the open circuit voltage, fill factor, maximum power and efficiency, were determined from their lineal dependence with the temperature for all the modules studied in this work. These values, calculated with respect to the calculated value corresponding to 25°C, are listed in table I expressed in %°C. From Table I, it can be observed that the amorphous silicon panel presents less decrease effect from temperature. The polycrystalline silicon module lost 6 times more power than the corresponding amorphous silicon, for each increased degree in temperature. Greater recombination at the grain boundaries, activated by temperature could be the cause of this mechanism, which is dimmed in the other polycrystalline materials due to their photoconducting behavior.

In order to have a clearer idea of this asseveration, the temperature coefficients for the maximum power without standardizing have been written in Table II. The decrease in the efficiency of the panels with increasing temperature with respect to its value at 25°C is also shown in Table II. From these results we conclude that the best solar module under temperature variations typical of Mexico City's environmental conditions is the module processed with amorphous silicon technology. Nevertheless, it is necessary to add other considerations like the average time of utility of the module

TABLE I. Comparison between the temperature coefficients of the electrical parameters for PV modules fabricated with different technologies. The coefficients were calculated at a fixed solar radiation of 82.5 mW/cm^2 and module temperatures between 25 and 42°C.

Electrical parameter	Polycrystalline silicon	Monocrystalline silicon	Amorphous silicon	CdTe
V_{oc}	-0.52	-0.40	-0.49	-0.43
P_{max}	-1.05	-0.64	-0.33	-0.56
FF	-0.33	-0.25	+0.26	+0.02
η	-1.05	-0.66	-0.33	-0.55

TABLE II. Temperature coefficients for the modules maximum power, expressed in W/°C and module efficiency decrease with temperature with respect to its value reported at 25°C.

	Polycrystalline silicon	Monocrystalline silicon	Amorphous silicon	CdTe
P_{max} (W/°C)	-0.64	-0.23	-0.10	-0.22
η (% of loss with respect to 25°C)	21	13	6	11

(lifetime limited by degradation processes), cost of the Watt peak (Wp) supplied by each technology and the efficiency which is directly related to the area occupied by panels to obtain the same power production. Due to all these considerations and the specific conditions of installation, we decided to use the polycrystalline silicon technology in the facilities of the ICyTDF, which is an historical building from the 18th century where the available area and weight of the PV system are restricted. This last technology guarantees modules with efficiencies higher than 16%, which assures about 205 Wp in 1.5 m^2 of area, whereas the thin film technologies with efficiencies between 6 and 7% would need an area of 3.5 to 4 m^2 to obtain a similar Wp value. This analysis demonstrates that it is necessary to consider the environmental and architectonic parameters in the specific place where a PV installation will be made, to be able to take the most appropriate decision.

4. Conclusions

The ecological impact of the installed photovoltaic system in the ICyTDF is equivalent to a forest area with more than 700 adult trees (7 forest hectares).

Considering the results presented in this work, we can project that the installation of 100 photovoltaic systems per year with a capacity between 5 and 10 kW of installed power on roofs of governmental and non-governmental buildings, would represent an approximated production of 1752 MWh per year. Having 100 installed systems would be equivalent to saving 137 tonnes of petroleum per year, avoiding more than 744 tonnes of CO_2 emissions. If the program were permanent, it would mean that in the next 10 years thousand tonnes of CO_2 would not be emitted to the atmosphere, due to the saving of thousand tonnes of petroleum used nowadays to produce electricity.

The electrical parameters of four modules manufactured with different solar cells technologies were studied as a function of module temperature. In the range of 20 to 40°C the module less affected by temperature was the one manufactured with amorphous silicon solar cells, that loses 6% of its efficiency value with respect to the reference value at 25°C, followed by the module fabricated with CdTe cells who lost 11%, and finally, the modules of crystalline silicon and polycrystalline silicon with 13% and 21%, respectively. From these results we conclude that the best solar module for the environmental conditions of México City is the module processed with amorphous silicon technology, because it is exhibits the best stability under temperature variations. Nevertheless, it is necessary to add other considerations like the average time of utility of the module (lifetime limited by degradation processes), cost of the Watt peak (Wp) supplied by each technology and the efficiency which is directly related to the area occupied by panels to obtain the same power production.

Acknowledgments

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