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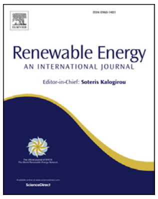

Life cycle cost of photovoltaic technologies in commercial buildings in Baja California, Mexico

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ABSTRACT

The appropriate use of photovoltaic technologies is essentially based on the identification of the available solar resource at the location in which they will be installed and the energy demand concerned. The purpose of this paper is to identify the geometric orientations that provide the best life-cycle cost for a multi-crystalline photovoltaic module, in order to supply electric energy for commercial buildings in three locations in Baja California, Mexico. The energy production of photovoltaic technologies was estimated on TRNSYS® according to a Typical Meteorological Year (TMY) simulated through spatial interpolation methods in Meteonorm®. Energy generation was compared in different orientations and inclinations of the photovoltaic array, its cost was calculated from the grid of the Federal Electricity Commission of Mexico. As a result, it was observed that in the city of Mexicali (hot-dry climate) the highest cost-benefit factor (3.17) and the shortest return on investment (13.02 years) was reached. The results showed that the multi-crystalline silicon photovoltaic cells represent a feasible investment option when installed in commercial buildings.

1. Introduction

There is an increasing concern for environmental issues, depletion of energy resources and their supply difficulties. As a result, governments tend to focus increasingly on the dissemination of technologies that exploit renewable energy sources [1].

Solar energy is the most abundant, inexhaustible and clean of all existing energy resources [2]; due to this, solar-based systems have notably increased their popularity as an alternative to reduce the consumption of fossil fuels and greenhouse gas emissions [3].

The solar energy applications go beyond power generation and water heating, common applications are useful for heating, steaming, drying and dehydration processes; preheating, concentration, pasteurization, sterilization, lavage, cleaning, chemical reactions, amongst others [4]. This energy, is suitable to supply electricity in the residential, commercial or industrial sector, but especially in remote or rural communities. The potential of solar energy on earth surface is near 1.8 × 1011 MW, which is 10,000 times greater than the global energy consumption [5].

Irradiance on earth's surface during the day is not uniform, because this depends on aspects, such as solar zenith angle, the length of the day, air turbidity, water vapor content in the air and the type and amount of clouds.

The Solar irradiance data on horizontal surfaces are commonly measured by meteorological services in stationary solar conversion systems throughout weather stations. However, in order to estimate the irradiance on tilted surfaces with high accuracy, several numerical models have been developed [6–9].

Thus, there are databases built up from satellite measurements, where models of solar radiation are embodied within geographical information systems (GIS); based on empirical equations, these may provide fast and accurate radiation on different regions, taking

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into account the tilting surface orientation and shading effects. Although these methods provide information at continental level or even globally, they can also generate wrong predictions, especially where there are mountain ridges where the shading of the surface can cause significant fluctuations in irradiance.

Some of the best known databases are the European Solar Radiation Atlas (ESRA), the Surface meteorology and Solar Energy (SSE) from NASA, as well as the one provided by National Renewable Energy Laboratory (NREL), the high-resolution information available from SolarGIS and finally the Photovoltaic Geographical Information System (PVGIS) which includes free information of Europe, Africa and Asia [10–14].

This paper focuses on the solar resource analysis for three different locations in Baja California, Mexico; Mexicali (Lat. 32° 39′ N, Long. 115° 29′ W) with a hot-dry climate, San Felipe (Lat. 31° 02′ N, Long. 114° 50′ W) with a hot-humid climate and Tijuana (Lat. 32° 32′ N, Long. 116° 58′ W) with a temperate climate. Later, a study of the economic feasibility of the multi-crystalline silicon photovoltaic systems in commercial buildings for the locations cited was evaluated.

2. Antecedents

2.1. Photovoltaic module orientation for optimum power production

Several studies have been made to estimate the PV power stations in different latitudes. Yan et al. [15] found that the optimum tilt angle for this systems in Brisbane, Australia (Lat. 27.28° S), is 26° oriented due north. Randall et al. [16] showed that the optimal annual performance of monocrystalline PV array on field conditions in London, England is achieved with a south orientation and tilt angle of about 30°. Yet, at the same time, when the orientation was 45° due south–east, the output energy was near 95.7% regarding the optimum orientation and slope annual performance.

Asl-Soleimani et al. [17] evaluated the experimental performance of photovoltaic modules in Tehran, Iran (Lat. 35.71°N) using mono-crystalline modules with different tilt angles 0°, 23°, 29°, 35° and 42°, and two multi-crystallines, 16 mono-crystallines and one of thin film with a tilt angle of 45°. Results indicated that the maximum production of photovoltaic energy is reached with a tilt angle of 29°.

Hussein et al. [18] calculated via computational simulation, that maximum annual production for monocrystalline arrays is reached at south orientation and at a tilt range between 20° and 30° in Cairo, Egypt (Lat. 30° N). It also showed that east orientations produced a higher amount of annual energy than west orientations, was also identified that the horizontal arrangement obtain 95% of the optimal annual value for energy production.

Nakamura et al. [19] identified that energy production of monocrystalline modules installed in Shizuoka, Japan (Lat. 34.45° N) decreased one percent for a cell with horizontal arrangement regarding a tilted surface with a slope of 30° and oriented due south. Other studies have conducted more detailed analyzes to identify the optimum configuration for each month of the year. Kacira et al. [20] evaluated the optimum orientation and tilt for PV modules installed in Sanliurfa, Turkey (Lat. 37° N), the results were compared with the gain of a system of dual axis solar tracker.

Optimum inclinations varied around the year, with a minimum value of 13° in June and a maximum of 61° in December. The increased uptake of radiation of the tracking system was 1.1% higher over the year compared to the optimum setting for every month and 3.9% higher when it was compared to the latitude of the location.

Mondol et al. [21], indicated through numerical simulation that the highest energy production in maritime climate in Northern Ireland (Lat. 54° N) was achieved with a 30° tilt angle, oriented due south; although the optimum tilt angle changes throughout the year between 10 and 70°. Benghanem [22] found that the optimum tilt angle for PV systems around the year in Medina, Saudi Arabia (Lat. 24.28° N) was almost the same as the latitude of the location.

Kaldellis et al. [23] noted that to satisfy certain energy demands, is not essential the increase of the system capacity, but the tilt angle and orientation must fit the annual consumption pattern of the particular case. In this respect, Kaldellis y Zafirakis [24] experimentally analyzed tilted surfaces of 0°, 15°, 30°, 45°, 60° y 75° during 20 days in summer in Athens, Greece (Lat. 37.58° N); this research concluded that tilted surface of 15° produced the highest amount of electricity in summertime.

Hiraoka et al. [25] examined the performance of photovoltaic technologies installed with a tilt angle of 26.51° due south (monocrystalline), 26.51° due north (multi-crystalline and amorphous silicon cells) and horizontally (amorphous silicon cells) in Shinga, Japan (Lat. 34.51° N).

The results showed that the annual data of all orientations represent approximately 70% compared to the data of the south facing panels. The amorphous silicon cell arranged horizontally had the best performance in summer, while the south-facing monocrystalline technology had the best performance in winter.

Useful considerations come up with concepts for cross-comparison, such as Performance Ratio (PR), which refers to the ratio of the energy of a PV plant that is actually available for export to the grid after deduction of thermal and conduction losses, regardless of location. That is to say; the PR is a factor that describes the existing relationship between real and theoretical output power of a photovoltaic system, this parameter – for example-have resulted a powerful tool to compare an enormous amount of facilities studied by Leloux et al. [26].

Various authors have compared PR values from several PV technologies in Chipre throughout different climate seasons. Results shown that monocrystalline technology has the best performance in winter, along with CIGS and CdTe, but these two with a shorter breadth [27]. Some others evaluate experimental results of grid-connected PV systems finding an average PR of 77.28% in mono-crystalline silicon cells [28].

Meanwhile, the International Energy Agency (IEA) [29] has developed a set of guidelines for the development of life-cycle assessment of photovoltaic technologies through the Photovoltaic Power Systems Program (PVPS) where sets the PR to consider are site-specific or a default value of 75%–80% roof and ground mounted, installed in optimal orientation and tilt (Hyung et al. [30], Mason et al. [31] and Pfatischer [32]).

It is considered that a photovoltaic plant has a high performance when the performance ratio exceeds 80%. Overall performance ratio increases with the decrease in temperature and the monitoring of photovoltaic systems for early detection of defects. This means that with good ventilation and large-scale installations increased performance is obtained.

2.2. Economic feasibility of photovoltaic modules

Some studies have conducted comparative economic feasibility between different countries. Muhammad-Sukki et al. [33] showed that in the residential sector, despite having a higher installation cost, Japan requires less time to recover the investment (7.70 years) than the UK (7.80 years) and Germany (12.32 years).

Similarly, in the non-residential sector, Japan has the highest installation cost; however, payback period of the investment is about eight years long for Japan, while for the UK and Germany is over nine years. Pillai et al. [34] identified that residential photovoltaic systems interconnected to the electric grid in India obtain a profits in the short term; distinct from the case of UK, this is mainly due to low uptake of solar radiation. Spertino et al. [35] examined the main constraint to achieve parity with the electricity grid in residential and tertiary sectors on several cities from Germany and Italy.

The study led to identify that just in the case of residential sector in Italy the parity cannot be achieved due to its high interest rates (4–10%).

The photovoltaic plants in Petroleum-Exporting Countries seem far from achieving economic viability. Khalid y Junaidi [36] studied the economic viability from a PV plant in eight different cities in Pakistan. The price of the plant was found to be 30.8% more expensive than the electricity supplied by the electricity grid in Quetta, which was the area with the greatest potential. Harder and Gibson [37] made an economic study of photovoltaic plants installation in Abu Dhabi, United Arab Emirates.

The authors' conclusion demonstrated that to achieve economic viability should be considered the environmental benefits or the initial costs should be reduced by 55%. Ramadhan and Naseeb [38] evaluated economically the PV plant installation in Kuwait: The levelized cost of electricity for a 1 MW PV plant was about $0.20/kWh. However, the cost-benefit indicated that saves 0.09 $/kWh in electricity production at a price of 0.02 $/kWh for the cost of CO_2 emissions, decreasing the levelized cost of energy to 0.17–0.05 $/kWh, concluding that under these premises, the photovoltaic installation is completely possible.

In other hand, Lakhani, et al. [39] showed that a facility in rural communities (14.2 ¢/kWh in the village Blythe) is more effective, than a residential or commercial buildings (18.8 ¢/kWh and 18.9 ¢/kWh respectively, in the city of Los Angeles).

Future prospects that have been developed to indicate that at medium term PV systems will have a leading role in the energy supply. Raugei y Frankl [40] based on financial incentives, considered that photovoltaic energy can be an important part in the energy mix between 2020 and 2030. Even so, de La Tour et al. [41] estimated a 67% decrease in the cost of PV modules between 2011 and 2020, from a model proposed.

Thus, the levelized cost of energy (LCOE) is reached in locations where solar radiation exceeds 2000 kWh/year. Van Sark et al. [42] made weekly inventories of PV system costs in order to analyze evolution on the Dutch market.

It was found that the sale prices of modules, inverters and systems installed on roofs decreased 44.3, 14 and at the range of 7.3–10.2% respectively, to study 2012 with regard to 2011. This indicates that LCOE was approximately 10 and 15 euro cent (€) lower than the existing in the electric grid when the PV system is installed optimally.

However; in some cases, the parity is about to be reached, Bhandari and Stadler [43], felt that considering the progress of the 2009 experience curve of 80%, in 2021 PV system will have the parity in respect of the domestic grids in Colony, Germany. Swift [44] compared the financial performance with and without state and federal incentives of grid interconnected PV systems in Honolulu, Hawaii; Newark, New Jersey; Phoenix, Arizona; and Minneapolis, Minnesota.

Honolulu provided 31.60% IRR, while Minneapolis obtained the lowest IRR percentage; 8.27%. The author concludes that without incentives, the installation of photovoltaic systems would have to decrease substantially to achieve grid parity.

Dong y Wiser [45] evaluated the economic impact of authorization processes from over 3000 photovoltaic installations in 44 cities in California during 2011. Results indicated that best practices reduce costs between 4 and 12%, which meant $1000 in savings for a 4 kW installation.

3. Method

As described before; on a regular basis, the methodological structures used to evaluate PV technologies and associated with economic diagnostics predict array optimum configurations through the use of many solar resource assessment tools; this, results – commonly-in a surface with a tilt angle almost equivalent to latitude of the studied location and an orientation guided towards the terrestrial equator.

However, the orientation in which the PV array produces the greatest amount of energy and where the greatest solar resource is obtained, are not necessarily the same; which is detrimental in terms of economic feasibility.

The methodological procedure employed in this study instead, is intended to provide alternatives with a similar economic performance to solve scenarios where the best power generation configuration cannot be set up. Thus, this paper aims to extend the LCC analysis by mean of the inclusion of environmental, energy generation and economic performance parameters within a joint procedure, in order to integrate a broader perspective in terms of installation and sustainable use of PV technologies. The procedure is shown in Fig. 1.

3.1. Electric power consumption

The electricity consumption of a commercial building was studied for the purpose of this paper, with an equivalent consumption of a shoe/clothing store. The billing costs were projected from the current fees and charges applied in the Baja California state in compliance with the Federal Electricity Commission of Mexico, which corresponds to a commercial building with high consumption in low-voltage transmission line on a typical weather conditions obtained from hourly data sets in TMY2 file format.

The analysis of electricity consumption in this research implied the use of high efficiency lamps, computers, printers and electronic devices for employees use. The exterior lamps consumption was variable in accordance with the sunlight for each season. The difference in monthly consumptions shown in Fig. 2 is due to air conditioning, for every type of climate.

During January, February, November and December there is no variation on the electrical consumption of the building on different

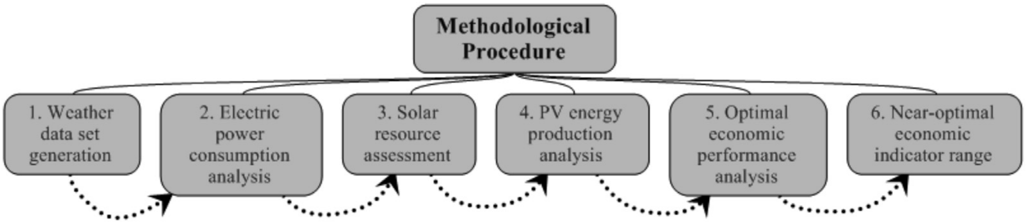

Fig. 1. Methodological structure.

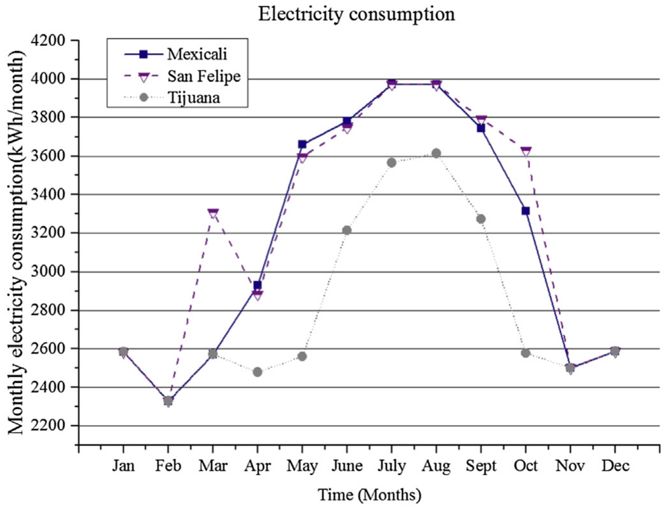

Fig. 2. Electricity consumption in the commercial building prototype.

locations, because this is the climatic season where lowest annual temperatures take place. Those temperatures are very similar between them.

San Felipe has a warm humid climate and contains temperatures where cooling is required from March. In the case of Mexicali, which has a warm dry climate, cooling is required between the months of April and October. Tijuana has a temperate climate, hence the need for cooling is presented only for four months; i.e., from June through September.

3.2. *Solar resource assessment*

For the analysis of the solar resource in Mexicali, San Felipe and Tijuana, the same typical meteorological year (TMY2) file generated via METEONORM® software cited in previously was used. The software processes the files from the latitude, longitude, time zone, height above mean sea level (AMSL) and classification of territorial formation of a location.

Subsequently simulations were made with TRNSYS® software to determine the solar resource from Mexicali based on Perez diffuse irradiance model for tilted surfaces [46], tilt of surfaces were fixed every 5°; i.e. 0°–90° and the orientation, every 10° azimuth angle; i.e. 0–360°.

TRNSYS® software estimates the solar radiation on surfaces based on the interconnection of components that function as data readers, unit converters, quantity integrators, etc.

3.3. *Energy production assessment of photovoltaic arrays*

To determine the electrical performance of a photovoltaic technology, photovoltaic arrays of 250 Wp polycrystalline panels that make up a 1 kWp an installed PV array were considered using TRNSYS® components, they incorporate an iterative search routine to calculate the equivalent circuit model largely developed by Townsend through the Equation (1):

$$\frac{\partial \mathrm{V_{oc}}}{\partial \mathrm{T_c}} = \mu_{voc} = \frac{\gamma k}{q}\left[\ln\left(\frac{I_{sc,ref}}{I_{o,ref}}\right) + \frac{T_c \mu_{Isc}}{I_{sc,ref}} - \left(3 + \frac{q\varepsilon}{AkT_{c,ref}}\right)\right] \tag{1}$$

where

$$A = \frac{\gamma}{N_S} \tag{2}$$

This equation where $\mathrm{V_{oc}}$: Open-circuit voltage, $\mathrm{T_c}$: Module temperature, μ_{voc}: Temperature coefficient of open-circuit voltage, γ: Empirical PV curve-fitting parameter, k: Boltzman constant, q: electron charge constant, $\mathrm{I_{sc,ref}}$: short circuit current at reference conditions, $\mathrm{I_{o,\ ref}}$: diode reverse saturation current at reference conditions, μ_{Isc}: temperature coefficient of short-circuit current, ε: semiconductor bandgap, $\mathrm{N_s}$: number of individual cells in module and $\mathrm{T_{c,ref}}$: module temperature at reference conditions is derived by taking the analytical derivative of voltage with respect to temperature at the reference open-circuit condition [47].

3.4. *Capital budgeting*

The present paper takes into consideration the currency value over time as an economic indicator for the financial evaluation of projects, in order to consider the payback period. The net present value requires the discount of the net cash flows, the resulting value is subtracted from the initial net investment. The Equation (3) to calculate the Net Present Value (NPV) is:

$$NPV = \frac{NCF_1}{(1+i)^1} + \frac{NCF_2}{(1+i)^2} + \dots \frac{NCF_n}{(1+i)^n} - \frac{INI - SV}{(1+i)^n} \tag{3}$$

where:

NPV: Net Present Value.
NCF: Net cash flow
INI: Initial net investment.
i: Discount rate
SV: Salvage value.
n: Cash flow generation year.

An investment project of photovoltaic technologies is profitable if the NPV is greater than or equal to zero for a period of 25 years, therefore, the net present value is equal to the internal rate of return (IRR). Another condition is the cost-benefit ratio (CB), which measures the net cash flows that are taken after retrieving the required rate of interest on the investment project. Surplus cash flow regarding investment amount represents the additional gain in percentage of the updated initial investment.

CB is the sum of the cash flows to present value, divided by the initial net investment to present value minus 1, multiplied by 100. The Equation (4) is described as follows:

$$CB = \left[\sum \frac{NCF_2}{(1+i)^2} \Big/ INI - \frac{SV}{(1+i)^n - 1}\right] {*}100 \tag{4}$$

When CB ratio is a negative value, there is a percentage of the investment missing; in this case, the investment is not covered by the CB. General inflation in Mexico in the last 10 years has increased by 7.89% on average. With regard to inflation in the cost of electricity for the corresponding rate for businesses in Baja California, has had an increase on the average of 4.22%.

Local suppliers of PV systems provide every watt installed at the price of $4 USD. This price includes the inverter and the mounting structure (BOS). In this study, a loan for the purchase of solar panels was not considered. However, two replacements of the inverter were estimated, the first at 10 years and the second at 20 years.

For inverter replacements, no linear costs are considered. That is, inverters or combinations of inverters for proper power management were selected. Through this, the replacement costs of inverters from different installed capacity were between $40 and up to $700 USD for the actual costs in 2014. Even though, aspects such as increases–decreases on energy consumption due to climatic change or efficiency in PV systems and regional-global financial contingencies represent very complex perturbation factors that may affect the analysis.

4. Results

4.1. Solar resource

4.1.1. Solar resource in Mexicali

By mean of a detailed solar incidence study, it was found that more than 6 h peak are obtained in the 25–35° tilt angle area and at a range of 10° east or west of azimuth angle orientation closest to south (Fig. 3).

The surface oriented due south with an inclination of 30° obtained the largest annual irradiance; 2204 kWh/m^2/year. As seen, radiation perceived is greater in south orientations, but slightly higher in the west.

It was also observed that the lowest radiation for every different orientation is provided in the vertical surfaces. In February, November and December, the less solar resource is estimated, since the total radiation does not exceed 175 kWh/m^2/month in any orientation. In contrast, the months of May and June exceed 225 kWh/m^2/month.

The horizontal surface captures 89% of annual radiation in respect of the optimum annual orientation and has a percentage of 58% and 57% during January and December respectively, regarding the optimal orientation of the same month and over 99% compared to the same optimal orientation in the months of May, June and July.

4.1.2. Solar resource in San Felipe

The increased uptake of San Felipe's annual radiation reached 2015 kWh/m^2/year, at a tilt angle of 29° with a deviation of 2° toward the southwest. The distribution of radiation is similar to the case of Mexicali, where radiation values are greater on south facing surfaces, although slightly higher in the east than in the west as shown in Figs. 4 and 5.

As noted, the most significant radiation values are located in planes near the latitude, i.e. near 30° in three cases. In January, February, November and December, the lowest solar resource is obtained, since the irradiance does not exceed 175 kWh/m^2/month in any orientation. In contrast, the month of July is over 190 kWh/m^2/month. The horizontal surface captures 90% of annual radiation in respect of the optimum annual orientation and reaches its lowest percentage in relation to monthly optimal orientation in December (59%) and over 99% during May, June and July.

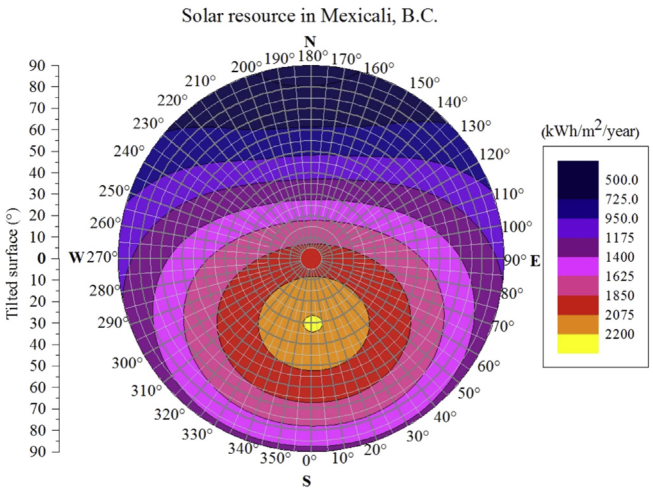

Fig. 3. Annual total solar radiation in Mexicali, B.C.

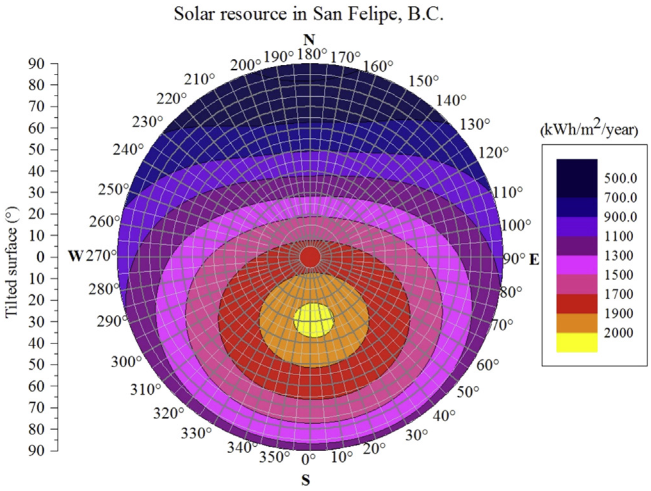

Fig. 4. Annual total solar radiation in San Felipe, B.C.

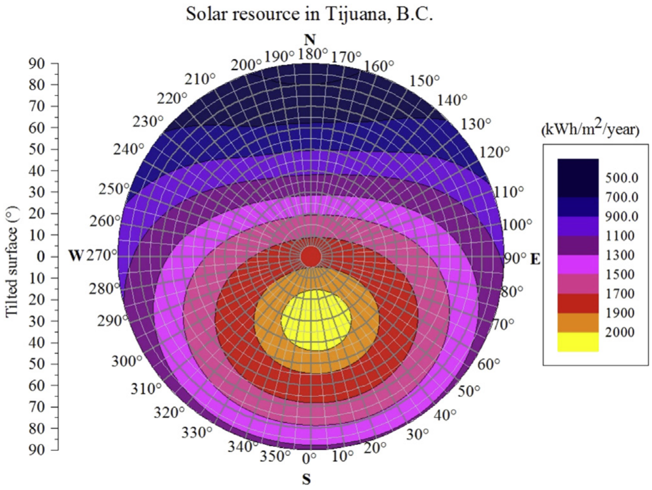

Fig. 5. Annual total solar radiation in Tijuana, B.C.

4.1.3. Solar resource in Tijuana

The highest uptake of Tijuana's annual radiation reached 2049 kWh/m2/year, at a tilt angle of 30° with a deviation of 3° toward the southeast, as shown in Fig. 5 where yellow (in the web version) color indicates 2000 kWh/m^2/year and higher values.

The distribution of radiation is similar to cases of Mexicali and San Felipe. In January, February, November and December, the lowest solar resource is obtained, since the irradiance does not exceed 175 kWh/m^2/month in any orientation. Furthermore, July exceeds 190 kWh/m^2/month. The horizontal surface captures 90% of annual radiation in respect of the optimum annual orientation and reaches its lowest percentage in relation to monthly optimal orientation in December (57%) and close to 100% during May, June and July.

4.2. Energy production of photovoltaic systems

In all three cases it was observed that the orientation in which the PV array produces the greatest amount of kWh/year differs from the direction where the greatest solar resource is obtained.

Moreover, the installed kWp photovoltaic energy produced greater amount of energy at a higher inclination angle and orientations toward east direction, in relation to the direction where the greatest solar resource is reached.

This variation is due to the effect of weather conditions, especially the dry bulb temperature on the photovoltaic modules, this is shown in Table 1, where solar resource and electricity production are compared in order to identify the impact of the optimum orientation, not only via solar radiation, but dry bulb temperature fluctuation, etc. In Mexicali, the installed kWp produces 2494 kWh/year at an azimuth angle of 1° eastward in relation directly due south and at a tilt angle of 31°.

For Tijuana, the installed kWp produces 2309 kWh/year at an azimuth angle of 4° eastward in relation directly due south and at a tilt angle of 31°. In San Felipe, the installed kWp produces 2240 kWh/year at an azimuth angle of 3° eastward relating directly south and at a tilt angle of 30°, as shown in Fig. 6.

4.3. Economic assessment

In Mexicali, the shorter payback period resulted in 13.02 years with 4 kWp installed. The greatest cost-benefit factor obtained was 3.17, as shown in Fig. 7.

Fig. 8 shows in San Felipe, the shorter return on investment time resulted in 14.28 years with 6 installed kWp, while the greatest cost-benefit factor found was 2.80.

Meanwhile, in Tijuana the lower return on investment was estimated to around 13.92 years with 4 installed kWp. The highest cost-benefit factor was defined as 2.91, as seen in Fig. 9.

4.4. Near-optimal economic indicators

Figs. 10–12 show the ranges of inclinations and orientations of the photovoltaic modules that have a similar economic

Table 1
Surface orientation with the highest solar resource and energy production in kWh/year per installed kWp.

City	Solar resource (best orientation)			PV array production (1 kWp)		
	kWh/m^2/year	Az.	∠	kWh/m^2/year	Az.	∠
Mexicali	2204.09	0°	30°	2494.84	1°	31°
San Felipe	2015.63	2°	29°	2240.74	3°	30°
Tijuana	2049.98	3°	30°	2309.98	4°	31°

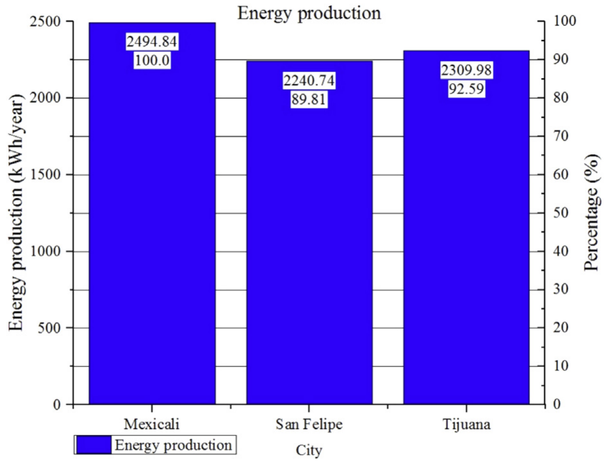

Fig. 6. Energy production per installed multicrystalline kWp.

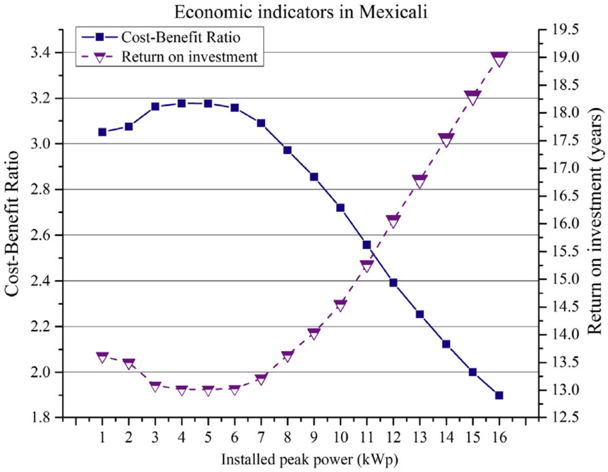

Fig. 7. Economic indicators for the case of optimum orientation PV panel in terms of electricity generation in Mexicali (azimuth 14°, tilt angle 33°).

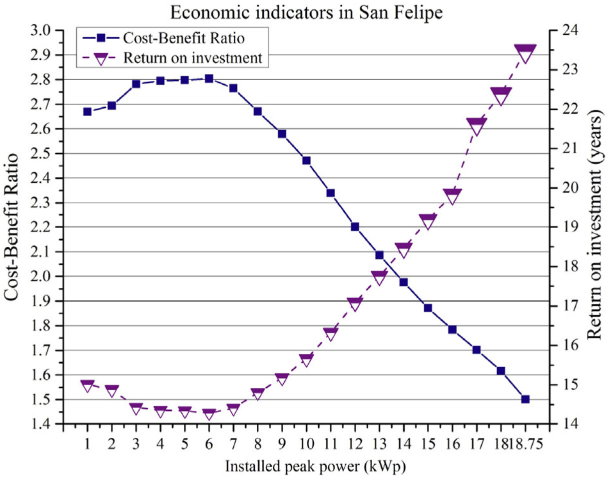

Fig. 8. Economic indicators for the case of optimum orientation PV panel in terms of electricity generation in San Felipe (azimuth 15°, tilt angle 30°).

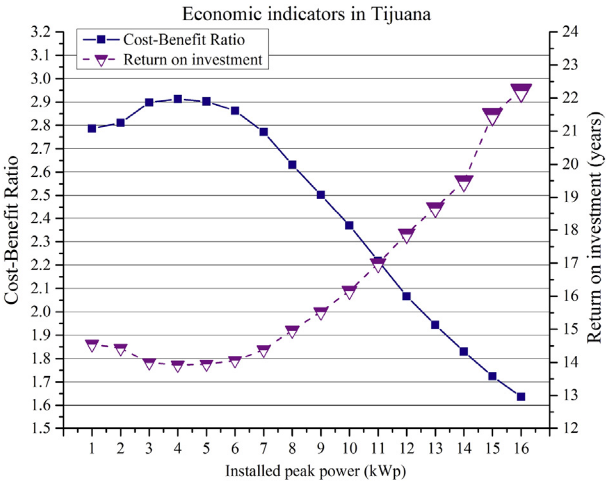

Fig. 9. Economic indicators for the case of optimal orientation PV panel in terms of electricity generation in Tijuana (azimuth 12°, tilt angle 32°).

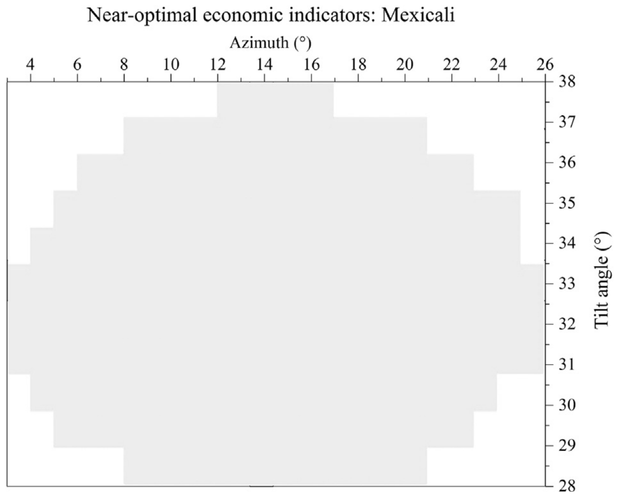

Fig. 10. PV array configurations with near-optimal economic indicators in Mexicali (azimuth: 14°, tilt angle: 33°).

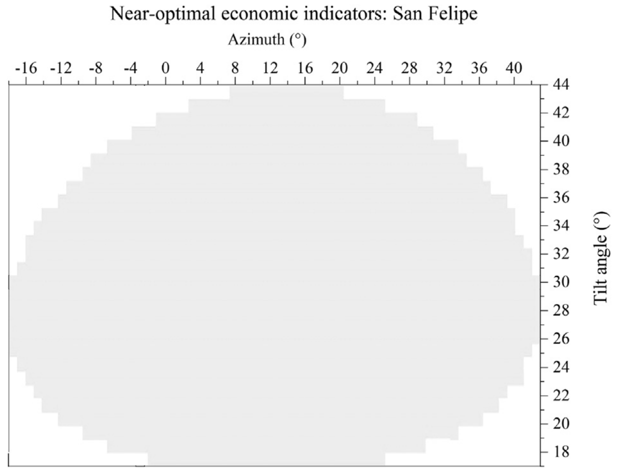

Fig. 11. PV array configurations with near-optimal economic indicators in San Felipe (azimuth: 15°, tilt angle: 30°).

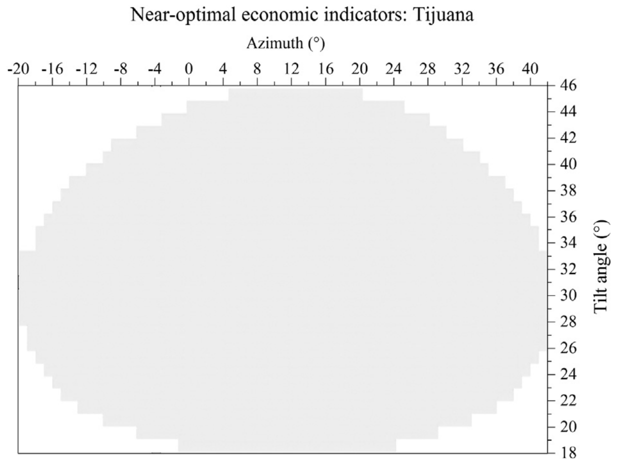

Fig. 12. PV array configurations with near-optimal economic indicators in Tijuana (azimuth: 12°, tilt angle: 32°).

performance relative to optimal; that is, a return of investment and cost-benefit equivalent factor (+0.1). This means that there is a significant range of options for configuring the PV array at each location with a low performance affectation.

The figures show configurations that provide values close to the optimal configuration, these are used as nodes to create a gray polygon, which illustrates the alternative combinations of feasible solutions, note that azimuths negatives/left mean west while positives/right mean east in compliance with what is shown in solar resource figures.

For the case of Mexicali, it is observed that 253 configurations kept proximity to the optimal; meaning that the effect of tilt has the higher weighted impact in the overall performance.

In San Felipe, 1736 combinations where PV modules are close to the optimal were obtained. The fact that Mexicali has fewer combinations than San Felipe, it is mainly because this location has a shorter period of payback, this is shown in Fig. 10 where the optimal case is found at inclination of 30° and south facing position with 15° deviation to the west.

In the case of Tijuana, 1575 configurations close to the optimal orientation were observed. It is interesting the fact that an exponential growth of close-to-optimal configurations it is mainly generated because Tijuana has a lower electricity consumption than the cases presented in Mexicali and San Felipe; a condition perfectly related with dry bulb temperature oscillation and relative humidity present in that location.

5. Conclusion

The results show that the orientation where greatest solar resource, does not necessarily correspond to a south facing array. This is because the sky is cloudier in the afternoon than in the morning in the case of San Felipe and Tijuana. Furthermore, it was shown that neither the orientation where the greatest solar resource is obtained, it is necessarily the typical in which the PV array produces the highest amount of electricity. Factors such as temperature and ventilation modify the performance described above.

Mexicali reached the shortest return on investment period; 13.02 years with an installed capacity of 4 kWp and the highest cost-benefit factor; 3.17. Due to its lower solar resource, San Felipe scored a larger return on investment and a cost-benefit factor lower than Tijuana, however economic indicators are similar in both cities. Therefore, the energy consumption of the commercial building prototype in Tijuana is 13% lower than in San Felipe.

The methodology conducted in this paper promotes more accurate technical and economic evaluations of photovoltaic systems and in turn, facilitate the appropriate alternative selection in cases where optimal configurations of photovoltaic systems are not possible due to a multifactorial condition; such as cloudiness, shading elements, geometric limitations, amongst others.

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