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Solar PV technologies selection for the design of photovoltaic installations in Mexico based on the analysis of meteorological satellite data from the region

Ricardo MIRANDA-JIMÉNEZ[1], Osvaldo VIGIL-GALÁN[2], Jesús Roberto GONZÁLEZ-CASTILLO[2]*, Ángel Refugio TERÁN-CUEVAS[3], María Eugenia GUTIÉRREZ-CASTILLO[3] and Luis Raúl TOVAR-GÁLVEZ[3]

[1] *Centro Mexicano para la Producción más Limpia, Instituto Politécnico Nacional, Av. Acueducto s/n, Ticomán, 07340 Ciudad de México, México.*
[2] *Escuela Superior de Física y Matemática, Instituto Politécnico Nacional, Av. Instituto Politécnico Nacional s/n, Edificio 9, Col. San Pedro Zacatenco, 07738 Ciudad de México, México.*
[3] *Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Ambiente y Desarrollo, Instituto Politécnico Nacional, 30 de Junio de 1520 s/n, Ticomán, 07340 Ciudad de México, México.*
*Corresponding author; email: g_c_j_r@hotmail.com

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RESUMEN

El extenso territorio de México abarca diversas condiciones climáticas, lo cual influye directamente en la selección de tecnologías fotovoltaicas comerciales. Este estudio utiliza datos de irradiancia solar, temperatura e índice de nubosidad (derivados de fuentes satelitales) para generar un mapa de idoneidad de las tecnologías de paneles solares comerciales, a través de la metodología del proceso analítico jerárquico incorporado a los sistemas de información geográfica. El mapa muestra que las calcopiritas y el telururo de cadmio emergen como las tecnologías más adecuadas en el 47.12 % del territorio nacional. Les sigue de cerca el silicio amorfo, que cubre el 30.45 % del territorio, en tanto que el silicio monocristalino y policristalino representan el 22.43 %. El objetivo principal de este artículo es proporcionar orientación para la adecuada selección del tipo de tecnología de paneles solares que mejor se alinee a las condiciones climáticas de México. Este enfoque estratégico ayuda a fortalecer la planificación y viabilidad de los proyectos de energía solar fotovoltaica en todo el país.

ABSTRACT

Mexico's expansive territory spans diverse climatic conditions, which directly influences the selection of commercial photovoltaic technologies. This study utilizes solar irradiance, temperature, and cloud index data (derived from satellite sources) to generate a suitability map for commercial solar panel technologies through the Analytical Hierarchy Process-Geographical Information Systems methodology. The map illustrates that chalcopyrites and cadmium telluride emerge as the most suitable technologies in 47.12% of the national territory. Following closely behind is amorphous silicon, covering 30.45%, while monocrystalline and polycrystalline silicon account for 22.43%. The primary objective of this paper is to guide the proper selection of solar panel technology types that align optimally with Mexico's climatic conditions. This strategic approach aims to strengthen the planning and viability of photovoltaic solar energy projects nationwide.

Keywords: photovoltaic solar energy, Geographic Information Systems (GIS), Analytical Hierarchical Process (AHP), suitability map.

1. Introduction

The average solar energy density in Mexico is 5.5 kW h m^{-2} (Weber et al., 2020). With an approximate area of 1 964 375 km^2, the average daily solar energy available is of the order of 10^{13} kW h, which constitutes two orders of magnitude above the electrical energy consumed in 2021 (~ 2.9×10^{11} kW h) (Expansión/Datosmacro.com, n.d.).

In recent years, the installed capacity of photovoltaic energy has grown with 5630 MW installed in 2020 (IRENA, 2021), ranking third among renewable energy sources, after hydroelectric and wind plants. Due to its extension, Mexico has different climates (see map in Fig. 1) that must be considered to propose the most appropriate type of photovoltaic installations according to the climatic variables of each region.

Currently, the photovoltaic solar panel market is primarily led by monocrystalline and polycrystalline silicon solar cell technologies, which account for 80% of the commercial panel market (Paredes-Vázquez et al., 2018). Thin film technologies of cadmium telluride (CdTe), chalcopyrites (CIGS), and amorphous silicon complete the remaining 20% of the market (Lee and Ebong, 2017).

Solar cells with a concentration system of up to 1000 Suns, with parabolic concentrators, are also part of the technological portfolio of solar cells (Coventry, 2005). Other commercially available cells are semi-transparent (Miyazaki et al., 2005) and bifacial (Guerrero-Lemus et al., 2016). The former are used in (building integrated photovoltaics (BIPV) (Jelle and Breivik, 2012), based on the concept of taking advantage of the lateral area of buildings and growing photovoltaic systems in height, and the latter are based on taking advantage of the diffuse radiation in the rear part of the cell that is lost in simple monofacial solar cells. In a bifacial panel, the electrical power delivered can increase by up to 25% compared to a monofacial panel, indicating that this technology is already considered in the development programs of photovoltaic solar energy. In addition, bifacial solar panels better couple the power delivered during daytime when there is more demand for electricity consumption than monofacial solar panels. Hence, photovoltaic solar panels have been designed and

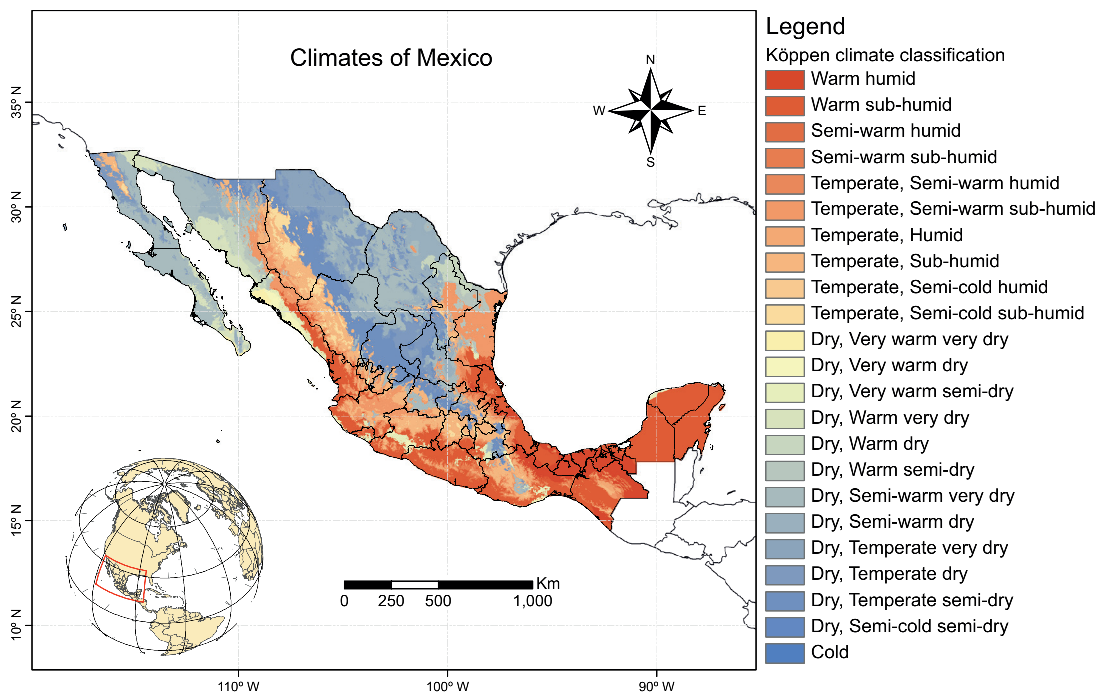

Fig. 1. Köppen climate classification adjusted to Mexico and modified by García. Map made by García and CONABIO (1998) data.

commercially produced to address various challenges and meet diverse climatic conditions.

In this context, this work aims to evaluate the specific type of commercial technologies available for existing photovoltaic panels that best adapt to the climatic conditions of each region of the country, considering their electrical parameters and type of structure. The study has been carried out through a rigorous analysis of satellite data obtained through Amazon Web Service (AWS) by the National Oceanic and Atmospheric Administration (NOAA) and processed with Analytical Hierarchical Process (AHP) coupled with Geographical Information Systems (GIS). Previous investigations have exclusively utilized AHP-GIS for generating suitability maps to identify areas suitable for the development of solar photovoltaic (PV) projects (e.g., Noorollahi et al., 2016; Al Garni and Awasthi, 2018; Haddad et al., 2021; Coruhlu et al., 2022, etc.). However, our work introduces a variation in the use of AHP-GIS methodology by generating a suitability map recommending solar panel technologies based on various climatic factors. Moreover, it provides relevant geographic information to enhance the criteria and facilitate decision-making for each region of Mexico. Furthermore, this work allows the development of similar methodologies in other countries or regions of Latin America with irradiance values that justify the utilization of solar resources for photovoltaic energy. Finally, to provide context for the results obtained from satellite data and to align them with the most relevant aspects of state-of-the-art photovoltaic solar technology, a supplementary section related to the subject has been included.

2. Methodology

The proposed methodology for the study is detailed in the flowchart exhibited in Figure 2. This methodology is based on three main stages:

1. Climatic criteria. Literature review and definition of criteria of the study area.
2. GIS processing. Climatic criteria have different value ranges, so a process must reclassify the values for each criterion. The reclassification process changes input values to a numerical scale. In this study, the scale ranges from 1 to 5. At the same time, this numerical scale corresponds to a type of technology. Furthermore, the reclassification process homogenized the spatial resolution of each criterion to 2 km.
3. Analytical Hierarchical Process. In this stage, climatic criteria are evaluated by the Saaty criteria score on a pairwise comparison matrix to calculate the relative weights of each criterion. The reclassified climatic criteria are multiplied by the relative weight estimated in the AHP. Those weights are determined as correct if the consistency ratio (CR) is below 0.10 (Saaty, 1987). Finally, sums of each layer's values produce an integrated output raster layer, which was processed and edited by the ArcGIS 10.8 software using different ArcMap tools to obtain the recommended PV solar energy technology suitability map.

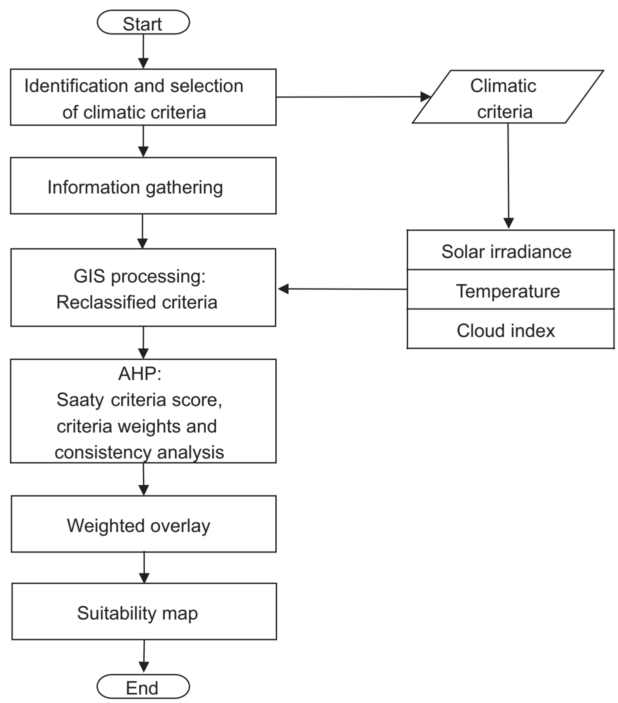

Fig. 2. Analytical Hierarchical Process-Geographic Information Systems (AHP-GIS) methodology.

2.1 Climatic criteria

The climatic criteria selected follow the literature review in studies that estimate the potential of photovoltaic solar energy using AHP in conjunction with

GIS and the information availability. The criteria selected for this study are temperature (Tahri et al., 2015; Suh and Brownson, 2016; Al Garni and Awasthi, 2018; Ruiz et al., 2020; Sengupta et al., 2021), cloud index (Noorollahi et al., 2016; Zoghi et al., 2017; Sengupta et al., 2021), and solar irradiance (Tahri et al., 2015; Watson and Hudson, 2015; Noorollahi et al., 2016; Suh and Brownson, 2016; Asakereh et al., 2017; Zoghi et al., 2017; Al Garni and Awasthi, 2018; Mohamed, 2020; Haddad et al., 2021; Ríos and Duarte, 2021; Sengupta et al., 2021; Coruhlu et al., 2022).

The quality of the terrestrial observations in Mexico is questionable because the sensors installed in meteorological stations that measure surface solar irradiance (the most important variable in this study) do not receive constant calibration. Therefore, the databases usually have errors, therefore in this situation, the reliability is low when characterizing the spatial distribution patterns of surface solar irradiance (Huang et al., 2019). In this case, satellite information is established as a great alternative source of information in areas where the quality of terrestrial observations is poor.

Daily annual average values derived from the Land Surface Temperature (LST) product were utilized for the temperature criterion. Through Python, the data was downloaded hourly throughout 2020 via AWS by NOAA (NOAA, 2022) and processed.

The cloud index criterion was estimated with radiance values of the Advanced Baseline Imager (ABI) sensor from Geostationary Operational Environmental Satellites, R Series, better known as GOES 16, using Heliosat methodology (Diabaté et al., 1989). The radiance values were downloaded every hour throughout 2020, processed, and then used to calculate the daily annual average cloud index. Subsequently, the cloud index was employed to calculate the atmospheric transmission factor, which in turn was used to estimate global surface solar radiation using the Heliosat methodology. Finally, the daily annual average of solar irradiation was computed. Radiance values were obtained from AWS by NOAA (NOAA, 2022) and processed using Python scripts.

2.2 Geographic Information Systems processing

The characteristics of climatic criteria are shown in Table I. The variables used share practically the same characteristics, therefore their GIS processing steps are almost identical. The GIS data were processed and edited using ArcGIS 10.8 software, employing various tools.

The first step involved interpolating the data layers using the "Natural neighbor" tool. The resulting layers were classified using the "Natural Jenks" methodology, which maximizes the distinctions between categories. It is important to note that the temperature criterion was an exception and was classified manually. Then the reclassification process changed the input values of the climatic criteria to a numerical scale. In this study, the scale range is from 1 to 5. At the same time, this numerical scale corresponds to a specific type of technology (Table II) to associate the values of each climatic criterion with corresponding technology types based on the electrical characteristics provided in Tables SIV and SV of the supplementary material.

Table II. Numerical scale of each technology evaluated.

Solar panel technology	Numerical scale
Monocrystalline silicon	1
Polycrystalline silicon	2
Amorphous silicon	3
CIGS	4
CdTe	5

Table I. Characteristics of the climatic criteria used in this study.

Criteria	Unit	Year	Scale	Shapefile format	Spatial reference system
Temperature	ºC	2020	2 km	Point	WSG84
Cloud index	DI	2020	2 km	Point	WSG84
Solar irradiance	W m^{-2}	2020	2 km	Point	WSG84

DI: dimensionless.

Table III. Results of climatic criteria reclassification.

Climatic criteria (unit)	Criterion value	Reclassification value	Category (technology)	Area (km^2)	Percentage (%)
Solar irradiance daily annual average (W m^{-2})	< 421	1	M-silicon	129 482	6.59
	421-448	2	P-silicon	335 061	17.06
	> 448-471	4	CIGS	638 693	32.51
	> 471-497	5	CdTe	626 380	31.81
	> 497	3	a-silicon	234 760	11.95
Temperature daily annual average (ºC)	< 24	1	M-silicon	822 883	41.89
	24-26	2	P-silicon	558 673	28.44
	> 26-28	3	a-silicon	403 481	20.54
	> 28-30	4	CIGS	156 151	7.95
	> 30	5	CdTe	23 187	1.18
Cloud index daily annual average (dimensionless)	< –0.246	3	a-silicon	18	< 0.01
	–0.246-0.126	5	CdTe	378 583	19.27
	> 0.126-0.161	4	CIGS	1 035 624	52.72
	> 0.161-0.201	2	P-silicon	361 856	18.42
	> 0.201	1	M-silicon	188 294	9.59

The reclassification process (Table III) was determined based on the information provided in Tables II, SIV, and SV. When the average solar irradiance is high, it is advisable to opt for solar panel technologies with lower efficiency, and conversely, when it is low, technologies with higher efficiency are recommended (see Table SIV). For regions with high average temperatures, it is advisable to use solar panels with the lowest negative temperature coefficient (see Table SV). Regarding the reclassification of the cloud index, we considered solar panel technologies capable of utilizing diffuse radiation, such as monocrystalline silicon and polycrystalline silicon. The cloud index is a normalized value that quantifies the atmosphere's reflective properties concerning the ground's reflective properties. Values close to or below 0 indicate clear conditions, while values close to 1 suggest cloudy conditions. A high cloudiness index signifies greater diffuse radiation and lower temperatures.

2.3 Analytical Hierarchical Process

AHP has established itself as the most widely used multi-criteria decision-making (MCDM) method when used with GIS for determining specific objectives in regional areas, as demonstrated by the previously cited studies. This study follows Saaty (2001) in the development of AHP methodology.

The first step is to determine the objective and the criteria to use. The objective is to recommend solar panel technologies based on different climatic criteria (solar irradiance, cloud index, and temperature) in Mexico. The second step is to determine priorities among climatic criteria based on a pairwise comparison matrix (Table IV). The priorities were established through a literature review, where the number of authors citing the selected climatic criteria was observed. The total number of articles using each climatic criterion determined its priority in this study (Table V). The values used for each element in these pairwise comparison matrices are used by Saaty (1987).

The third step is calculating the weight of each climatic criterion. The previous pairwise comparison matrix must be normalized to calculate the weight for

Table IV. Pairwise comparison matrix for climatic criteria.

Criteria	Solar irradiance	Cloud index	Temperature
Solar irradiance	1	3	3
Cloud index	0.33	1	0.5
Temperature	0.33	2	1
Total	1.66	6	4.5

Table V. Prioritization of climatic criteria based on literature review.

Criteria	References										Use of criteria (total)
	Rios and Duarte, 2021	Haddad et al., 2021	Mohamed, 2020	Coruhlu et al., 2022	Tahri et al., 2015	Noorollahi et al., 2016	Suh and Brownson, 2016	Ruiz et al., 2020	Zoghi et al., 2017	Noorollahi et al., 2022	
Solar irradiance	×	×	×	×	×	×	×	×	×	×	10
Temperature					×	×	×	×	×	×	5
Cloud index					×	×	×	×	×	×	3

each criterion from an average of each row (Table VI). The weight demonstrates the importance of each climatic criterion to achieve the goal. To finish this step, it is necessary to calculate suitability scores using Eq. (1).

$$Ss_i = \sum_{i=1}^{n} x_i w_i \tag{1}$$

where Ss_i represents the suitability scores, x_i, is the criterion value assigned by Saaty's criteria score (Saaty, 1987), w_i is the weight calculated for each criterion, and n is the number of selected criteria.

The last step is the calculated consistency ratio to verify inconsistencies in the pairwise comparison matrices. This step is crucial to ensure a correct valuation. Eqs. (2), (3), and (4) were used to calculate the consistency ratio (Table VII).

$$\lambda_{max} = \sum_{i=1}^{n} \frac{Ss_i}{w_i} \tag{2}$$

$$CI = \frac{(\lambda_{max} - m)}{(m-1)} \tag{3}$$

Table VI. Normalized pairwise comparison matrix.

Criteria	Solar irradiance	Cloud index	Temperature	Weight (%)	Ss_i
Solar irradiance	0.60	0.50	0.67	59	1.822
Cloud index	0.20	0.17	0.11	16	0.481
Temperature	0.20	0.33	0.22	25	0.767
Total	1	1	1	100	

Table VII. Consistency indices.

Consistency indices	Values
Consistency index (CI)	0.007
Random index (RI)	0.580
Consistency ratio (CR)	0.012

$$CR = CI/RI \quad (4)$$

where:
CI is the consistency index, m the matrix size, RI the random index value is according to Saaty (1987), CR the consistency ratio, which must be < 0.10 to determine consistency, and λ_{max} the maximum eigenvalue of the pairwise comparison matrix.

To finalize the methodology chapter, the weighted overlay tool in ArcGIS was employed. This tool incorporates the reclassification values (Table III) to homogenize the varying numbering ranges of the climatic criteria, considering the input values of the criteria and the electrical characteristics of solar panel technology types (Tables SIV and SV). The reclassified values are subsequently multiplied by the relative weights obtained through the AHP method for each criterion. Finally, the resulting values are summed together to generate an output raster, which is then used to create the suitability map.

3. Results

3.1 Climatic criteria maps

The technological recommendation for commercial solar panels in each climatic criterion is influenced by several factors. These include the electrical parameters of the solar panel (Tables SIV and SV), the spatiotemporal variation of the climatic criteria (Figs. 4-6), and the chosen data classification method. With these considerations in mind, the following results are obtained:

According to the solar irradiance criterion (Table III), CIGS and CdTe emerge as the most recommended commercial solar panel technologies, covering approximately 32.51 and 31.81% of Mexico's total area, respectively. Areas where CIGS and CdTe are recommended exhibit a daily annual average solar irradiance ranging from 448 to 497 W m^{-2}. The solar irradiance map (Fig. 3) allows us to identify that the states with the highest daily annual average solar irradiance include Morelos (526 W m^{-2}), Guerrero (504 W m^{-2}), and Colima (498 W m^{-2}), and the lowest values are found in Quintana Roo (421 W m^{-2}), Veracruz (430 W m^{-2}), and Yucatán (432 W m^{-2}) (for the rest of the states see the supplementary material).

Based on the temperature criterion (Table III), monocrystalline silicon is the most recommended commercial solar panel technology, covering 41.89% of Mexico's total area. Monocrystalline silicon is recommended for areas with a daily annual average temperature below 24 ºC. For the remaining areas of the country, solar panels with lower temperature coefficients are advisable. The temperature map (Fig. 4)

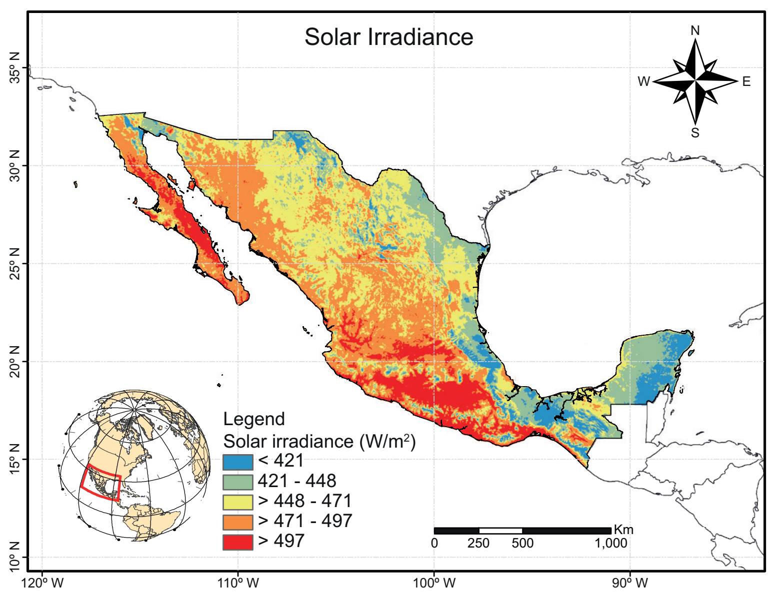

Fig. 3. Map of solar irradiance daily annual average (W m^{-2}) in Mexico, 2020.

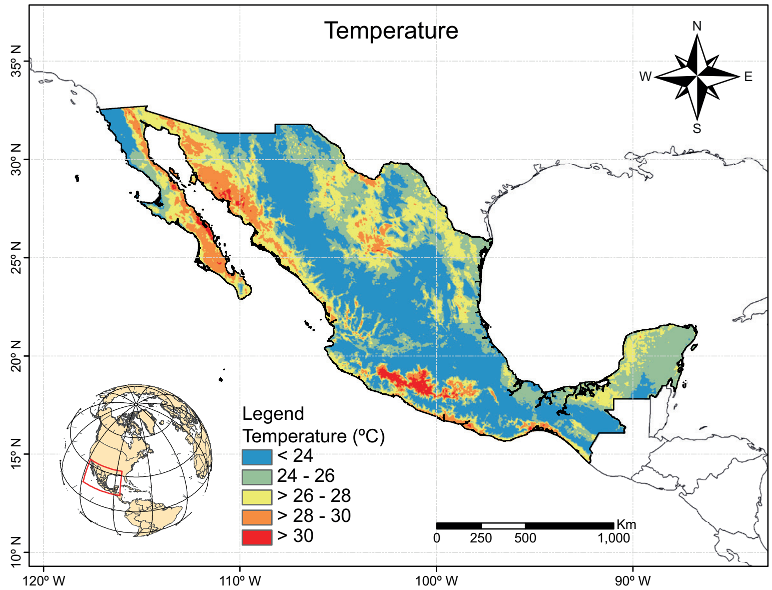

Fig. 4. Map of temperature daily annual average (ºC) in Mexico, 2020.

allows us to identify that the states with the highest daily annual average temperature are Baja California Sur (28 ºC), Sonora (27 ºC), and Sinaloa (27 ºC), and the lowest values are found in Tlaxcala (18 ºC), Mexico City (18 ºC), and Mexico State (18 ºC) (for the rest of the states see the supplementary material).

Temperature is the most significant factor affecting the degradation of electrical power delivered by solar panels. The electrical power calculated in a photovoltaic system depends on the series-parallel arrangement of the electrical connections between the panels and their quantity, determined by the required current and voltage output. Losses occurring at the point of maximum power due to temperature increases result in a reduction of this parameter, causing the actual value to decrease in comparison to the calculated one. In states with the highest average temperatures, it is advisable to use solar panels containing solar cells with lower temperature coefficient values to minimize these losses. In this scenario, amorphous silicon and CdTe solar panels are recommended due to their relatively lower temperature coefficient values. Alternatively, oversizing the photovoltaic system by increasing the number of solar panels can also be considered as a solution for other types of technology.

According to the cloud index criterion (Table III), CIGS is the most recommended commercial solar panel technology with 52.72% of Mexico's total area. CIGS is recommended for areas with a daily annual average cloud index ranging from > 0.126 to 0.161. The cloud index map (Fig. 5) allows us to identify that the states with the highest daily annual average cloud index values are Quintana Roo (0.21), Chiapas (0.20), Veracruz (0.20), and Yucatán (0.20). Conversely, the states with the lowest cloud index values are Baja California (0.11), Morelos (0.11), and Sonora (0.12) (for the rest of the states see the supplementary material).

On the other hand, in states with a high cloud index, the use of bifacial solar cells is advisable since they harness the diffuse component of light on their rear face. Bifacial solar cells based on silicon technology have shown the most promising results to date and are considered the leading technology in this field.

3.2 Suitability map

The spatial distribution of recommended solar panel technologies in the suitability map of Mexico reveals a discernible pattern (Fig. 6). Monocrystalline and polycrystalline silicon technologies, which share similar characteristics, are primarily recommended in states around the Gulf of Mexico and northern Chihuahua. These areas are characterized by a high cloud index and low solar radiation values. In

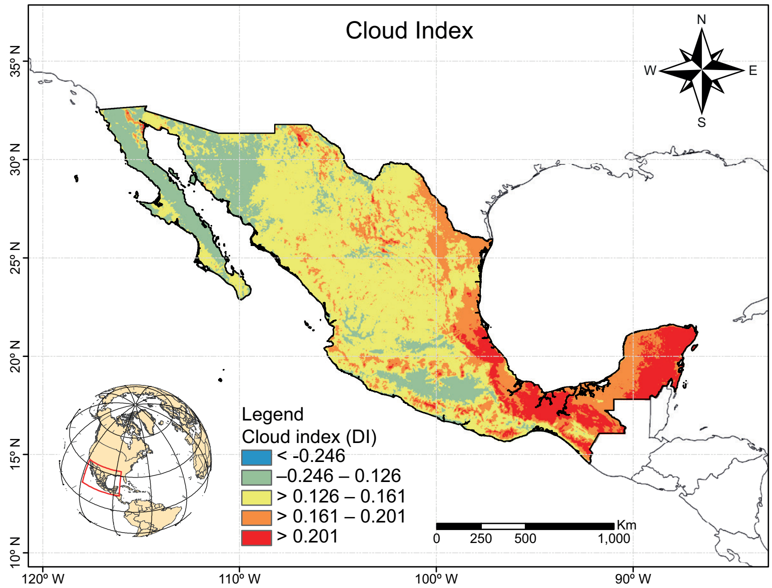

Fig. 5. Map of cloud index daily annual average (dimensionless) in Mexico, 2020.

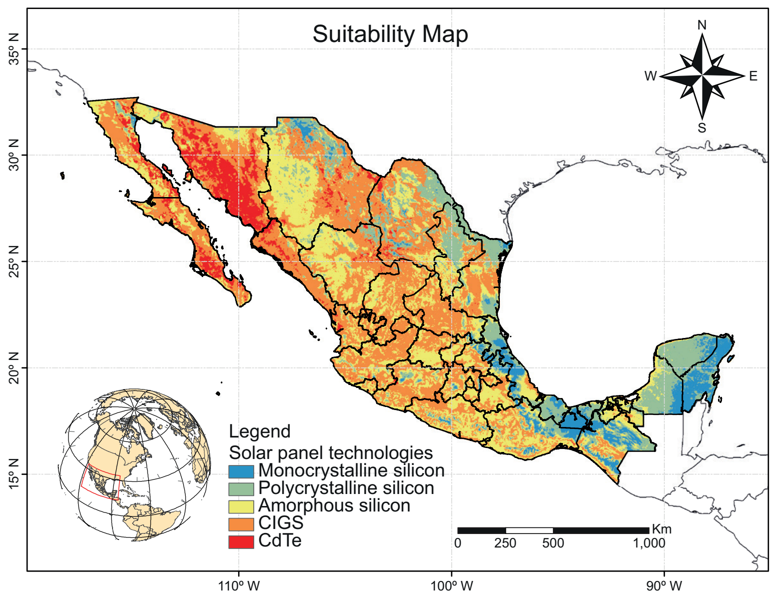

Fig. 6. Suitability map of solar panel technologies in Mexico.

contrast, CdTe and CIGS technologies are predominantly recommended in states around the Gulf of Cortés and some areas in central and northern Mexico, which feature high temperatures, low cloud index values, and high-intensity solar radiation. Amorphous silicon exhibits the most versatile distribution pattern in Mexico, making it well-suited for a wide range of climatic conditions. Complementary details on irradiance, cloud index, and temperature results in the 32 States of the Mexican Republic and experimental data of the characterization of solar panels and cells in different parts of the country can be found in the supplementary material.

According to Table VIII, CIGS and amorphous silicon are the most suitable solar panel technologies for Mexico. This determination is primarily

Table VIII. Available areas for the different solar panel technologies in Mexico.

Solar panel technology	Area (km^2)	Percentage (%)
Monocrystalline silicon	120 391	6.13
Polycrystalline silicon	320 110	16.30
Amorphous silicon	598 422	30.45
CIGS	788 436	40.14
CdTe	137 016	6.98
Total	1 964 375	100

Table IX. States with the highest solar irradiance.

State	W m^{-2}
Morelos	526
Guerrero	504
Colima	498
Baja California Sur	493
Querétaro	488
Mexico City	484

Table X. States with the highest cloud index.

State	DI
Quintana Roo	0.21
Chiapas	0.20
Veracruz	0.20
Yucatán	0.20
Campeche	0.19
Tabasco	0.19

DI: dimensionless.

Table XI. States with the highest temperature.

State	ºC
Baja California Sur	28
Sinaloa	27
Sonora	27
Colima	26
Morelos	26
Yucatán	26

attributed to how climatic criteria were classified and reclassified within the GIS process, as well as the weights estimated in the AHP methodology. It is worth noting that if an alternative method for data classification had been chosen, the results might have been different. However, given the absence of direct references from similar works in Mexico, this study represents the pioneering effort to recommend the most suitable solar panel technology for the country based on the evaluated climatic criteria.

The characteristics of the solar panel technologies analyzed in this study suggest that in areas where monocrystalline silicon is deemed suitable, polycrystalline silicon can also be a viable recommendation, and vice versa. Similarly, this holds true for CIGS and CdTe technologies. Consequently, the choice between technologies may hinge on additional factors such as available investment or market availability.

4. Conclusions

Based on the satellite analysis results in all 32 states of Mexico Republic, the average irradiance and cloud index exceed 421 W m^{-2} and 0.11, respectively. Regarding average temperature, except for Mexico City, Tlaxcala, and the State of Mexico, the rest of the states record temperatures above 20 ºC (as detailed in Table SI of the supplementary material). The states with highest daily annual average values of irradiance, cloud index, and temperature are shown in Tables IX, X and XI, respectively.

The outcomes of this study will serve as a valuable resource for guiding the selection of the most suitable solar panel technology based on the specific climatic variables in the location of a photovoltaic solar energy project.

The proper selection of solar panel technology has a direct and immediate impact on the project's investment. While there is often an inclination to opt for commercial panels with higher efficiency to maximize energy production, this study's results challenge this notion. The suitability map (Fig. 6) highlights that CIGS and CdTe are the most appropriate commercial solar panel technologies for installation in 47.12% of Mexico's territory. Amorphous silicon technology is recommended for 30.45%, while monocrystalline and polycrystalline silicon are suitable for the remaining 22.43%.

The present study has established multiple criteria based on satellite data, thus ensuring a higher degree of accuracy and reliability in the results. This approach involved excluding data from meteorological stations due to issues related to sensor calibration and deterioration. As a result, we have confidence in the precision and trustworthiness of the findings presented in this research.

The suitability map generated through the AHP-GIS methodology is directly influenced by the intrinsic characteristics of the satellite data used. In this study, data with a spatial resolution of 2 km were employed, which means that the results are more suitable for regional-scale projects. It is important to note that the suitability map provides a general idea of the type of technology that may be suitable for local projects, which can be complemented with other variables and specific aspects before making final decisions on the technology to be used.

Based on the suitability map of photovoltaic technologies, a site selection study could be conducted for specialized recycling plants that recycle solar panel materials. This would help reduce costs associated with material transportation. For instance, the suitability map shows that the state of Sonora is ideal for the use of CdTe technology, while in the states of the Yucatan Peninsula, monocrystalline and polycrystalline silicon technologies are preferably recommended. This indicates the need for recycling plants with different recycling processes. Such an approach could facilitate the strategic placement of recycling plants, optimizing resources and minimizing environmental impacts associated with long-distance material transportation. However, it is important to note that the feasibility and viability of establishing recycling plants in specific locations will depend on various factors such as infrastructure availability, local regulations, and recycling demand in the region.

Furthermore, it is recommended to update the suitability map of photovoltaic technologies annually to observe if the selection of photovoltaic technology changes due to the accelerating climate change. Additionally, it is preferable to make the study more robust each time by incorporating more climatic variables and considering other factors such as the costs associated with solar panels.

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Supplementary material

Table SI. Daily annual average of solar irradiance, cloud index and temperature in the 32 states of Mexico in 2020.

No.	State	Solar irradiance ($W m^{-2}$)	Cloud index (dimensionless)	Temperature (ºC)
1	Aguascalientes	479	0.14	23
2	Baja California	477	0.11	25
3	Baja California Sur	493	0.12	28
4	Campeche	437	0.19	26
5	Mexico City	484	0.15	18
6	Chiapas	442	0.2	22
7	Chihuahua	458	0.14	23
8	Coahuila	454	0.15	25
9	Colima	498	0.13	26
10	Durango	466	0.15	22
11	Mexico State	481	0.15	18
12	Guanajuato	494	0.14	23
13	Guerrero	504	0.14	25
14	Hidalgo	470	0.16	21
15	Jalisco	484	0.14	23
16	Michoacán	490	0.14	24
17	Morelos	526	0.11	26
18	Nayarit	484	0.14	25
19	Nuevo León	452	0.16	24
20	Oaxaca	471	0.17	22
21	Puebla	484	0.15	21
22	Queretaro	488	0.14	22
23	Quintana Roo	421	0.21	25
24	San Luis Potosí	472	0.15	23
25	Sinaloa	475	0.14	27
26	Sonora	473	0.12	27
27	Tabasco	448	0.19	26
28	Tamaulipas	454	0.16	25
29	Tlaxcala	475	0.16	18
30	Veracruz	430	0.2	24
31	Yucatán	432	0.2	26
32	Zacatecas	474	0.14	22

S1. Isolated systems and systems connected to the electrical network

According to data from the Population and Housing Count, more than 80 000 communities in Mexico with less than 80 inhabitants do not have basic services, including the supply of electricity, with the consequent decrease in the quality of life. For these localities, a program of installations of isolated photovoltaic systems is a priority.

In addition to installations with these characteristics that solve a vital social problem, isolated photovoltaic systems are successfully used in many other applications such as electronic toll and video-supervision systems, bus stops, monitoring of climatic parameters in weather and rainfall stations in remote areas, and water pumping, among others.

The systems interconnected to the electricity grid are subdivided into simple systems, such as those of houses or businesses, or complex ones, made up of microgrids. The additional element in these installations is the bidirectional meter, which measures the energy supplied by the system to the electrical network and the energy consumed by the system from the electrical network. Obviously, in systems interconnected to the electrical network, the use of batteries is eliminated, which can increase the cost by up to 30%.

Microgrids are defined as a group of interconnected loads and distributed energy sources with clearly defined boundaries that act as a single controllable entity regarding the general distribution network.

Regarding the development of electrical microgrids in Mexico, there is a strategic project to develop these facilities, based mainly on the generation of energy from renewable energy sources with a preponderant focus on the use of solar photovoltaic and wind systems (Becerra-López, 2011).

The regulations for interconnection to the electrical network of photovoltaic systems are reflected in the document CFE G0100-04 (CFE, 2008).

S2. Characterization of some photovoltaic systems, cells, and solar panels in Mexico

The electrical characterization of monocrystalline silicon photovoltaic solar panels manufactured in Mexico that comprise an installation connected to the low-voltage power grid with a nominal power of 3 kW in the city of Mazatlán, Sinaloa, was reported. The results showed an 18% loss in the electrical power delivered by the panel regarding the nominal value given by the manufacturer, while the losses of the same parameter due to the inclination and orientation of the solar panel were within 10% (Mejías-Brizuela et al., 2017).

A study on the electrical characteristics of solar panels made of monocrystalline, polycrystalline, and amorphous silicon, as well as CdTe thin-film was carried out in the north of Mexico City, measuring the average temperature and insolation over a period of seven months. The results of the measurements are shown in Tables SII and SIII.

A study of the behavior of three crystalline, polycrystalline, and amorphous silicon photovoltaic panels with nominal efficiencies of 18, 14 and 13% was carried out in Altamira, southeast of the state of Tamaulipas, in the period between August 2014 and June 2015. From the results it was concluded that the monocrystalline silicon panel showed the best performance. Cloudiness was the parameter that had the

Table SII. Comparison between temperature coefficients of the electrical parameters for photovoltaic panels fabricated with different technologies.*

Electrical parameters	Polycrystalline silicon	Monocrystalline silicon	Amorphous silicon	CdTe
Voc	– 0.52	–0.40	–0.49	–0.43
Pmax	– 1.05	–0.64	–0.33	–0.56
FF	– 0.33	–0.25	0.26	0.02
Efficiency	–1.05	–0.66	–0.33	–0.55

*Coefficients were calculated at a fixed solar radiation of 82.5 W cm^{-2} and module temperatures between 25 and 42 ºC. The coefficients are expressed in % $ºC^{-1}$ (Paudyal and Imenes, 2021).

Voc: voltage open circuit; Pmax: maximum power rating; FF: fill factor.

Table SIII. Temperature coefficients for the panels maximum power, expressed in W $ºC^{-1}$ (Jiménez-Olarte, 2012).

Electrical parameters	Polycrystalline silicon	Monocrystalline silicon	Amorphous silicon	CdTe
Pmax (W $ºC^{-1}$)	–0.64	–0.23	–0.10	–0.22
(% of loss with respect to 25 ºC)	21	13	6	11

Pmax: maximum power rating.

greatest impact on panel performance, followed by solar irradiance and temperature (Saleme-Vila, 2016). A comparative study of monocrystalline silicon bifacial solar cells in vertical and inclined configurations was also carried out in Altamira for six months in 2021, comparing both configurations with a standard monofacial solar cell of the same material. The results in Figure S1 show that bifacial solar cells installed in an optimal tilt angle to the south produce, on average, 26% more daily energy than tilted monofacial solar cells, while vertical bifacial solar cells produce a similar energy to inclined monofacial cells, but with a better energy distribution coupled to the hours of greatest energy consumption.

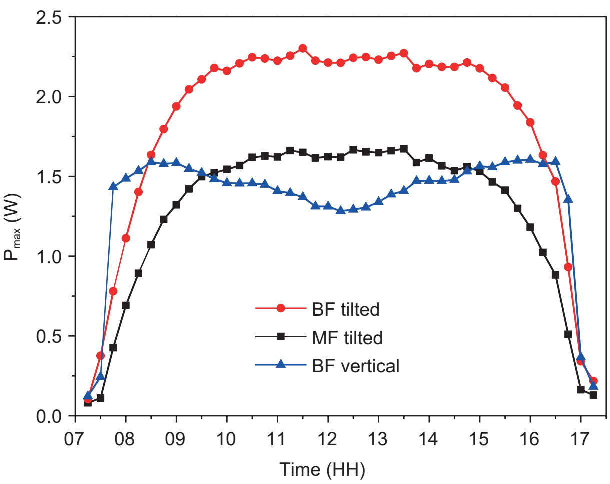

Fig. S1. Measured power profile of the three test cells: bifacial titled, monofacial titled, and bifacial vertical.

This result corroborates those reported by other authors in different environmental conditions.

A prototype of a solar tracker was designed with metallic materials that resist weathering, which allows comparing a solar cell that follows the relative path of the sun with respect to the earth with that of a fixed cell. The average daily power values were measured in Mexico City and Altamira, Tamaulipas. The typical power generated by the cell in the solar tracker and by the fixed cell depending on the time of day in the city of Tampico, Tamaulipas is shown in Figure S2 (Rojas-Lozano et al., 2019).

The monitored solar cell generates 38.3 and 39.6% more daily power than the fixed one in the cities of Tampico and Mexico, respectively. Furthermore, for low irradiance values (at dawn and dusk) the power delivered by the tracking solar cell can be up to six times greater than that of the fixed cell.

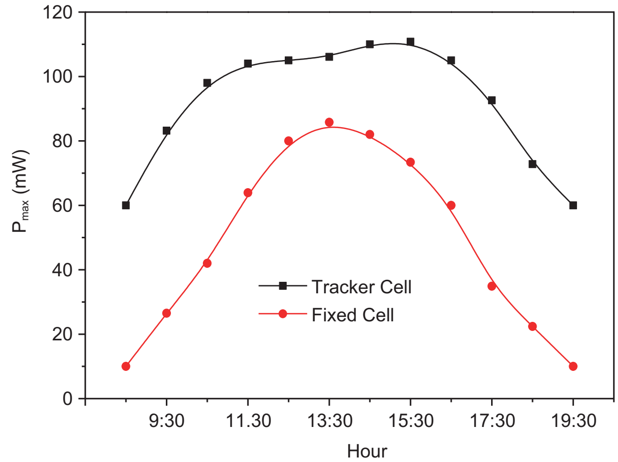

Fig. S2. Typical power generated by the monitoring cell and by the fixed cell depending on the time of day in the city of Tampico, Tamaulipas during a sunny day.

These results of the in-situ study of solar panels and cells in different regions of Mexico are necessary to guide the choice to install one type of photovoltaic solar cell technology, but it is insufficient to establish the criteria of which type of technology is the most appropriate depending on the climatic conditions of a chosen region.

Parameters such as solar radiation, temperature, relative humidity, dust, and the brightness index of insolation have been selected as climatic criteria for studies to determine the suitability of photovoltaic solar installations (Al Garni and Awasthi, 2018). The climatic criteria followed in this work were irradiance, cloud index, and temperature.

S3. Efficiency of the available solar cell technologies

The efficiency (%) of a panel is effectively calculated by dividing the maximum power rating or Pmax (W) at standard test conditions (STC) (irradiance: 1000 W m^{-2}, 25 ºC) by the total panel area measured in meters squared.

$$Efficiency(\%) = \frac{P_{max}}{Area \times 10^3\ W\ m^{-2}} \times 10$$

In environmental terms, higher efficiency generally means that a solar panel will recover the embodied energy (the energy used in the extract and synthesis of the raw materials of solar cells used to make the solar panel) in less time. Based on a detailed life cycle analysis, most silicon-based solar panels recover the embodied energy within 2 years, depending on the place where the installation occurs. When the panel efficiency is increased beyond 20 %, the payback time is reduced to less than 1.5 years in many locations. Higher efficiency also means that a solar system will generate more electricity over an average solar panel lifetime of 25 years and recover the initial cost sooner, meaning the return on investment (discussed later) will improve even more. Table SIV shows the most efficient solar panels fabricated with different technologies.

Table SIV. Reported values of the most efficient commercial solar panels in 2022 (Green et al., 2022).

Technology	Efficiency (%)
Monocrystalline silicon	24.4
Polycrystalline silicon	20.4
Amorphous silicon	12.3
CIGS	19.2
CdTe	19.5

Note: better efficiency does not always equivalent to better panel quality. In addition to efficiency, reliability, performance, and return on investment must be considered.

Table SV. Loss of output power with respect to maximum power (Virtuani et al., 2010).

Technology	Power loss (% ºC^{-1})
Monocrystalline silicon	–0.50
Polycrystalline silicon	–0.41
Amorphous silicon	–0.33
CIGS	–0.23
CdTe	–0.22

S4. Return on investment in the installation of a photovoltaic system

This economic concept is of great importance in the installation of a photovoltaic system.

Article 34 of the Mexican Income Tax Law establishes in section XIII a 100 % deduction for machinery and equipment used in the generation of energy from renewable sources or efficient electricity cogeneration systems. This means that the cost of the components and installation of a photovoltaic system is completely tax deductible. Considering that the benefits acquired with a solar panel system are for savings and not for income, this is very relevant since the savings are not subject to taxes.

Let us consider a daily consumption of 10.5 kW h^{-1}, and a photovoltaic day of 5 h with solar panels of 200 W (1 kW h^{-1}). To satisfy the energy consumption of 10.5 kW h^{-1}, 11 solar panels are needed (2200 W). For a useful 25-year life of the solar panels, the energy delivered by the 11 panels of 200 W should be 220 × 11 × 5 h × 356 days × 25 years = 110 412 kW h^{-1}. The electrical energy delivered monthly would be 110 412 × 300 = 368 kW h^{-1}. At a rate of 1.35 MXN per kW^{-1}, which is the rate of the Compañía Federal de Electricidad (Mexico's state-owned electricity company) the cost per consumption would be 368 × 1.35 = 496.8 MXN.

Considering an offer of 40 MXN per installed Watt (turnkey), the 2200 photovoltaic W would cost 88 000 pesos; therefore, the payback time of the investment is: 88 000 × 496.8 MXN = 177 months = 14.8 years.

As can be seen, the time is excessively long to promote a policy of incentives for photovoltaic system installations. Therefore, the government must establish mechanisms to reduce the investment recovery time. For example, the price of the injected watt by local photovoltaic systems connected to the electrical network should be the same as the watt consumed.

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