PROJECT, DESIGN AND MANAGEMENT

ISSN: 2683-1597

PROJECT DESIGN & MANAGEMENT

How to cite this article:

Cruz Arellano, M. & Castillo Tellez, M. (2021). Approach of a descriptive energy model applicable to the installation of grid-interconnected solar photovoltaic systems through distributed generation: case study in Nuevo Laredo. *Project, Design and Management, 3*(1), 112-137. doi: 10.29314/pdm.v3i1.587

PROPOSAL OF A DESCRIPTIVE ENERGY MODEL APPLICABLE TO THE INSTALLATION OF SOLAR PHOTOVOLTAIC SYSTEMS INTERCONNECTED TO THE GRID THROUGH DISTRIBUTED GENERATION: CASE STUDY IN NUEVO LAREDO

Martin Cruz Arellano
Universidad Internacional Iberoamericana (Mexico)
mcruzautnl@outlook.com - https://orcid.org/0000-0003-0623-5217
Margarita Castillo Tellez
Universidad Autónoma de Campeche (Mexico)
mcastill@uacam.mx - https://orcid.org/0000-0001-9639-1736

Abstract. World energy consumption continues to increase due to population growth and technological development; however, 73 % of the energy used comes from fossil sources highly polluting for the planet, whose world reserves are being rapidly reduced. Using at least a smaller percentage of renewable energy could mitigate global warming and climate change and ensure global energy sustainability. Aware of this national and global problem, a descriptive energy model is proposed that methodologically includes the steps to follow to determine the viability of installing photovoltaic solar systems in any region of the world, through the analysis of the renewable energy resource available, of the environmental and electrical variables and, human, material and financial resources. The proposed model is developed and designed to collect, integrate, and analyze various sources and research work related to the joint subject as a comprehensive system that graphically displays and describes the information blocks to be obtained. As a particular case study, the model is applied in Nuevo Laredo, concluding that the necessary conditions exist to install photovoltaic systems. The measurement of variables in situ using special instruments and those obtained from databases or special software is considered. They are analyzed and compared with standards, manufacturer specifications, regulations, and reference parameters, making it possible to determine the region's viability to install photovoltaic solar systems. Finally, the application of the model requires preparing a technical report of the results obtained.

Keywords: photovoltaic system, distributed generating, energetic model, solar radiation, meteorological variables.

PLANTEAMIENTO DE UN MODELO ENERGÉTICO DESCRIPTIVO APLICABLE A LA INSTALACIÓN DE SISTEMAS SOLARES FOTOVOLTAICOS INTERCONECTADOS A LA RED MEDIANTE GENERACIÓN DISTRIBUIDA: CASO DE ESTUDIO EN NUEVO LAREDO

Resumen. El consumo de energía a nivel mundial continúa incrementándose debido al aumento demográfico y desarrollo tecnológico, sin embargo, el 73 % de la energía utilizada proviene de fuentes fósiles altamente contaminantes para el planeta y cuyas reservas mundiales se reducen aceleradamente, utilizando únicamente un porcentaje menor de energías limpias o renovables que mitiguen el calentamiento global, el cambio climático y aseguren la sustentabilidad energética mundial. Conscientes de esta problemática nacional y mundial, se propone un modelo energético descriptivo que incluya metodológicamente los pasos a seguir para determinar la viabilidad de instalar sistemas solares fotovoltaicos en cualquier región del mundo, mediante el análisis del recurso energético renovable disponible, de las variables medioambientales y eléctricas y, de los recursos humanos, materiales y financieros. El modelo propuesto se desarrolla y diseña mediante la recopilación, integración y análisis de diversas fuentes y trabajos de investigación relacionados al tema, conjuntado como un sistema integral que muestra gráficamente y describe los bloques de información que deben considerarse. Como un caso particular de estudio el modelo se aplica en Nuevo Laredo, para demostrar que existen las condiciones necesarias para instalar sistemas fotovoltaicos. Se considera la medición de variables in situ mediante instrumentos especiales y las obtenidas de bases de datos o software especial, se analizan y se comparan con normas, especificaciones de fabricantes, regulaciones y parámetros de referencia, lo que permite determinar la viabilidad de la región para instalar sistemas solares fotovoltaicos. Finalmente, la aplicación del modelo requiere elaborar un reporte técnico de los resultados obtenidos.

Palabras clave: Sistema fotovoltaico, generación distribuida, modelo energético, radiación solar, variables meteorológicas.

Introduction

Currently, world energy consumption has had a growth of 13,975 Mtoe, where 73% comes from fossil sources and 27% from renewable energies (ENERDATA, 2020), reaching a world energy consumption increase of 2.35% in 2018 (World Energy Markets Observatory, 2019), and in Mexico at the beginning of 2018 there were only 6,464 million barrels of oil as proven reserves (Kühne et al., 2019), which are enough for 9 years according to current consumption. Additionally, the increase in the cost of electricity tariffs over the last 10 years (Flores Contreras, 2018, p. 32), makes it necessary to look for electricity saving alternatives that reduce consumption and CO_2 emissions.

Under these conditions, although some countries in various regions of the world are already implementing programs that contribute to energy sustainability and sustainability through renewable energies, there is still much area of opportunity, particularly in Mexico due to its high levels of solar radiation throughout its territory according to data from the Geographic Information System for Renewable Energy in Mexico and the Solar Radiation Observatory of the Institute of Geophysics of the UNAM (Institute of Electrical Research, 2010). Observing irradiation values in most of the states above 5 kW/m^2 reaching maximum values of 6.89 kW/m^2, reflecting the large amount of solar resource available during most of the year. This competitive advantage of Mexico motivates the generation of electric energy through the implementation of distributed generation photovoltaic solar systems.

In addition, "grid parity" has now been achieved, which means that photovoltaic systems (PVS) are economically and environmentally competitive and superior to conventional energy production systems.

Global warming, environmental pollution, and the growing need for energy demanded by the regions due to population growth and technological development, forces the search for solutions that ensure its availability at competitive prices. Particularly the case of Nuevo Laredo, located in the region of the Burgos basin, where there are large deposits of gas and oil, which to extract it the companies demand a great amount of energy and motivates the development of this type of studies. For this reason the government of Tamaulipas is very interested in training highly qualified human capital to carry out studies and energy projects, provide energy to companies that could be installed in the city with the objective of extracting these resources from the subsoil.

As an answer to the described problem, the development of a descriptive energy model is proposed to determine the feasibility of installing, interconnecting to the grid, and optimizing distributed generation PV systems in any region of the world. This is achieved by analyzing the input/output variables of PV systems with capacities from 1 kW and less than 0.5 MW, identifying the types of photovoltaic (PV) installations, considering the sizing of components, materials, and PV equipment, as well as human, material, and financial resources and the applicable specifications and regulations.

There is currently no methodology that encompasses and describes in a single block the most relevant aspects considered in PVS design, even though there is information from various sources such as studies, projects, technical reports, theoretical models, doctoral theses, and other sources on related topics. Most of them deal with specific topics without a global vision of the factors involved, which makes it possible to exclude important variables or aspects that should be considered, since omitting them would result in an incomplete final design that would affect the operation of the PV system.

Table 1 mentions research works taken as a reference and describes the additional aspects considered in the proposed energy model that are not addressed in these works and that are relevant to consider in the design and commissioning of distributed generation interconnected PV systems (IPVS).

Table 1

Comparison of benchmark studies and the model proposed in this study

Reference models and studies	Problems they address	Additional aspects addressed by the proposed model
Sustainable energy planning model using multi-criteria optimization techniques (Falcón Roque, 2018).	Energy planning of a region with renewable energies applying multi-criteria techniques and considering universal access to energy in isolated rural communities, taking into account economic, social, and environmental aspects, formulating abstract analyses through objective functions to maximize the use of renewable energies over those coming from fossil resources, reducing polluting emissions, minimizing costs, and suggesting the best renewable source for a certain region.	The proposed model considers the analysis of the renewable resource and local environmental variables, whose assessment determines whether or not it is feasible to install renewable energy systems in the region. The energy planning model analyzes in a general way different types of renewable energy resources in the region, emphasizing technological, application, planning, and environmental aspects without considering in situ measurements or detailed and comparative analysis of each variable that affects energy generation according to the available energy resource.
The study "Solar photovoltaic energy, competitiveness and economic evaluation, benchmarking and modeling" (Collado Fernández, 2009).	It analyzes in general terms the current state of solar photovoltaic energy in the world: installed capacity, demand, generation, its contribution to greenhouse gas reduction, regulatory framework, costs vs. gas-based energy, users, and return on investment.	In addition to these aspects, the proposed model considers the detailed analysis of each variable in the region that affects the generation of the PVS, which allows determining the feasibility of its implementation.
The study "Contribution to the integration of grid-connected photovoltaic systems: solar resource and generation output" (Masa Bote, 2014).	Analyzes the prediction of electric power generation in the integration of photovoltaic systems in buildings in urban environments in comparison with centralized systems, considering shading effects and weather prediction models.	The reference model focuses mainly on the analysis of losses due to shading and analyzes radiation, the effect of temperature and the efficiency of the inverter in the generation of electricity, without considering other variables such as wind speed, humidity, precipitation, applicable regulations, and other human, material, and financial resources that are included in the proposed model.
The study "Feasibility analysis for the installation of a clean energy system by means of photovoltaic cells for power supply of building 4 at ITSLV" (Hernández Gallegos, 2017).	To analyze the feasibility of installing a clean energy system using photovoltaic cells to supply electricity to building 4 of the Instituto Tecnológico Superior de la Venta, in order to reduce electricity billing costs, considering the types of photovoltaic cell technologies, energy consumption, available space, and cost-benefit.	Although the baseline study includes aspects indicated in the proposed model, it does not make reference to the detailed analysis of some environmental variables that affect the generation of the PVS such as humidity, rainfall, and hail, but rather emphasizes on the cost benefit of the PVS as a whole. Although it points out aspects of wind speed, it does not make reference to manufacturers' specifications that must be met to ensure continuous operation of the PVS, as indicated in the proposed model.

Note: Source: Own elaboration.

Method

Design

The design and development of the energy model was defined through conceptual research, studies, measurements, and analysis of PV projects, integrating all this information into a single functional block. The model relates various aspects and input/output variables involved in the generation of PV electric energy, describing how each variable affects the PV generation process, allowing to reduce the effects and improve the overall efficiency of the PV system.

The orderly and methodological application of the model allows obtaining, plotting, analyzing, and comparing the values of the variables of the region under study, with the applicable standards and the specifications of PV component manufacturers, including the sizing of such components and interconnection regulations.

The model methodology involves preparing a technical report with the results obtained, which allows inferring whether or not it is feasible to install PVS in a particular region, or if it is possible to optimize the generation of energy from PVS in case it is operating.

As a particular case, the model is applied to demonstrate that in Nuevo Laredo, Tamaulipas, Mexico, the solar resource, meteorological parameters, and other components included in the model, are adequate to install distributed generation PVS, also promoting the use of renewable energy and mitigating the environmental pollution of the city, due to the daily crossing between Mexico and the United States of more than 12,930 cargo trucks (Duarte, 2017) that consume highly polluting diesel. Nuevo Laredo is located on the southern bank of the Rio Bravo border boundary between Mexico and the United States of America, with 405,000 inhabitants according to the 2018 census. The climate is the driest and most extreme in the state, an average annual temperature of 22.6 °C with large oscillations ranging from 2.5 °C in winter, to 40.50 °C in summer; its average annual rainfall is 472.5 mm and the prevailing winds come from the south.

For the study, two PV systems are considered, one of 3 kW and the other of 4 kW located in different parts of the city; both PV systems use polycrystalline technology and central inverters of the mentioned capacities.

Participants.

The human resources, composed of research professors, students, and through the support of some government agencies to provide information and private owners of the PVS used in the study. Additionally, the facilities of the Universidad Tecnológica de Nuevo Laredo to perform tests on the PVSs and measurements with laboratory equipment.

Instruments.

The variables defined in the model are collected using ad hoc formats and tested with the instruments shown in Table 2:

Table 2
Instruments for data collection

Equipment	Description	Operating range
Use of ad hoc tables or existing official formats.	For the collection of data measured in situ and those obtained from software or databases.	Applicable to all variables.
Two PVSs used as samples.	With polycrystalline technology, for on-site measurement of electrical input/output variables.	PVS of 3 kW and 4 kW.
Fluke Multimeter.	For voltage and electric current measurements.	CAT III, 600V, ACV ± (1.0 %+3), DCV ± (0.5 %+2).
Solar radiation meter.	Amprobe Solar-100 model.	Range: 1999 W/m2; accuracy ± 5-10 W/m2; resolution 0.1W/m2.
Fluke 434-II Power Quality Analyzer (ACE-Fluke 434-II).	To measure the variable harmonic distortion, power, and electrical energy generated by the PVSs.	Accuracy: Voltage: 0.5 % of rated voltage, Current: 0.5 %, Power: 1 %, Frequency: 0.01 Hz).
Weather station.	Model PCE-FWS 20 with remote data access from a PC.	Resolution 0.1 ºC (0.2 ºF); temperature range -40 ºC - +65 ºC, wind speed range 0 - 240 km/h (0 ~ 100 mph).

Note: Source: Own elaboration.

Data analysis

The data of each variable measured in situ are plotted for comparative analysis and interpretation, observing monthly and annual trends, inferring the degree of affectation in the generation of PVS and proposing actions for improvement of the system under study, the analysis allows:

a. Observe trends, behaviors, averages, ranges, and limits.

b. Establish comparisons with applicable standards and manufacturers' specifications to optimize the PVS.

c. Suggest improvement actions, proposing equipment and materials that will withstand the climatic conditions of the region, ensuring a good performance during the PVS's useful life.

d. Issue recommendations or redesign the PVS to operate optimally.

Variables

The variables described in the model are analyzed and plotted to determine their impact on PV generation, the data obtained with measurement instruments and those obtained from official sources such as RetScreen, Meteonorm, CONAGUA, or other sources available on the internet, are recorded in ad hoc tables.

The variables defined in the model are of the quantitative type (Hernández Sampieri et al., 2010), multiple measurements are taken at various times, being analyzed graphically to know their impact and take actions to optimize PV generation, as mentioned in related studies (Caamaño Martín, 1998) and (García Barrios, 2018). Similar studies analyze environmental variables and their effects on PVS (Vigil Galán et al., 2018).

PVS input variables

These are meteorological and solar irradiation variables available in the region under study, analyzed during the design stage of the PV system to know their tendency and that can be determinant to install PV systems in a certain location, refer to Table 3.

Table 3
Photovoltaic system input variables

a. Solar irradiance (G) measured in kWh/m^2, a quantitative and continuous independent variable.
Daily on-site average measurements are obtained by the Apsystem monitoring system from two sample PVSs used during the 12 months of the year and monthly average data from other sources such as RetScreenExpert and Meteonorm V7.1, the average determines whether the region has sufficient solar radiation to ensure optimal PV generation.
b. The ambient temperature (T) measured in °C, a continuous quantitative independent variable.
Daily average measurements are obtained in situ during the 12 months of the year from a meteorological station and from the meteorological station of the Nuevo Laredo International Airport (EMAINL) during a period of 20 years of monitoring. The average of the T measurements is obtained, and the minimum, average, and maximum values are compared to infer the degree of affectation in the generation of PVS.
c. Wind speed (WS) measured in km/h, a continuous and independent quantitative variable.
Daily average measurements taken in situ during the 12 months of the year are obtained from a meteorological station and from the EMAINL during a period of 20 years of monitoring, the average of the WS measurements is obtained, the minimum, average, and maximum values are compared to suggest the degree of robustness that the mounting structures of the PV modules (PVM) should have, and the resistance to wind loads that the PVM installed in the region should withstand.
d. Relative humidity (RH) measured in percent, independent variable.
Daily average measurements taken in situ during the 12 months of the year are obtained from a weather station and from data obtained from the national meteorological system in monthly averages, which are averaged and compared to determine their degree of dispersion. High RH values imply premature corrosion and greater affectation by potential-induced degradation (PID), caused by moisture seepage inside the encapsulation reducing PVS performance by up to 30% in the medium term (Sol Energy, 2018). In places where RH is high, it is recommended to use anodized aluminum structures and PVM approved in PID.
e. Atmospheric pressure (Pa) measured in hPa, a continuous and independent quantitative variable.
Daily average measurements taken in situ during the 12 months of the year are obtained from a meteorological station and from the EMAINL, and the average values are compared to infer possible effects on the PVS performance caused by humidity. Pressures lower than the typical local pressure cause storms and consequently increase humidity, affecting the PVS.
f. Pluvial precipitation (PP), variable measured in mm.
Daily average measurements taken in situ during the 12 months of the year are obtained from a weather station and from the EMAINL, averaged and compared graphically to determine the precipitation levels to recommend the most suitable type of PID PVM, since high rates imply higher humidity and consequently greater possibilities of filtration and corrosion. However, there is also a greater natural cleaning of the PVM reducing the frequency of maintenance due to the accumulation of dust or other debris.
g. Hail and snow (HS), independent variable measured in number of events per year.
Its analysis determines the frequency of occurrence of this phenomenon, which allows the use of PVMs that comply with the IEC 61215 ed.2 standard and avoid irreparable damage.
h. Peak solar hours (PSH), variable measured in h.
The PSH (Pérez Martínez et al., 2017) is a variable obtained from the solar irradiance of the region divided by the standard test value of the PVMs (STC) equivalent to 1,000 W/m^2. Multiplying the PVS capacity by the PSH of the region yields the daily electric power production.

Note: Source: Own elaboration.

PVS output variables

The values are obtained when the PVS is operating, their analysis allows adjustments to be made for optimum performance. These variables are shown in Table 4 indicating their units of measurement, the monitoring period, the source of the measurements, and providing a brief explanation on the interpretation, analysis, and use of the data.

Table 4
Photovoltaic system output variables

a. The generated voltage measured in Volts (V), corresponds to daily measurements taken in periods of 15 minutes during a week.
Variable measured at the point of common coupling (PCC) of the PVS and the network using a multimeter or an ACE-Fluke 434-II. It is verified that the V_{AC} level is within the distortion specifications indicated by the standard for interconnected PVS. The V_{DC} corresponds to the generated voltage measured at the PVM terminals.
b. The generated current measured in Amperes (A), variable measured daily in 15-minute periods during one week.
It is measured at the PCC of the PVS and the network by means of an ammeter or an ACE-Fluke 434-II. It is verified that the I_{AC} signal demanded by the loads is within the harmonic distortion limits allowed by the applicable standard. The I_{DC} corresponds to the generated current measured at the terminals of the PVMs.
c. The electrical power generated (P), measured in Watts (W), corresponds to daily measurements taken in periods of 15 minutes during a week.
Variable measured at the PCC of the PVS and the grid using an ACE-Fluke 434-II. It is verified that the power generated corresponds to the PVS capacity.
d. The electrical energy generated (EE) measured in kWh, corresponds to daily measurements taken in 15-minute periods during a week.
Variable measured at the PVS PCC and the grid using an ACE-Fluke 434-II. The power delivered by the PVS will depend on the loads connected to the circuit, checking that the PVS delivers the electrical power according to the design capacity.
e. The total harmonic distortion (THD) measured in percentage, corresponds to daily measurements taken in periods of 15 minutes during one week.
Variable measured at the PCC of the PVS and the network by means of an ACE-Fluke 434-II, an important parameter that must comply with the applicable standards according to the country, which for Mexico is CFE L0000-45.

Note: Source: Own elaboration.

Results

The design and development of the energy model is based on a series of functional blocks composed of solar irradiation, climatological and electrical variables, sizing of PV components, applicable regulations, manufacturers' specifications, types of users, human, material, financial and technological resources, all compiled from various bibliographic sources and integrated into a single schematic diagram of information shown in Figure 1.

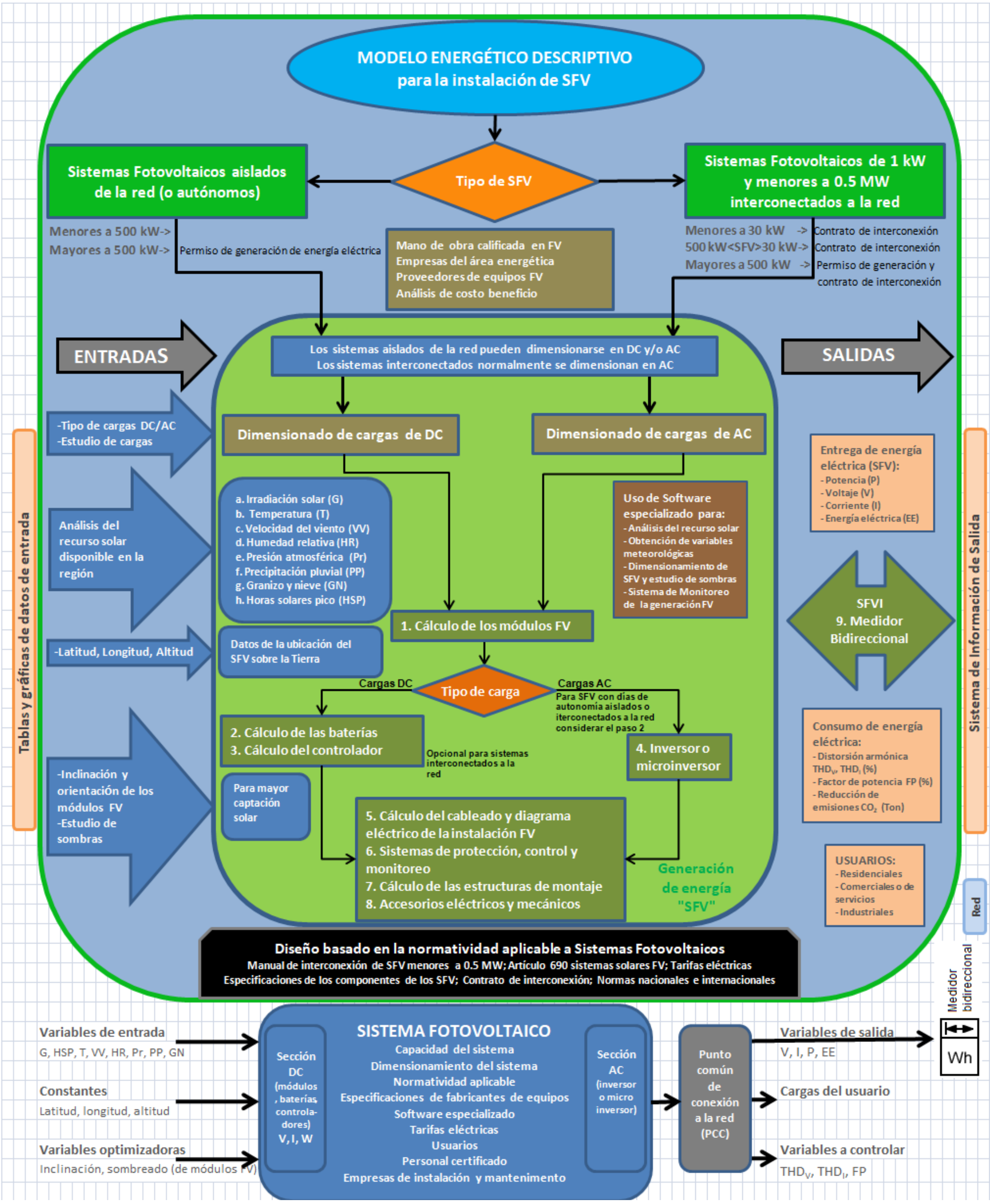
The model developed in addition to considering the analysis of input/output variables, also includes the study of other complementary aspects such as government regulations for grid interconnection, allowing a complete view of the inherent aspects that affect and/or benefit PVS performance coinciding with the study (Masa Bote, 2014) and complementing with the analysis of additional variables such as WS, RH, Pa, and PP.

Through the methodological application of each block and analyzing the trend of the variables referred to in the model, it can be inferred whether the region under analysis located anywhere in the world meets the necessary and sufficient conditions to install PV systems to the distributed generation network. This allows for improvement actions to be taken to the PV systems in operation if the results show vulnerable conditions that were not considered during the design stage of the system or due to the premature degradation of its components. Each block can be broken down according to the flow diagram in

Figure 2 and existing calculation tools or software can be used to facilitate the analysis of the PVS. The function of the main blocks of the proposed model is described in the following sections.

a. Block description of the descriptive energy model

Figure 1 shows all the blocks involved in the solar photovoltaic electric power generation process, describing the function and impact of each one. It is important to point out that the correct application of the model implies considering the analysis of all the blocks avoiding omitting any of them, allowing to obtain a complete result that reflects the reality of the energy conditions of the region and/or the current PV system, which will determine the feasibility of installing new PV systems, or allow improvements to the existing ones.



Descriptive model of a grid-connected solar photovoltaic energy system.
Note: Source: Own elaboration.

b. Type of photovoltaic system

There are two relevant characteristics in every PVS depending on its connection to the installation that will feed the user's loads, being necessary to define whether the system will be autonomous or interconnected to the grid, since the components and sizing of the PVS will be different depending on each case.

c. Skilled labor, companies, and PVS suppliers

The methodology establishes the importance of having specialized labor in the installation of PV systems, and it is convenient to check the availability of certified personnel in the region. Likewise, the local existence of installation service companies or suppliers of PV equipment and materials is relevant in order to obtain a better cost-benefit and post-service during the operation of the PV system and to facilitate the application of guarantees.

d. Use of specialized software

Although the model establishes the measurement of variables in situ, it also considers the use of historical data of these variables obtained from a database using free or licensed software, allowing averages to be obtained between these values and those measured in situ, which is why the model's methodology refers to their use.

e. PVS sizing in alternating current and direct current (AC/DC)

The PV design in commercial, industrial, or residential applications must consider DC or AC loads, since if only DC loads will be fed, it is not necessary to install an inverter because they can be connected directly to the DC circuit. If the PVS will feed AC loads, the inverter must be sized correctly. Using software or manual calculations, the PVS components are sized as listed in Figure 1 (modules, batteries, controller, inverter, wiring, protection systems, electrical and mechanical structures, and accessories).

f. Design based on the regulations applicable to PVS

This block highlights the importance of designing PV systems in accordance with the applicable standards according to the region or country where they will be installed, including both national and international standards applicable to equipment, materials, the level of distortion allowed for electrical variables, including the personal safety standards that must be observed when installing the PV system. The consideration of all applicable standards ensures reliability and functionality of the project, facilitating the registration and connection to the PV system network by complying with all the requirements required by governmental agencies.

g. PVS location data on the Earth (latitude, longitude, and altitude)

It is important to define the place where the VFS will be installed, being necessary to know the geographic coordinates of the place defined by latitude, longitude, and altitude. Particularly for Nuevo Laredo we have the following values:

North Latitude: 27º29'48" (27.43º),

West Longitude: 99º30'01" (-99.56º),

Altitude=138 meters above sea level (masl).

These three parameters are constant values used to locate a point on Earth; however, for the exact choice of the location either at ground level, on the roof, or on facades, it implies considering other factors described in section h.

h. For greater solar gain

The model suggests considering the main variables that affect the capture of solar radiation during the operation of the PVS, some of them being the inclination of the PVM according to the season of the year and user needs, and the orientation towards the south for systems located in the northern hemisphere or oriented towards the north for PVS located in the southern hemisphere.

Another variable that affects the collection is the projection of shadows on the PVM, being necessary to carry out a shadow study to analyze possible affectations. Specialized software is available to estimate the losses caused by shading of the PVMs, in case they cannot be completely avoided due to physical obstacles such as buildings or trees.

i. Type of users

Considering that this research refers to the study of PV systems with capacities of less than 0.5 MW of distributed generation, it is important to distinguish that the largest market of users for the installation of PV systems comes from residential users and small or medium-sized businesses. For this reason, government support programs to promote renewable energies should be focused according to the type of users to which they are directed.

j. Analysis of solar resource and meteorological variables

This relevant block of the model includes the data collection and analysis of each variable of the region under study as indicated in the flow chart in Figure 2, particularly exemplified for Nuevo Laredo.

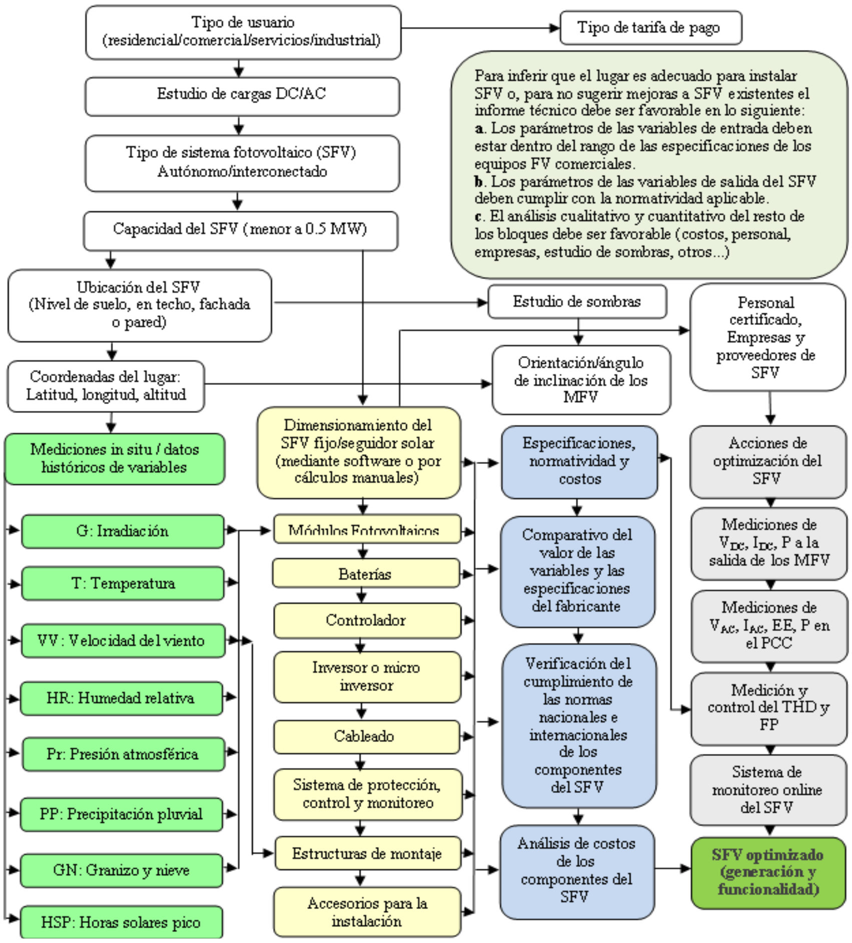


Figure 2. Flow diagram of a grid-connected PV energy system.
Note: Source: Own elaboration.

j1: Solar irradiance (G)

Obtaining this variable according to the methodology described in previous sections shows that Nuevo Laredo has an average irradiation of 4.81 kWh/m^2 during the year, exceeding this value in the months of May to August with values of up to 5.19 kWh/m^2 according to (Electric Research Institute, 2010).

Figure 3 shows the solar irradiation values measured in situ and those obtained using the RETScreen and Meteonorm software in monthly averages, showing a data range of 0.70 kWh/m^2 during the 12 months of the year. Figure 3 shows the congruence of the data from the sources referred to, which can be used to calculate PVS production, reaffirming the great potential for global and diffuse radiation and albedo in the region (De Juana Sardón et al., 2009).

Figure 3 also shows solar radiation readings taken in situ during the 12 months of the year under clear to slightly cloudy sky conditions, using the Amprobe Solar-100 meter. Average values of 940 W/m^2 and 1,163 W/m^2 measured at 27° and perpendicular to the sun respectively were observed, higher than the STC (standard test conditions) parameter of 1,000 W/m^2 used by manufacturers to test the efficiency of the PVMs and a NOCT (nominal operating cell temperature) of 800 W/m^2 (Messenger and Ventre, 2005).

In regions with high solar irradiation, cells with medium performance and affordable cost technologies can be used (Vigil Galán et al., 2018), still maintaining high levels of generation motivating local investment in PV projects by installing PVS with good performance and of lower cost. PV technologies with high yields are more expensive and are recommended in places with low levels of solar irradiation.

To install stand-alone PVSs, an average solar radiation of 3 kW/m^2/day to 4 kW/m^2/day is required and, for PVSs interconnected to the grid, a solar radiation higher than 4 kW/m^2/day (Vanegas Chamorro et al., 2015), a condition that is met for Nuevo Laredo.

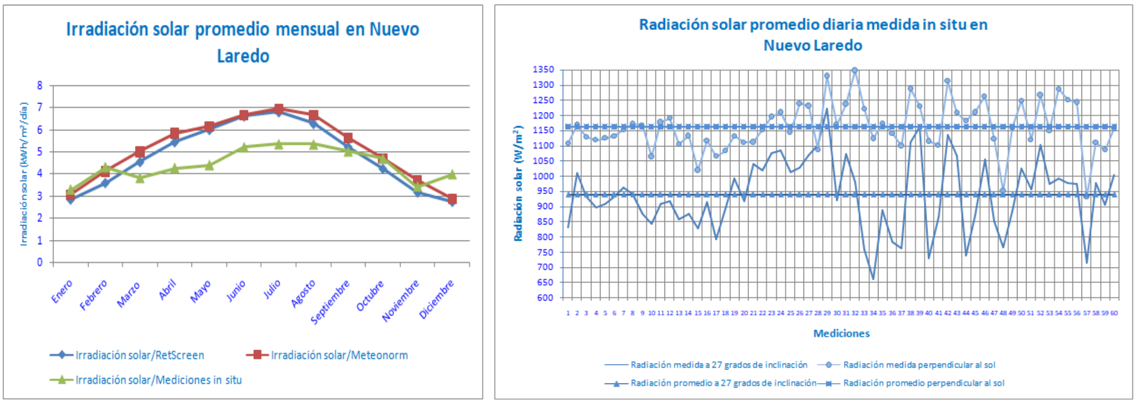


Figure 3. Solar irradiance and radiation measurements

Note: Source: Own elaboration with data from RetScreen software, Meteonorm, and in situ measurements.

j2: Temperature (T)

The obtaining of this variable according to the methodology previously described is shown graphically in Figure 4, reaching maximum average temperatures of 40.50 ºC in the hottest months and 2.5 ºC in the coldest months, causing possible effects on PV generation if the selection of PV components is not adequate, since at operating temperatures above 25 ºC, appreciable losses are generated in the performance of the cells (Mazón Hernández, 2014).

The actual operating temperature of a PVM normally reaches between 15 ºC and 20 ºC above ambient temperature (Pérez Regalado, 2010), making it necessary to use PVMs with high thermal coefficients to withstand the temperature level of the region. High temperatures reduce the voltage and power generated and, at temperatures of zero or below 0 ºC the voltage generated increases according to a factor specified in article 690.7 of the National Electric Code by up to 20%, which can affect the operation of the inverter and cause failures of the entire PVS. There is a wide range of PVM and commercial inverters with temperature coefficients wide enough to be used in every region and affect the performance of the PVS to a lesser degree.

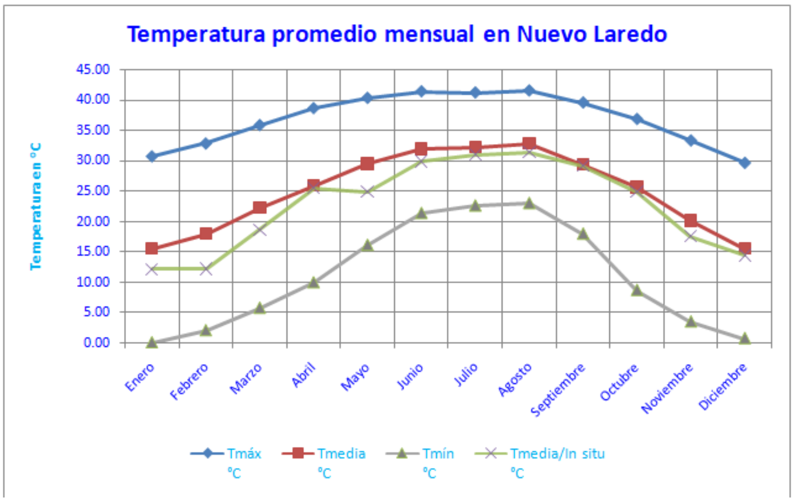


Figure 4. Monthly temperature trend.

Note: Source: Own elaboration with data from EMAINL and in situ measurements.

Figure 5 shows that 47% of 42 PVM manufacturers analyzed have a power temperature coefficient (P_{max}) higher than 0.4%/ºC, meaning that for every degree Celsius above 25 ºC in the cell working temperature, 0.4% of the nominal power generated by each PVM cell is lost.

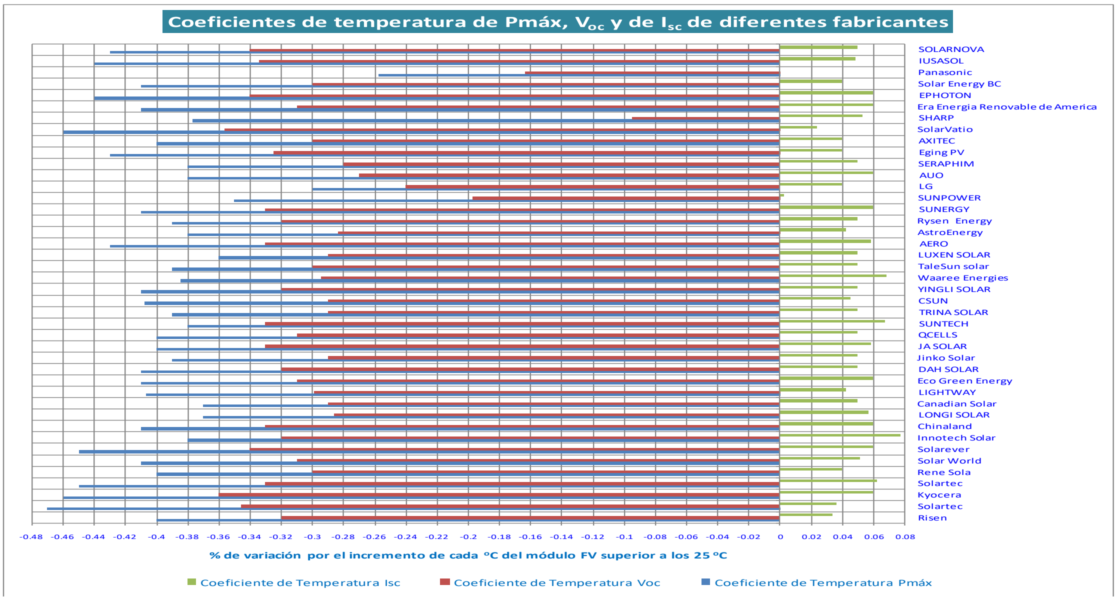


Figure 5. PVM temperature coefficients (I_{sc}: short circuit current; V_{oc}: open circuit voltage)

Note: Source: Own elaboration with data from manufacturer's data sheets.

It is recommended to use modules with low power temperature coefficients, avoiding those with higher coefficients since they present higher losses reducing power. For this reason, it is suggested that modules with temperature coefficients of -0.4%/ºC or lower be used in Nuevo Laredo, guaranteeing better performance. The nominal operating temperature of the PVMs also affects their performance. Figure 6 shows that 78% of the PVMs of the 42 manufacturers mentioned above withstand operating temperatures from -40 ºC to +85 ºC, 5 % from -40 ºC to +80 ºC, and 17 % withstand operating temperatures from -40 ºC to +85 ºC.

According to the temperature analysis shown above, it is observed that the PVMs of the 42 manufacturers comply with the temperature parameter required for Nuevo Laredo, even if the module temperature reaches 60.50 ºC (40.50 ºC +20 ºC), a value within the operating range that any PVM can withstand as shown in Figure 6, a condition that is also widely met for temperatures below zero.

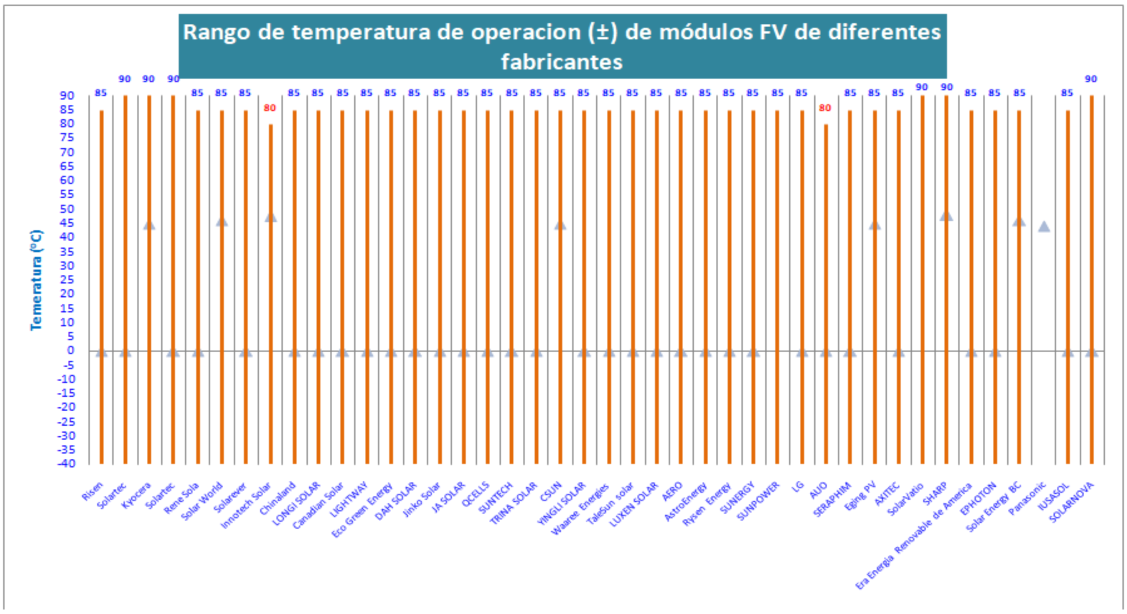


Figure 6. PVM operating temperature
Note: Source: Own elaboration with data from manufacturer's data sheets.

j3: Wind speed (WS)

Wind speed and its mechanical force of impact (Reguera Gil, 2015) is another relevant variable to be considered when planning and developing distributed or centralized photovoltaic generation projects; this variable is obtained according to the methodology previously described in this article. Figure **7** shows that the average maximum WS oscillates between 39 km/h with maximum gusts of up to 55 km/h, still being a moderate speed without major risk as a mechanical force of impact on the PVMs and their structures, since it is within the limits indicated by the manufacturers, acting only as a natural cooling system of the PVS when its speed increases (Mazón Hernández, 2014).

Knowing the average WS and the maximum gusts of the region, in this case for Nuevo Laredo, they are compared with the specifications of different PVMs in terms of their capacity to withstand wind loads. Figure 8 shows the load capacity caused by wind and snow forces supported by the PVMs according to the specifications of 42 manufacturers, showing that they support wind forces from 2,400 Pa to 5,400 Pa, in accordance with the European standard IEC 61215, which indicates a standard value of 2,400 Pa. The maximum value of 5,400 Pa is relevant in areas where the WS is very high during the year, which is not the case for Nuevo Laredo. For these WS, the use of anodized aluminum structures is recommended for mounting the PVMs due to their high resistance to mechanical strength and corrosion.

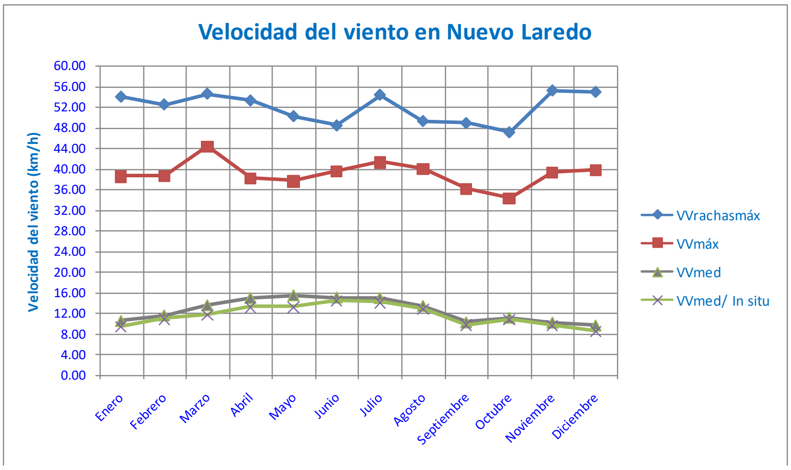


Figure 7. Average, maximum wind speed and maximum wind gusts.
Note: Source: Own elaboration with data from EMAINL and in situ measurements.

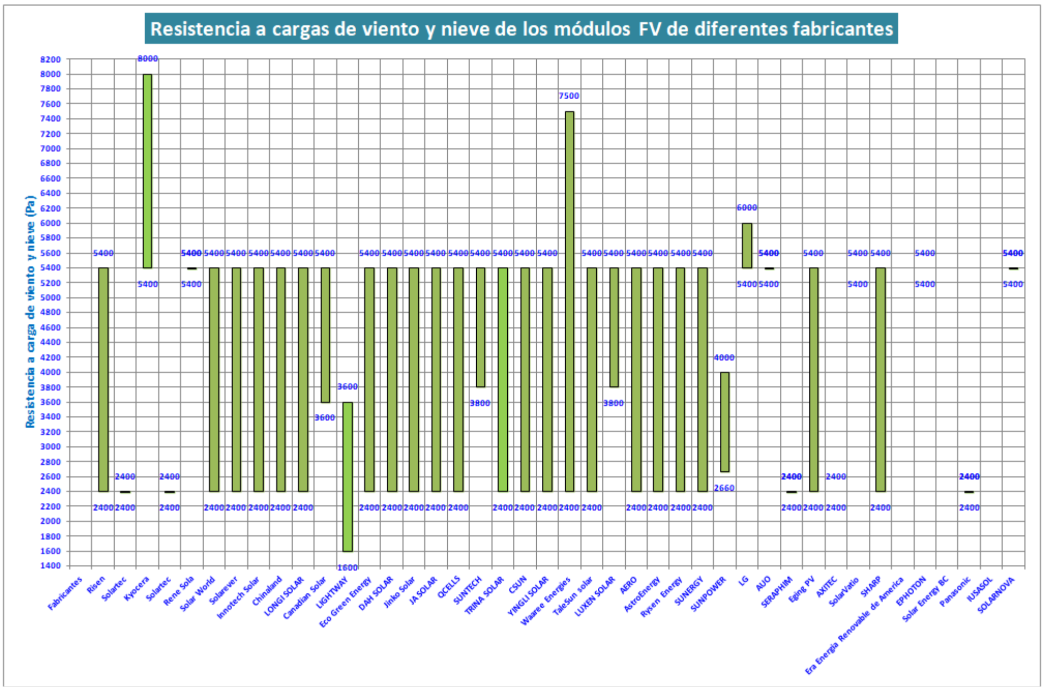


Figure 8. Resistance to mechanical loads of PVMs
Note: Source: Own elaboration with data from manufacturer's data sheets.

J4: Relative humidity (RH)

Figure 9 shows the monthly and annual behavior of relative humidity in Nuevo Laredo with data taken in situ and from the Nuevo Laredo international airport weather station (EMAINL). It is observed that the general average is between 55% to 60%, which is acceptable due to the fact that Nuevo Laredo has an extreme dry climate with large temperature oscillations from -3 ºC in winter to 46 ºC in summer, with August being the hottest month and January the coldest month (Institute for Competitiveness and Foreign Trade of Nuevo Laredo, 2021). Although the maximum humidity value ranges between 85%, the frequency of occurrence per month is from 1 to 3 days and mostly occurs in the coldest months of the year, prevailing average RH values that do not cause premature oxidation or failure of the PVMs by potential induced degradation (PID) caused by moisture seepage in the encapsulated PVMs.

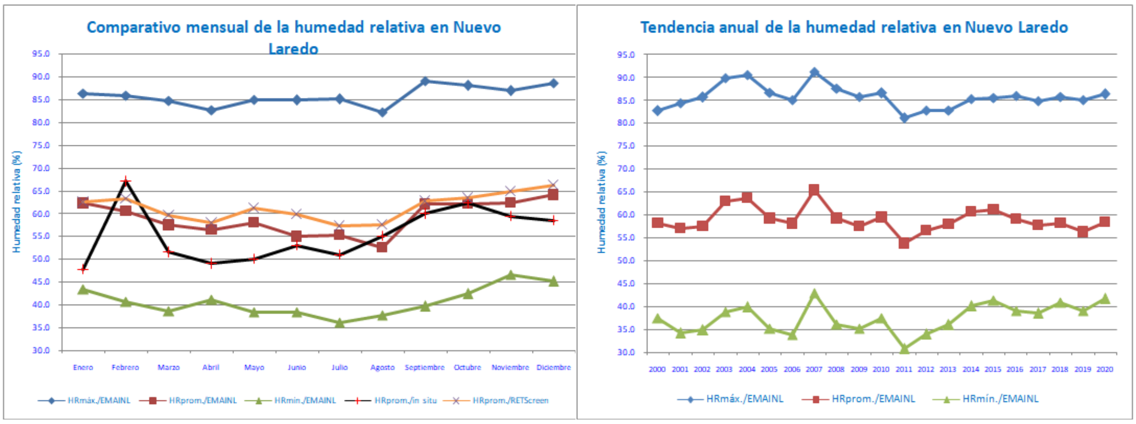
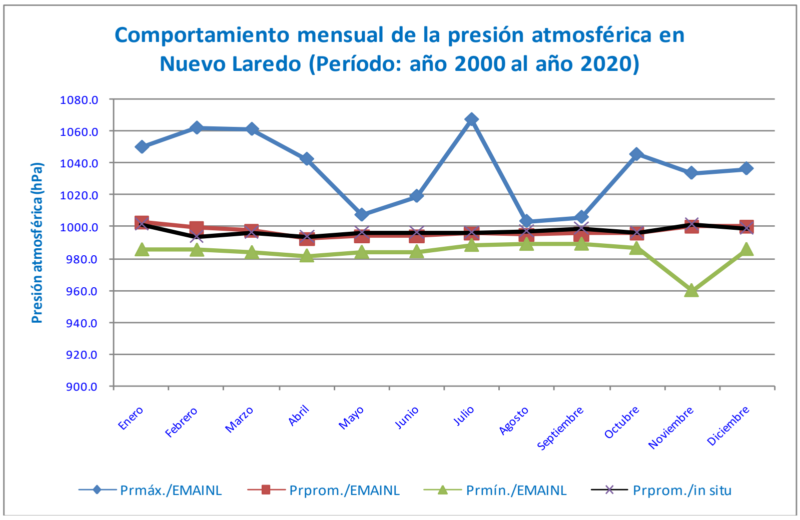


Figure 9. Relative humidity trend in Nuevo Laredo.
Note: Source: Own elaboration with data measured in situ and from EMAINL.

J5: Atmospheric pressure

The atmospheric pressure above sea level is 1,013.25 hPa and at higher elevations is reduced to less than 700 hPa, given that Nuevo Laredo has an altitude above sea level that varies from 138 m to 150 m, the effect is negligible and is not considered to have a major effect on the performance of the PVS to be installed in this region of Tamaulipas. Lowering the pressure below the local atmospheric pressure generates storms or bad weather, which is not typical in Nuevo Laredo where most of the time the weather is dry and with low precipitation.

Figure 10 shows a very stable trend in pressure variation which is largely attributed to the semi-desert climate in Nuevo Laredo, maintaining a monthly average of 997 hPa. This variable is not considered in the manufacturers' specifications because it does not directly affect the PVM, but rather through its effects, especially when it presents a very wide range of variation.



Atmospheric pressure trend in Nuevo Laredo.
Note: Source: Own elaboration with data measured in situ and from EMAINL.

J6: Rainfall Analysis

Precipitation in Nuevo Laredo varies from 550 mm to 600 mm (Tamaulipas Civil Protection, 2011), showing in Figure 11 that during the months of May to October precipitation is higher, reaching an annual average of 553.8 mm. Due to Nuevo Laredo's semi-desert climate, rainfall during most of the year is scarce with a daily average of approximately 45 days during a 20-year analysis period, i.e., only 12% of the days of the year are rainy.

Rain is a natural way of cleaning the PVMs, but when it is very frequent it causes oxidation in the support structures, for this reason, anodized aluminum is frequently used and, in rare cases, iron structures are used. According to this analysis, precipitation in Nuevo Laredo does not represent a major problem that causes premature oxidation or PID problems in the PVMs. However, to ensure long life, the use of anodized aluminum structures for the attachment of the PVMs is recommended.

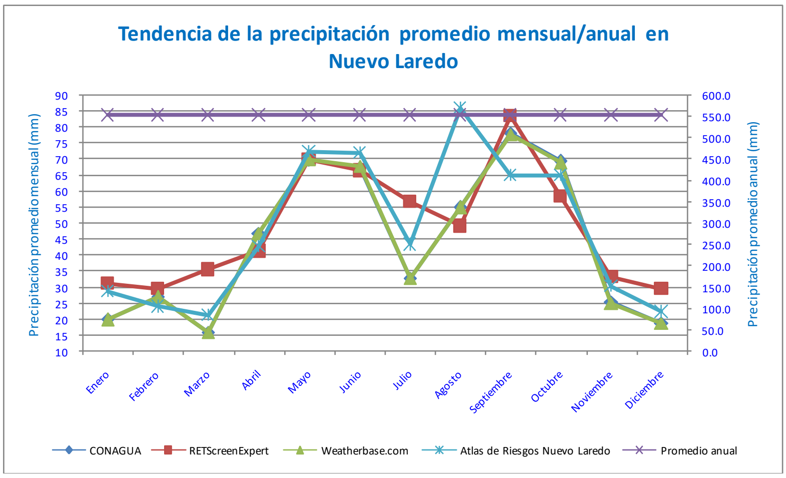


Figure 11. Rainfall trend in Nuevo Laredo.
Note: Source: Own elaboration with data from different database sources.

J7: Hail and snow analysis

Figure 12 shows the trend of hail fall in Nuevo Laredo and the region, showing a low recurrence being a low risk variable; however, it is convenient that the PVMs meet certain standards to the impact force. In the referred figure, an annual maximum of 2 days per year is observed, being normally one day per year, even during several years there is no hail fall.

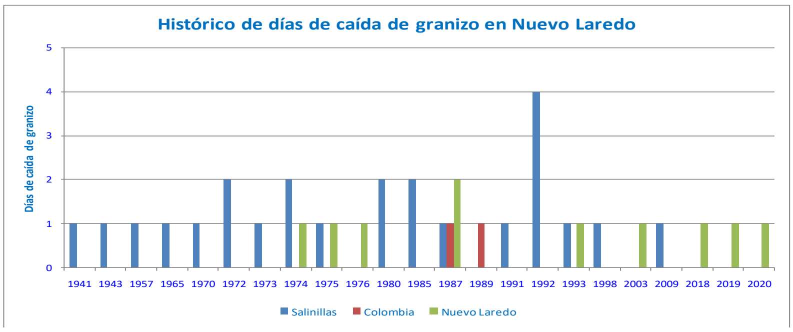


Figure 12. Annual behavior of hail fall in Nuevo Laredo.
Note: Source: Own elaboration with data from the National Meteorological System (SMN).

As a regional reference, the hail fall in 2 neighboring municipalities located less than 50 km away is plotted, showing a similar trend.

Nuevo Laredo is not a snowfall area and on rare occasions a light layer of snow has fallen, so its analysis is irrelevant.

J8: Peak solar hours

The PSH (Pérez Martínez et al., 2017) is a variable obtained from the solar irradiance of the region divided by the STC of the PVMs equivalent to 1,000 W/m^2. The average PSH in Nuevo Laredo is obtained from the average insolation divided by the STC value resulting in 5.0 h according to monitoring data taken in situ during a period of 18 months and of 5.027 h in annual average according to SAM software (system advisor model) as shown in Figure 13, being both values similar and acceptable for modules with efficiencies higher than 16% to be installed in Nuevo Laredo.

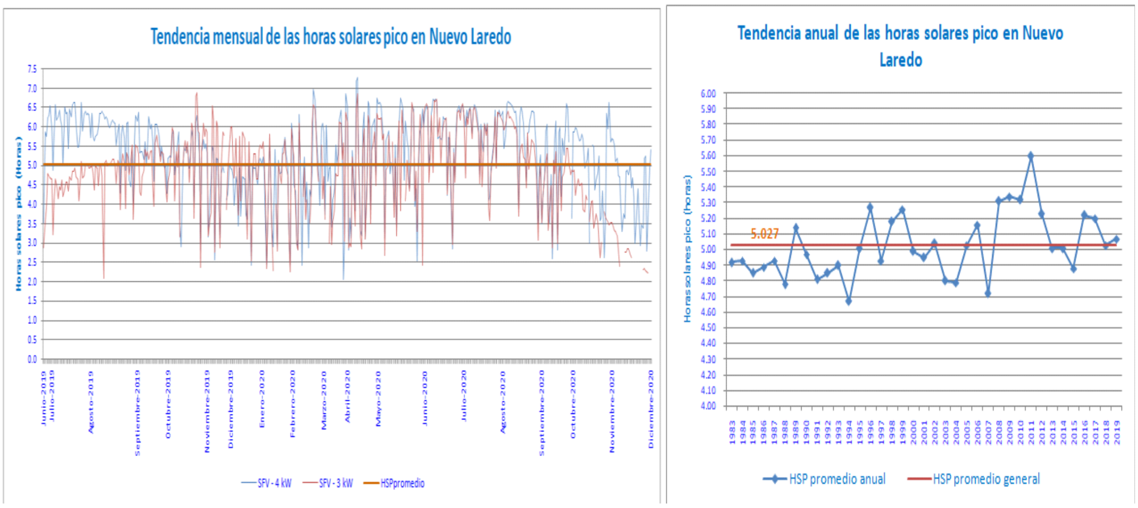


Figure 13. Monthly and annual trend of PSH in Nuevo Laredo.
Note: Source: Own elaboration with data taken in situ and from SAM software.

J9: Correlation analysis between variables

The analysis referred to in the energy model considers reviewing the correlation between variables with the objective of analyzing the behavior of the PVS. Figure 14 shows the hourly electric power generation capacities of two PVSs used as a sample, located at a distance of 25 km from each other, during a sampling period from 31-May to 23-June-2020.

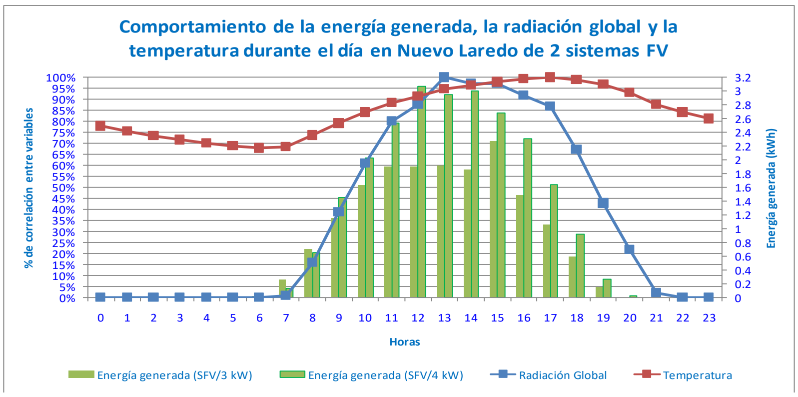


Figure 14. Comparison of meteorological variables and PV-generated energy.
Note: Source: Own elaboration with data from https://www.meteoblue.com/es/tiempo/archive/export/nuevo-laredo and Apsystem.

It is observed that as the irradiation increases so does the temperature and the energy generated in both PVS (Granda Gutiérrez et al., 2013); however, after a certain time of the day, although the temperature still remains high, the radiation is reduced and also the energy generated in both PVS in a proportional way. Proving that the energy generated depends directly on the radiation and, in this case, the temperature has a minor effect due to the fact that the temperature coefficient of the modules used is less than -0.4%/ºC.

Discussion and conclusions

Discussion

The detailed analysis of the variables referred to in the proposed energy model allows considering the most important parameters when designing a PVS to ensure optimal generation, selecting the materials and equipment with the most appropriate specifications to withstand the environmental conditions of the region under study, and determining whether or not the site is viable for installing PVS.

The model considers most of the variables that affect or optimize PV power generation to ensure a robust, reliable design that guarantees a return on investment for residential, commercial, service, and industrial users through financial analysis (Caamaño Martín, 1998).

Table 5 shows the parameters obtained by applying the methodology according to the proposed model, noting that the site is viable for installing PVS.

Table 5
VFS input variables for Nuevo Laredo

Variable	Average range of the variable	Comment
Irradiance (G)	4.81-5.03-5.19 kWh/m^2	High average value of the Mexican Republic.
Temperature (T)	10 ºC minimum average 25 ºC average 37 ºC maximum average	Although there are occasional extreme values of -3 ºC in winter and up to 45 ºC in summer, the average values are as indicated and are within the specifications of the PVM manufacturers.
Wind speed (WS)	30-39-45 km/h average top speed	Although there are occasional gusts of up to 55-80 and rarely 100 km/h, these values are still within the specifications of the PVM manufacturers.
Relative Humidity (RH)	55 % – 60 %	There are occasional values of 85 %, but the average is 55 %, which is not a risk of high humidity accelerating oxidation or leaching in the PVM encapsulates.
Atmospheric pressure (Pr)	987.1 - 1,012.2 - hPa	Little variation, with no major effect due to the region's low altitude of 138 masl. Monthly average 997 hPa.
Pluvial precipitation (PP)	550 - 553.8 - 600 mm	Low values that do not represent risks for the deterioration of the PVM.
Hail and snow (HN)	20 - 50 mm of ϕ	Diameter of porous hail, occasional fall once a year.
Peak solar hours (PSH)	4.81 - 5.027 - 5.19 h	High insolation value

Note: Source: Own elaboration.

By using this model as a methodological guide for the design and development of PV projects, the risks of system malfunction during its lifetime can be reduced by considering manufacturers' specifications. In the study "Improvement strategies for distributed electricity generation with solar, wind, or hybrid equipment" (Cadena et al., 2012), the feasibility of using renewable resources to cover the demand for electricity is mentioned by analyzing the available resource in the region; however, it only refers to certain variables involved in PV systems, which are already considered in the proposed model.

This model aims to bridge the existing gap between systems that integrate most of the conditions necessary to design and install PVS and the information from various studies that currently exist separately, i.e., the existing information is isolated and is not concentrated or integrated into a single functional block that allows a comprehensive or holistic view of the aspects to be considered.

The use of commercial or free software complements and facilitates the development of each block of the model, resulting in a final technical report that can be used to decide to install or improve the PV project under study.

Conclusions and future work

The analysis of each block of the proposed model applied to Nuevo Laredo, allows inferring that the region meets the necessary and sufficient conditions for the installation of PV systems according to Table 5. It is shown that most of the variables analyzed are within the acceptable ranges when complying with the commercial specifications of PV equipment, ensuring the feasibility of the project.

By breaking down and developing each block of the proposed model, performing the measurements and calculations of the indicated variables, comparing them with applicable standards and regulations according to the region or country, considering the specifications of PV equipment manufacturers, differentiating the types of users to perform demand planning studies (Falcón Roque, 2018), and correctly sizing the system, a robust and complete design that makes the development of the PV project viable will be ensured.

Additionally, the model requires in situ data collection of solar radiation, information that is lacking in most regions of Mexico, relying only on data obtained from measurement stations closer to the study area that are several kilometers away, or satellite data that have certain percentages of error (Grossi Gallegos, 1999). The study (Osseweijer et al., 2017) considers the importance of the involvement of industry (suppliers, consumers), academia (to conduct research and training of skilled labor) and, the government (to establish regulations) as stakeholders in the use and promotion of PVS, conditions that are included in the proposed study.

Currently, in Nuevo Laredo, there are more than 100 PV systems installed with capacities from 1 kW to 202 kW. However, there is still a captive market of 126,127 domestic users, 9161 in PDBT6 tariff (small demand in low voltage), 1754 with GDMTO6 tariff (high demand medium ordinary voltage), and 644 users in GDMTH6 (high demand medium hourly voltage) to implement distributed generation PV projects.

By developing and integrating in a final report all the aspects included in each block of the model and according to the flow diagram in Figure 2 previously mentioned, the results, in addition to being used for the purposes described, could also be used as a reference and complement for the development of future research that requires analyzing the variables and other characteristics and aspects inherent to PVS, resulting in more complete studies.

As future and complementary work to this research project, an abstract analysis of the variables and their mathematical representation as a function of those that are affected by the behavior of others is proposed, being an example the power generated from the PVS (P) as a direct function of the irradiation (G) incident on the PVMs and of the operating temperature of the system (T), that is, P→ (G, T). Further work should consider the use of equations for both sizing and calculation of meteorological and electrical variables.

The development of mathematical models on the degradation of PVMs (Reguera Gil, 2015), according to the region where they are installed, are also topics of interest and complementary to this project.

References

Becerra López, H., Agredano Díaz, J., and Huacuz Villamar, J. (2010). *User's Guide to Grid-Interconnected Photovoltaic Systems, Small-Scale Applications* (No. 1). Electrical Research Institute. https://www.ineel.mx/flipbook/libros/PVSI.pdf.

Caamaño Martín, E. (1998). *Grid-connected photovoltaic buildings: characterization and analysis*. (Doctoral thesis). Universidad Politécnica de Madrid. http://oa.upm.es/1322/.

Cadena, C., Salazar, G., Javi, V., and Tilca, F. (2012). *Improvement strategies for distributed electric power generation with solar, wind or hybrid equipment*. In *IV Congresso Brasileiro de energía solar e V Conferencia de Latino-americana da ISES.* National Council of Scientific and Technical Research. https://ri.conicet.gov.ar/bitstream/handle/11336/15092/CONICET_Digital_Nro.17885.pdf?sequence=1&isAllowed=y.

Collado Fernández, E. (2009). *Solar photovoltaic energy, competitiveness and economic evaluation, comparative and models* (Doctoral thesis). Universidad Nacional de Educación a Distancia. http://www.ieec.uned.es/PersonalDIEEC/archivos/tesis-doctoral-eduardo-collado.pdf.

De Juana Sardón, J. M., de Francisco García, A., Fernández González, J., Santos García, F., Herrero García, M. A., and Crespo Martínez, A. (2009). *Energías Renovables para el desarrollo (*1st. ed.). Paraninfo.

Duarte, E. (2017, May 23). Nuevo Laredo Bridge III, the giant of commerce. *T21mx.* http://t21.com.mx/logistica/2017/05/23/puente-iii-nuevo-laredo-gigante-comercio.

ENERDATA. (2020). *World Energy Statistical Yearbook 2020*: *Share of renewables in electricity production*. https://datos.enerdata.net/energias-renovables/produccion-electricidad-renovable.html.

Falcón Roque, E. J. (2018). *Development of a sustainable energy planning model using multi-criteria optimization techniques: an application to the province of Cajamarca, Peru*. (Doctoral dissertation). Universidad Politécnica de Madrid]. https://doi.org/10.20868/UPM.thesis.52109.

Flores Contreras, I. (2018). New electricity tariff scheme and its feasibility in photovoltaic projects (CONERMEX, Ed.).

https://www.conermex.com.mx/webinar/webinar-05-nuevo-esquema-tarifas%20ele%CC%81ctricas.html.

García Barrios, F. A. (2018). *Effect of environmental factors on the efficiency of photovoltaic solar panel arrays (*Master's thesis). Universidad Autónoma del Caribe. http://hdl.handle.net/11619/3786.

Granda-Gutiérrez, E. E. E., Orta, O. A., Díaz-Guillén, J. C., Jiménez, M. A., Osorio, M., and González Albarrán, M. A. (Eds.). (2013). *Modeling and simulation of solar cells and panels*. In *Congreso Internacional de Ingeniería Electrónica ELECTRO 2013.* (17-22). Instituto Tecnológico de Chihuahua. https://www.researchgate.net/publication/265767005_MODELADO_Y_SIMULACION_DE_CELDAS_Y_PANELES_SOLARES?channel=doi&linkId=541ad2180cf25ebee988c4ec&showFulltext=true.

Grossi Gallegos, H. (1999, January). Comparison of satellite values from the "surface solar energy (sse) data set version 1.0" with ground data from the solarimetric network. *Energías Renovables y Medio Ambiente*, 6, 1-6. https://www.researchgate.net/publication/279752278.

Hernández Gallegos, R. (2017). *Feasibility analysis for the installation of a clean energy system using photovoltaic cells for the power supply of building 4 at ITSLV*. (Master's thesis). CIATEQ Mexico]. http://ciateq.repositorioinstitucional.mx/jspui/handle/1020/97.

Hernández Sampieri, R., Fernández Collado, C. and Baptista Lucio, M. P. (2010). *Metodología de la investigación*. Mc Graw Hill.

Nuevo Laredo Institute for Competitiveness and Foreign Trade. (2020, February). *Prontuario socioeconómico binacional 2020 Región Laredos (*No. 4). http://www.iccedenuevolaredo.org/prontuario/condiciones.html.

Kühne, K., Sánchez, L., Roth, J., Tornel, C., and Gerasimchuk, I. (2019, June). Beyond *fossil fuels: Fiscal transition in Mexico*. https://www.iisd.org/system/files/publications/combustibles-fosiles-transicion-fiscal-en-mexico.pdf?q=sites/default/files/publications/combustibles-fosiles-transicion-fiscal-en-mexico.pdf.

Masa Bote, D. (2014). *Contribution to the integration of grid-connected photovoltaic systems: solar resource and generation prediction*. (Doctoral dissertation). Universidad Politécnica de Madrid]. http://oa.upm.es/29110/1/DANIEL_MASA_BOTE.pdf.

Mazón Hernández, R. (2014). *Study of the influence of natural and induced air cooling on the behavior of photovoltaic installations* (Doctoral Thesis). Polytechnic University of Cartagena Department of Thermal and Fluids Engineering. http://hdl.handle.net/10317/4780.

Messenger, R. A. and Ventre, J. (2005). *Photovoltaic Systems Engineering*. CRC Press LLC.

Osseweijer, F. J. W., van den Hurk, L. B. P., Teunissen, E. J. J. H. M., and van Sark, W. G. J. J. H. M. (2017). A review of the Dutch ecosystem for building integrated photovoltaics. *ELSEVIER, 111*, 974-981.

https://www.researchgate.net/publication/315976225_A_Review_of_the_Dutch_Ecosystem_for_Building_Integrated_Photovoltaics.

Pérez Regalado, M. J. (2010). *Thermographic study of the influence of temperature on photovoltaic modules*. (Engineering Thesis). Universidad Carlos III de Madrid]. https://docplayer.es/8249240-Universidad-carlos-iii-de-madrid.html.

Pérez Martínez, M., Morales Rodríguez, I. C. , and Castro, E. (May, 2017). The equivalent peak solar hour, definition and interpretation. *Journal of Energy Engineering*, *XXXVIII*(2), 126-131. https://rie.cujae.edu.cu/index.php/RIE/article/view/506.

Civil Protection Tamaulipas. (2011). Atlas de riesgos del Municipio de Nuevo Laredo. https://www.tamaulipas.gob.mx/proteccioncivil/wp-content/uploads/sites/36/2011/12/ATLAS-DE-RIESGOS-DE-NUEVO-LAREDO.pdf.

Reguera Gil, F. J. (2015). *Degradation analysis of photovoltaic modules*. (Master's thesis). International University of Andalusia]. http://hdl.handle.net/10334/3524.

Sol Energy (February, 2018). *Degradation in Solar Panels by Potential Induced Degradation (PID)*. https://www.solenergy.mx/es/principal/blog/degradacion-en-paneles-solares-por-potencial-inducido-pid#.

Vanegas Chamorro, M., Villicaña Ortíz, E., and Arrieta Viana, L. (2015, June). Quantification and characterization of solar radiation in the department of La Guajira-Colombia using atmospheric transmissivity calculation. *PROSPECTIVA, 13*(2). https://www.redalyc.org/pdf/4962/496250642007.pdf. https://www.redalyc.org/pdf/4962/496250642007.pdf

Vigil Galán, O., Jiménez Olarte, D., Contreras Puente, G. (2018). Effect of Mexican environmental conditions on the performance of photovoltaic modules of different technologies. *Revista Eficiencia Energética*, *4*(17), 13-16. http://www.fide.org.mx/wp-content/uploads/2018/05/eficiencia_energetica-17/.

World Energy Markets Observatory. (2019). *Crisis as opportunity*. https://www.capgemini.com/es-es/world-energy-markets-observatory-2019/.

Receipt date: 04/05/2021
Revision date: 06/15/2021
Acceptance date: 06/30/2021