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Research Article

A Simple and Inexpensive Method for Evaluating the Photovoltaic Potential: Its Validation in Buenos Aires and Antarctica

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The use of renewable energies requires a precise and detailed quantification of the resource available. Because of the cost of solar stations or limited availability of skilled human resources, in most emerging countries, this assessment is made only on a few points scattered over large areas. We report here a simple and inexpensive method to evaluate the photovoltaic (PV) potential for a specific geographic region and a given PV capture technology. The system allows for a direct evaluation of the energy actually obtainable by scaling the measurement array of photovoltaic cells. The proposed measurement system can be installed as a stand-alone unit, or as part of a measurement network, connected to a more sophisticated central hub. The measurement station consists of said PV array (or similar PV array), a resistor, and a portable data logger. The system is calibrated with a device composed of a small array of PV cells, a resistor load bank, and two multimeters. Due to its low cost, this system can be replicated as many times as required with minimal investment. This would make it possible to evaluate the available photovoltaic potential of large regions with accurate and detailed data. Measurements carried out in Buenos Aires and in Antarctica confirm the consistency of the method.

1. Introduction

The use of renewable forms of energy is imperative, mainly in emerging countries with large tracts of land with low population density. Alstone et al. [1] call for innovative approaches to address the energy needs of more than 1 billion people; Pillai and Banerjee [2] make a critical study about the use of renewable energy in India, where the majority of this country's population does not have access to electricity; Erisman et al. [3] claim to put people at the centre of a radical reforming in the management of the global change. Lack of energy of many of the world's population was the key point in the 4th International Conference on Applied Energy [4] and the 22nd World Energy Congress [5]; Yan et al. insist on the subject in two detailed articles [6, 7]. Ahuja [8] proposes five ways for 2 billion people to have access to electricity (i.e., "to turn on lights and drink clean water") and Meier [9] suggests innovative financing mechanisms for the PV development in emerging regions. In addition, Hauser et al. [10] make an interesting prospective study on the energy and environment situation for future generations through an "International Goods Game"; their results appear to have implications for policy interventions designed to sustain international public goods.

Systems connected to the network and distributed generation installations require knowing the energy actually available that for a given energy source obviously depends on the local potential and the type of technology used. In the case of photovoltaic (PV) solar energy, procedures to calculate the power response of PV modules and to evaluate their interaction with the primary source are being extensively studied [1, 11–13].

The currently used systems for evaluation of the incident solar energy are based on pyranometers or sensors made of silicon crystal associated with electronic devices. With this piece of equipment it is possible to quantify the PV potential through calibration procedures. The sensor is chosen according to its rate of response and other requirements [14, 15]. The correct design, calibration, and use of these sophisticated equipment provide good information about the irradiance at a given location [16, 17]. On the other hand, many papers aimed at improving the prediction of the performance of a PV energy capture system have been published [14, 18–23]. From an adequate analysis of direct solar measurements and the predicted response of the PV systems it is possible to calculate the energy obtainable for a given location [24, 25].

It is well-known that the response of PV modules is a function of irradiance (that influences mainly the current) and temperature (which produces voltage variations) [14, 18, 19].

In particular, the effect of temperature on the PV cell under operating conditions is very difficult to estimate on the basis of meteorological records or measurements made on the PV module in the laboratory; this is due to its dependence on many factors whose effects are difficult to quantify [26].

It has been reported that results from work stations installed in specific locations can be used as reference for other geographic places; obviously, corrections for different meteorological conditions must be done. In this way, a probable energy yield can be effectively calculated based on the reliability of the data obtained and the correct evaluation of the parameters used in the simulations. Zhang et al. reviewed the state-of-the-art technologies for evaluating the reliability of large-scale PV systems [27]; on the other hand, Arboit et al. assessed the solar potential of low-density urban environments [28, 29]. Salazar and Raichijk studied the assessment of cloud conditions for determining the characteristics of solar resource availability and proposed a way to predict the actual cloud status in high altitude sites [30]. Zegaoui et al. developed a generalized model in order to simulate PV cells behavior; this model was validated experimentally [31]. Quansah et al. presented an empirical model for estimating Global Solar Radiation (GSR) at the Ashanti Region of Ghana; they noticed the effect of using or not air temperature measurements in their calculations [32]. Osinowo et al. [33] made a similar study analysis of GSR in Nigeria, the same as Coulibaly and Ouedraogo made in Burkina Faso [34]. Recently, Chin et al. reviewed 70 important papers on PV models; they discussed the varying degree of trade-off between accuracy, speed, and technical convenience [35]. Salam et al. made a technological and state-of-the-art review about advantages and limitations of soft computing techniques for maximum power point tracking of PV systems [36]. Their work completed the excellent 2009 paper by Bakirci [37]. Salazar and coworkers proposed practical models to estimate solar irradiance under different sky conditions [38, 39]. Prediction models of stand-alone PV systems were extended to storage devices such as lead-acid batteries [40].

Although the use of sophisticated equipment provides accurate and detailed information regarding all variables concerning solar radiation, in most emerging countries detailed measurements of the solar potential are made only on a few points scattered over large areas [41–44]. Unfortunately, due to the cost of solar stations, the limited availability of skilled human resources, and low research budgets, it is impossible to install a sufficient number of measuring devices for the large areas under study [45–47]. Thus, important information related to the effect of local factors such as landforms, cloudiness, or presence of aerosols is not considered [28–30, 40].

For these reasons, in large and sparsely populated emerging countries, it would be important to measure the PV potential by means of instruments that are (1) cheap enough to be replicated in many places; (2) accurate and precise; (3) reproducible to obtain a detailed local PV evaluation; and (4) easy to install, calibrate, and use.

In this paper we propose a simple and inexpensive system to assess with great detail and good accuracy the solar PV potential in any point of a geographical region for a given PV technology. The proposed evaluation set can be installed as a stand-alone unit, or as part of a measurement network, connected to a more sophisticated commercial measurement unit working as a central hub. This new evaluation system allows projecting a PV plant by scaling up of the area of the measurement device, a main goal for our studies on PV applications in Antarctica.

The system is based on a PV module connected to a single discharge resistor; the voltage drop across this resistor is periodically measured and recorded by a data logger.

The appropriate resistor value is selected by means of a calibration device. This consists of a small array of PV cells, a resistor load bank, and two multimeters and allows obtaining the discharge curves of the PV module under different possible levels of power output (related to the incident irradiance).

Thus, a linear relationship can be established between the voltage drop across the selected resistor and the maximum power obtainable from the PV module. In this way it is possible to calculate the power and the energy delivered by a determined PV system in a given location; this is done by the periodic record of the voltage drop across the selected resistor. In order to avoid large deviations in the results (mainly due to temperature effects), it is advisable to make the calibration within ranges in the vicinity of the final measurement conditions.

The measurement device proposed here is intended to neither characterize a photovoltaic system nor record the weather conditions at a geographical point but to perform an *in situ* quantification of the photovoltaic potential obtainable from a given technology in a specific geographic location.

The device is especially useful for development countries, where the financial resources do not allow access to sophisticated equipment.

2. Experimental

Three commercial KS-3T 12 V Solartec polycrystalline silicon photovoltaic cell modules having a rated power of 3 W were used (module dimensions are 243 mm × 176 mm; standard reference parameters corresponding to a solar radiation

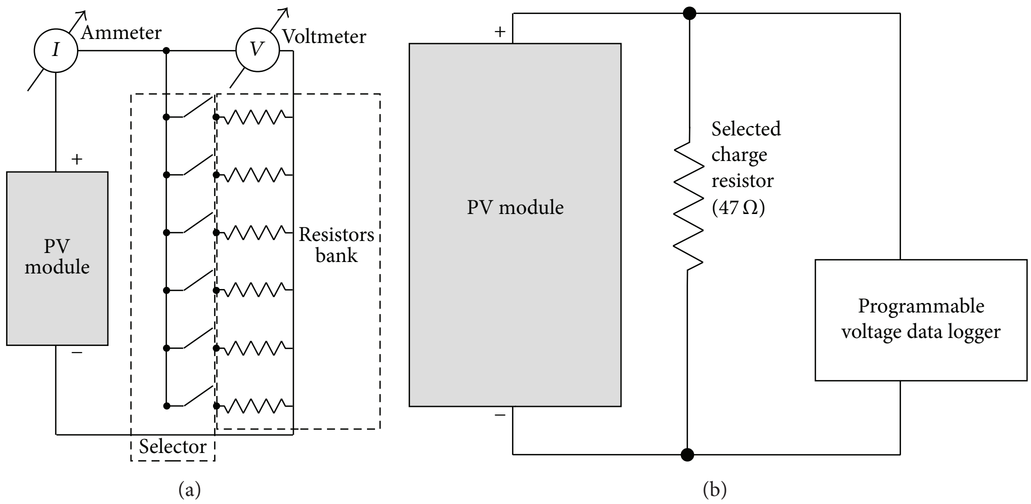

FIGURE 1: Calibration (a) and measurement (b) of circuit schemes.

intensity of $1\,kW/m^2$ and 25°C are rated voltage: 12 V; short-circuit current: 0.21 A; and open-circuit voltage: 21 V). Two Fluke 189 True RMS Multimeters were used for voltage and current measurements. The automatic data collection was performed using a Lascar Electronics EL-USB-3 0–30 V USB voltage data logger 0–30 V. A resistor load bank constructed in our laboratory was used to obtain the *I-V* response curves, which allow the characterization of the PV module; the resistance values ranged from 25 to 650 Ω. A diagram of the circuit used is shown in Figure 1(a). The calibration procedure was performed under irradiance levels greater than $1.10\,kW\,m^{-2}$. From the set of *I-V* curves obtained, the most appropriate resistance is chosen to build the measuring device (see diagram in Figure 1(b)); details of the procedure for this election are explained in the next section.

3. Results and Discussion

The resistive load bank was used to obtain the characteristic current-potential (*I-V*) curves for the PV module to be used under different irradiance conditions (Figure 2). These results are consistent with the behavior of PV cells and PV modules extensively documented in the literature [18, 19]. The curved zone for every *I-V* function constitutes the working region in which the PV module delivers maximum power.

In Figure 3, the straight lines corresponding to the different resistance values for all calibration curves under different irradiance conditions are shown.

From those straight lines, it is necessary to choose the one with the lowest slope for which all points corresponding to the whole range of irradiance measurements are located within the evaluation area (low voltage area). As well-known, the current in this zone is a linear function of irradiance; therefore, the voltage across the terminals of the resistor is proportional to the irradiance and, in turn, the maximum power on the *I-V* curve and the resistor voltage drop are linear functions of the irradiance (assuming constant temperature) [14, 19]. Thus, for a given irradiance, it is possible to establish a simple correspondence between the voltage measured for the selected resistance and the maximum power obtainable. It is also easy to see that, by using this straight line, the experimental errors are minimized.

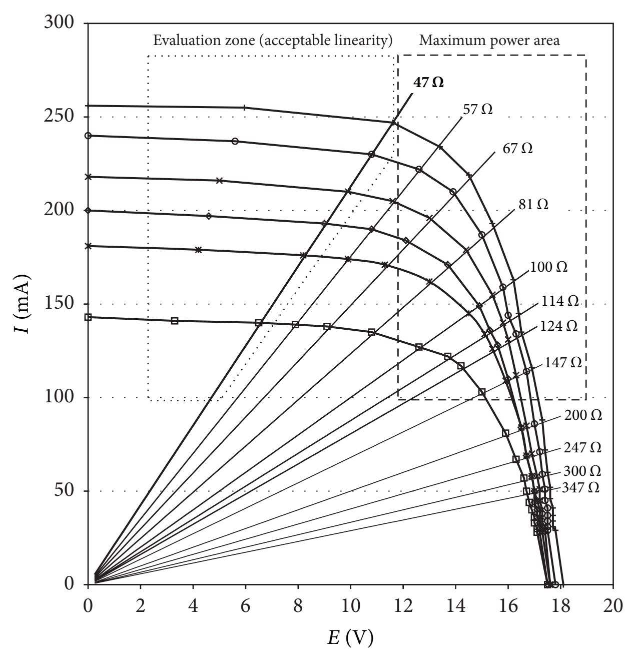

FIGURE 2: Load curves for one of the PV modules (calibration module) under different irradiance conditions. The dashed-line rectangle shows the area where maximum power is achieved. The area enclosed by the dotted lines is the evaluation zone in which acceptable linearity is observed for each characteristic *I-V* curve.

In our case, the straight line chosen corresponds to $R = 47\,\Omega$. For resistance values lesser than 47 Ω the voltage values corresponding to two different irradiance conditions would be almost identical, making it difficult to distinguish between them (this is due to the high slope of the straight lines).

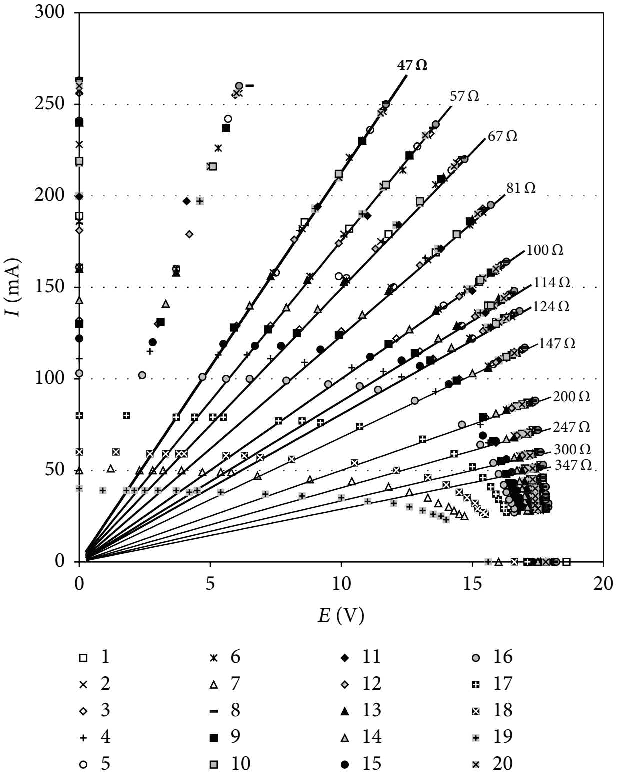

Figure 3: Complete set of load curves for calibration purposes (KS3T-12 V calibration module). The straight lines that correspond to the different resistance values for all calibration curves are shown.

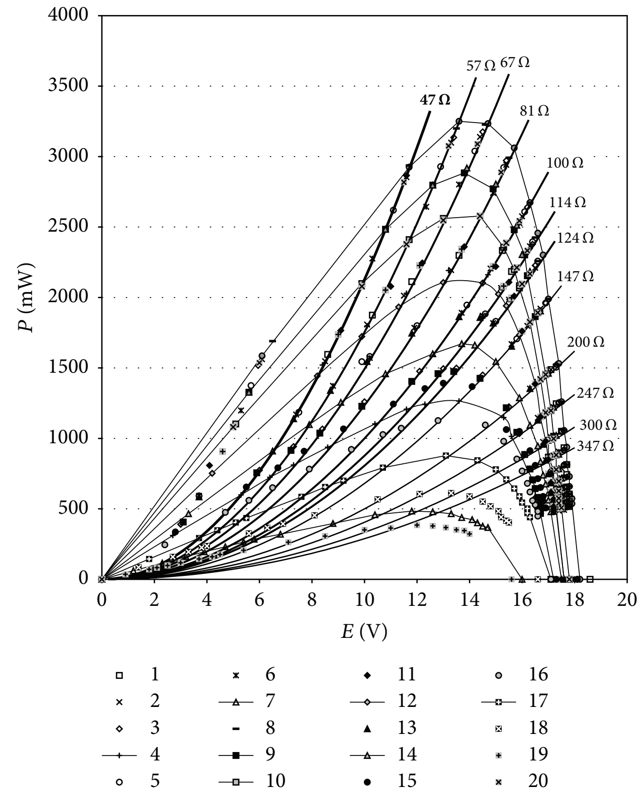

Figure 4: Power versus voltage curves obtained for the 20 load curves tested during calibration of the KS3T-12 V PV modules. The 47 Ω load curve is entirely within the linear region of all calibration curves. Plotted from data of Figure 3.

In Figure 4 the power-voltage (P-V) curves for different resistance values are shown. It can be seen that the curve $P = V^2/R$ for $R = 47$ ohms is in the linear region for all loads. Because it has the lowest slope of all the load curves in the evaluation zone, it is easier to distinguish between two adjacent irradiance conditions.

Plotting the maximum power output ($P_{\max}$) versus voltage for $R = 47$ ohm (E_{47}) for each irradiance condition a linear relationship is obtained; the correlation factor is excellent (Table 1 and Figure 5).

In Table 1, only at point 19 a very high percentage deviation is observed. This could be because the measured power is very low. However it should be noted that in the calculation of the total energy (obtainable by integration of the registered powers) the influence of this measurement is minimized.

In order to verify the validity of the $P_{\max}$-E_{47} linearity, measurements were performed under very different conditions for a calibration module and others similar to it (control module), as follows:

(i) Calibration module and control module under similar climatic conditions (Buenos Aires).

(ii) Control module under very different climatic condition (Esperanza Base, Antarctica).

Results are shown in Table 2 (see graph in Figure 6). It can be observed that, under similar climatic conditions,

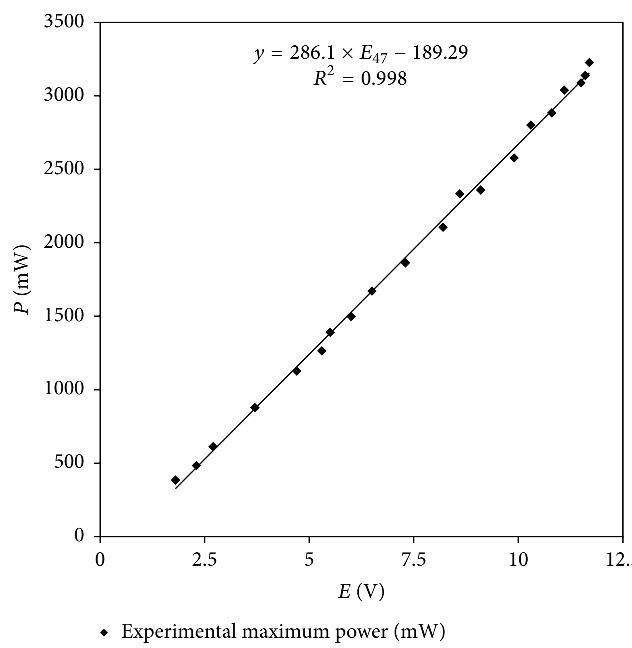

Figure 5: Graphical representation of experimental data from Table 1. Calculated linear regression is also shown.

deviations between the experimental and calculated values for the maximum power obtained for a given module are less

Table 1: Experimental and calculated maximum power delivered by PV module. Percent deviations are also shown.

N	E_{47} (for 47 Ω) (V)	Experimental maximum power (mW)	$286.1 \times E_{47} - 189.29$ Calculated maximum power (mW)	Deviation (%)
1	8.6	2333.3	2271.17	−2.7
2	11.6	3139.2	3129.47	−0.3
3	6	1498.5	1527.31	1.9
4	5.3	1264.8	1327.04	4.9
5	11.1	3038.8	2986.42	−1.7
6	10.3	2801.6	2757.54	−1.6
7	2.3	483.8	468.74	−3.1
8	11.7	3226.6	3158.08	−2.1
9	10.8	2884.2	2900.59	0.6
10	9.9	2577.6	2643.10	2.5
11	9.1	2359.8	2414.22	2.3
12	8.2	2106.0	2156.73	2.4
13	7.3	1863.2	1899.24	1.9
14	6.5	1671.4	1670.36	−0.1
15	5.5	1391.0	1384.26	−0.5
16	4.7	1126.4	1155.38	2.6
17	3.7	877.7	869.28	−1.0
18	2.7	611.8	583.18	−4.7
19	1.8	384.0	325.69	−15.2
20	11.5	3088.8	3100.86	0.4

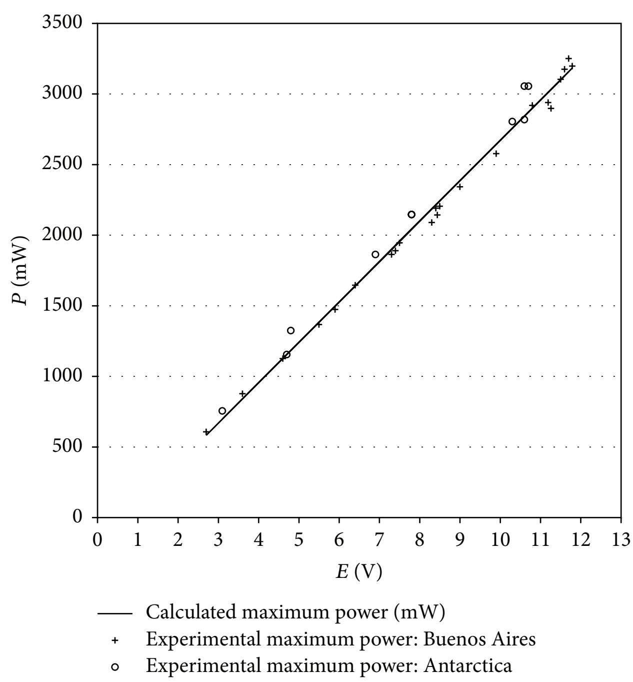

Figure 6: Experimental data compared to the calculated straight line.

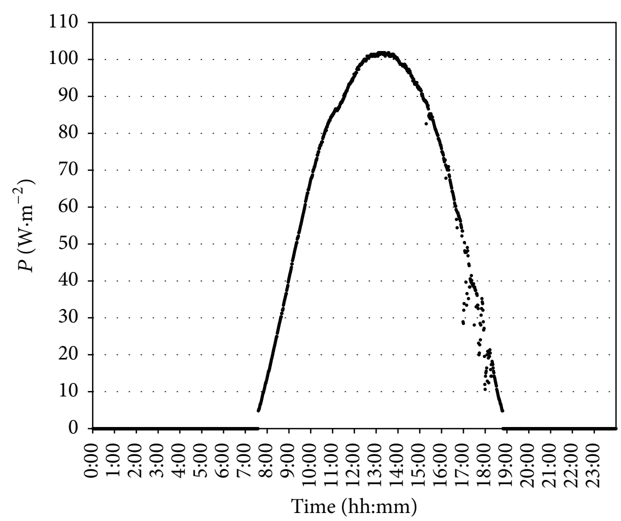

Figure 7: Calculated maximum power from the experimental data taken at Buenos Aires (one-day measurement; one data sample/min).

than 5%. Even for the experimental data taken with a different module, and under very different climatic conditions (Antarctica), the deviation of the calculated values remains less than 11%. This increase in error is mainly attributable to the significant temperature difference between the location of the measuring station and the location where the calibration was performed. However, the error remains within acceptable limits.

As an application example, the results for a sunny day in midsummer in Buenos Aires are shown. The voltages recorded by the data logger—one sample per minute [48, 49]—were used to calculate the power output during the period considered by applying the formula obtained previously (Figure 7). By integrating the power output over time, the total energy output is obtained. For the period considered,

Table 2: Results obtained from measurements carried out under similar climatic conditions for the calibration and similar modules and measurements carried out under very different climatic conditions for a similar but not the calibration module.

Register name: Month/measure number/location***	E_{47} (for 47 Ω) (V)	Measured maximum power (mW)	$286.1 \times E_{47} - 189.29$ Calculated maximum power (mW)	Dev. (%)	**Average temp. (°C) max/min
APR/1/BA	8.5	2205.2	2242.6	1.7	21.0/11.7
APR/2/BA	8.4	2191.2	2214.0	1.0	
APR/3/BA	7.5	1946.0	1956.5	0.5	
APR/4/BA	7.4	1890.6	1927.9	2.0	
APR/5/BA	11.6	3175.5	3129.5	−1.4	
APR/6/BA	5.9	1474.0	1498.7	1.7	
APR/7/BA	11.7	3250.4	3158.1	−2.8	
APR/8/BA	10.8	2919.0	2900.6	−0.6	
APR/9/BA	9.9	2577.6	2643.1	2.5	
APR/10/BA	9.0	2342.7	2385.6	1.8	
APR/11/BA	8.3	2089.8	2185.3	4.6	
APR/12/BA	7.3	1863.2	1899.2	1.9	
APR/13/BA	6.4	1645.6	1641.8	−0.2	
APR/14/BA	5.5	1367.7	1384.3	1.2	
APR/15/BA	4.6	1126.4	1126.8	0.0	
APR/16/BA	3.6	877.7	840.7	−4.2	
APR/17/BA	2.7	607.2	583.2	−4.0	
APR/18/BA	11.5	3103.1	3100.9	−0.1	
JAN/1/BA	11.3	2898.0	3032.2	4.6	29.8/19.6
JAN/2/BA	8.4	2143.5	2225.4	3.8	
JAN/3/BA*	11.2	2939.4	3012.2	2.5	
JAN/4/BA*	11.8	3197.3	3183.8	−0.4	
JAN/1/AN*	10.6	3056.0	2843.4	−7.0	2.3/−2.3
JAN/2/AN*	10.7	3056.0	2872.0	−6.0	
JAN/3/AN*	6.9	1863.0	1784.8	−4.2	
JAN/4/AN*	7.8	2146.2	2042.3	−4.8	
JAN/5/AN*	4.8	1324.8	1184.0	−10.6	
JAN/6/AN*	4.7	1155.0	1155.4	0.0	
JAN/7/AN*	7.8	2146.2	2042.3	−4.8	
JAN/8/AN*	10.3	2805.0	2757.5	−1.7	
JAN/9/AN*	10.6	2819.0	2843.4	0.9	
JAN/10/AN*	3.1	756.0	697.6	−7.7	

*Data taken from PV module similar to the calibration module.
**For reference, the average temperatures for the evaluation days.
***APR: April, autumn in southern hemisphere.
JAN: January, summer in southern hemisphere.
BA: Buenos Aires; Lat.: 34.5 S and Long.: 58.5 W.
AN: Esperanza Bay, Antarctica; Lat.: 63.4 S and Long.: 57.0 W.

the maximum energy obtainable was 739 Wh/m^2. By extending the period of integration, the total energy delivered by the PV modules for any period of interest can be determined.

4. Conclusions

The proposed method has proven to be a valuable, easy to use, and inexpensive tool for the evaluation of photovoltaic potential for a given technology and installation.

The method allows a detailed assessment of vast territories with minimal investment in infrastructure, equipment, and man-hours.

Although advisable, the calibration needs not be carried out in the same region to be evaluated. Obviously, climate conditions must be similar for both locations (as a matter of fact, the difference in average maximum temperature should not exceed 10°C; in addition, wind speed should not be dramatically different).

By appropriate characterization of different PV modules, results from a given technology could be extrapolated to other technologies.

This method does not intend to replace commercial solarimetric stations but allows additional or "satellite" evaluations to obtain a much more detailed map at a much lower cost.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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